User-Centric Power-Friendly Quality-based Network Selection Strategy for Heterogeneous Wireless Environments

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Student ID:___58119949__

Signed:________________

Date:_________________

To my dear parents

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Abstract

The '*Always Best Connected*' vision is built around the scenario of a mobile user seamlessly roaming within a multi-operator multi-technology multi-terminal multi-application multi-user environment supported by the next generation of wireless networks. In this heterogeneous environment, users equipped with multi-mode wireless mobile devices will access rich media services via one or more access networks. All these access networks may differ in terms of technology, coverage range, available bandwidth, operator, monetary cost, energy usage etc. In this context, there is a need for a smart network selection decision to be made, to choose the best available network option to cater for the user's current application and requirements. The decision is a difficult one, especially given the number and dynamics of the possible input parameters. What parameters are used and how those parameters model the application requirements and user needs is important. Also, game theory approaches can be used to model and analyze the cooperative or competitive interaction between the rational decision makers involved, which are users, seeking to get good service quality at good value prices, and/or the network operators, trying to increase their revenue.

This thesis presents the roadmap towards an '*Always Best Connected*' environment. The proposed solution includes an **Adapt-or-Handover solution** which makes use of a **Signal Strength-based Adaptive Multimedia Delivery mechanism (SAMMy)** and a **Power-Friendly Access Network Selection Strategy (PoFANS)** in order to help the user in taking decisions, and to improve the energy efficiency at the end-user mobile device. A **Reputation-based System** is proposed, which models the user-network interaction as a repeated cooperative game following the repeated Prisoner's Dilemma game from Game Theory. It combines reputation-based systems, game theory and a network selection mechanism in order to create a reputation-based heterogeneous environment. In this environment, the users keep track of their individual history with the visited networks. Every time, a user connects to a network the user-network interaction game is played. The outcome of the game is a network reputation factor which reflects the network's previous behavior in assuring service guarantees to the user. The network reputation factor will impact the decision taken by the user next time, when he/she will have to decide whether to connect or not to that specific network.

The performance of the proposed solutions was evaluated through in-depth analysis and both simulation-based and experimental-oriented testing. The results clearly show improved performance of the proposed solutions in comparison with other similar state-of-the-art solutions. An energy consumption study for a Google Nexus One streaming adaptive multimedia was performed, and a comprehensive survey on related Game Theory research are provided as part of the work.

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List of Abbreviations

3GPP: Third Generation Partnership Project
ABC: Always Best Connected
AC/AUC: Authentication Center
AHP: Analytic Hierarchy Process
AMR: Adaptive Multirate
AMPS: Advanced Mobile Phone System
AP: Access Point
AVC: Advanced Video Coding
ASN: Access Service Network
BCMCS: Broadcast and Multicast Services
BER: Bit Error Rate
BSA: Basic Service Area
BSC: Base Station Controller
BSS: Basic Service Set
BTS: Base Transceiver Station
CBR: Constant Bit Rate
CCK: Complementary Code Keying
CDMA: Code Division Multiple Access
CIR: Carrier-to-Interferences Ratio
CN: Core Network
CSN: Connectivity Service Network
DCCP: Datagram Congestion Control Protocol
DCF: Distributed Coordination Function
DCT: Discrete Cosine Transform
DS: Distribution System
DVB: Digital Video Broadcasting
EDCF: Enhanced Distributed Coordination Function

EDGE: Enhanced Data Rates for GSM Evolution

EGPRS: Enhanced GPRS

E-UTRAN: Evolved-UTRAN

EIR: Equipment Identity Register

eNB: evolved NodeB

EPC: Evolved Packet Core

ESS: Extended Service Set

FA: Foreign-Agent

FTP: File Transfer Protocol

GGSN: Gateway GPRS Support Node

GMSC: Gateway Mobile Switching Center

GOP: Group of Pictures

GPRS: General Packet Radio Service

GPS: Global Positioning System

GRA: Grey Relational Analysis

GRC: Grey Relational Coefficient

GSM: Global System for Mobile Communications

HA: Home Agent

HAP: High Altitude Platforms

HD: High Definition

HHO: Horizontal Handover

HIP: Host Identity Protocol

HLR: Home Location Register

HMIPv6: Hierarchical Mobile IPv6

HSCSD: High Speed Circuit Switched Data

HSPA: High-Speed Packet Access

HSDPA: High-speed Downlink Packet Access

HSS: Home Subscriber Server

HSUPA: High-speed Uplink Packet Access

HTTP: Hypertext Transport Protocol

IAPP: Inter Access Point Protocol

IEEE: Institute of Electrical and Electronics Engineers

IEC: International Electrotechnical Commission

IETF: Internet Engineering Task Force

IMS: IP Multimedia Subsystem

IP: Internet Protocol

ISO: International Organization for Standardization
ITU: International Telecommunication Union
JPEG: Joint Photographic Experts Group
LAN: Local Area Network
LMDS: Local Multipoint Distribution System
LTE: Long-Term Evolution
MAC: Medium Access Control
MADM: Multiple Attribute Decision Making
MAN: Metropolitan Area Network
MBMS: Multimedia Broadcast Multicast Service
MDC: Multiple Description Coding
MEW: Multiplicative Exponential Weigthing
MH: Mobile Host
MIHF: Media Independent Handover Function
MICS: Media-Independent Command Service
MIES: Media-Independent Event Service
MIIS: Media-Independent Information Service
MIMO: Multiple Input Multiple Output
MIP: Mobile IP
MIPv4: Mobile IPv4
MIPv6: Mobile IPv6
MMS: Multimedia Message Service
MME: Mobility Management Entity
MN: Mobile Node
MOS: Mean Opinion Score
MPEG: Moving Picture Experts Group
MSC: Mobile Switching Center
MTQI: Mobile TV Quality Index
Non-Ad: Non Adaptive
NMT-450: Nordic Mobile Telephone 450
NSS: Network Switching Subsystem
OFDMA: Orthogonal Frequency-Division Multiple Access
PAN: Personal Area Networks
PCF: Point Coordination Function
PDA: Personal Digital Assistants
PDF: Policy Decision Function

PDN: Packet Data Network

PEVQ: Perceptual Evaluation of Vide Quality

PMIP: Proxy Mobile IP

PMIPv6: Proxy Mobile IPv6

PoFANS: Power Friendly Access Network Selection Mechanism

PSNR: Peak-Signal-to-Noise-Ratio

PSS: Packet-Switched Streaming

PSTN: Public Switching Telephony Network

P-GW: PDN Gateway

QOAS: Quality Oriented Adaptation Scheme

QoE: Quality of Experience

QoS: Quality of Service

RAN: Radio Access Network

RAT: Radio Access Technology

RNC: Radio Network Controller

RSS: Received Signal Strength

RTP: Real Time Transport Protocol

RTCP: RTP Control Protocol

RTSP: Real Time Streaming Protocol

RTT: Round-Trip Time

SAMMy: Signal Strength-based Adaptive Multimedia Delivery

SAW: Simple Additive Weighting

SC-FDMA: Single Carrier FDMA

SCTP: Stream Control Transmission Protocol Mobile

ST-DEV: Standard Deviation

SDMA: Space Division Multiple Access

SGSN: Serving GPRS Support Node

S-GW: Serving Gateway

SIM: Subscriber Identity Module

SINR: Signal to Interference plus Noise Ratio

SIP: Session Initiation Protocol

SIR: Signal-to-Interferences Ratio

SMS: Standard Message Service

SNR: Signal to Noise Ratio

SSIM: Structural Similarity Index

STA: Station

TACS: Total Access Communication System
TCP: Transmission Control Protocol
TDMA: Time Division, Multiple Access
TD-SCDMA: Time Division Synchronous CDMA
TFRC: TCP-Friendly Rate Control
TOPSIS: Technique for Order Preference by Similarity to Ideal Solution
UE: User Equipment
UDP: User Datagram Protocol
UMB: Ultra Mobile Broadband
UMTS: Universal Mobile Telecommunications System
UTRAN: UMTS Terrestrial Access Network
UWB: Ultra-Wideband
VDP: Visual Differences Predictor
VHO: Vertical Handover
VLR: Visitor Location Register
VoD: Video on Demand
VQM: Video Quality Metric
VSQI: Video Streaming Quality Index
VTQI: Video Telephony Quality Index
WAN: Wide Area Network
WCDMA: Wideband CDMA
Wi-Fi: Wireless Fidelity
WiMAX: Worldwide Interoperability for Microwave Access
WLAN: Wireless Local Area Networks
WMAN: Wireless Metropolitan Area Networks
WP: Weighted Product
WPAN: Wireless Personal Area Networks
WRAN: Wireless Regional Area Network
WSNR: Weighted-Signal-to-Noise-Ratio
WWAN: Wireless Wide Area Networks

Chapter 1

Introduction

1.1. Research Motivation

The next generation of wireless networks is already making its way into our daily lives. Figure 1.1 presents an example scenario from the daily life of a mobile user (e.g., student, business professional, etc.) who prefers to be online anytime and anywhere. This enables them to use the e-mail system to keep in touch or close deals, take part in video conferencing, perform video streaming, use voice over IP (VoIP), mobile TV, entertainment services, download music or videos with the preferred band, watch a movie of interest, transfer files to and from business contacts or friends, to do online shopping, and use many other applications. Among these, using social networking applications based on web sites such as Twitter, Facebook, Linkedin, MySpace, etc. is also a possibility. These have become a part of one's daily life and are often used for business (e.g., to post a profile, or look for a job), to connect to people (e.g., share videos, music, photos) or share social media (e.g., news, personal experience, reviews). All these applications can be accessed by any networked-connected user from a variety of devices. Nowadays, with the advances in technology, mobile computing devices such as smartphones, PDAs, small netbooks, and other integrated mobile devices have become more and more affordable, easy to use, and powerful, mobile users expecting rich services at higher quality levels. These advances in mobile devices enable people to connect to the Internet from anywhere at any time even when on the move (e.g., going from home to the office, in the car, on the bus, stuck in traffic, etc.) or stationary (e.g., at home/office/airport/coffee bars, etc.).

The connection to the Internet is possible and can be done via wireline or wireless solutions. Depending on the user location, wireless connectivity is enabled by different Radio Access Technologies (RATs) such as: Global System for Mobile Communications (GSM), Enhanced Data Rates for GSM Evolution (EDGE), Universal Mobile Telecommunications System (UMTS), High Speed Packet Access (HSPA), Long Term Evolution (LTE), Worldwide Interoperability for Microwave Access (WiMAX), Wireless Local Area Networks (WLAN), Wireless Personal Area Network (WPAN), etc. Use of all these RATs is rapidly spreading, covering various geographical locations in an overlapping manner. Moreover, RATs differ in capacity, coverage area, monetary cost, connection speed, and can be deployed by one or more network operators.

Figure 1.1 Example Scenario of a Roaming User

According to Cisco, by 2015 there will be over 7.1 billion mobile-connected devices, approximately equal to the world’s population. Moreover, because of the growing popularity of video-sharing websites, the use of mobile video will more than double every year by 2015, representing the highest growth rate of any application category. By the end of 2011 mobile video traffic will account for 52.8% of the total mobile data traffic and by 2015 mobile video will represent two-thirds of the world’s mobile data traffic [1].

In terms of energy conservation, Information and Communications Technologies (ICT) are seen as part of the solution (e.g., video-conferencing) in order to avoid large carbon footprints, but ICT itself needs to become more energy efficient. For example the EU Commission is pushing for ICT to reduce its own carbon footprint by 20% by 2015 [1]. This makes the understanding of power consumption one of the key challenges in the next generation mobile multimedia networks in order to provide efficient power management.

1.2. Problem Statement

In order to deal with this explosion of mobile broadband data, network operators have started deploying different radio access technologies in overlapping areas. This solution enables them to accommodate more mobile users and to keep up with the traffic demands. In this context, the new challenge that the network operators are facing is to ensure seamless multimedia experience at high quality levels to the end-user in a multi-technology multi-application multi-terminal multi-user environment.

One solution adopted by the network operators in order to deal with this explosion of mobile broadband data is the use of WLAN offload. WLAN networks have had an important impact in the area of mobile communications and their use has grown significantly in recent years (e.g., extended coverage, low-latency, power-efficient connection, reduced loads, etc.). The Wireless-Fidelity (Wi-Fi) offload solution is already adopted by many service providers, (e.g., Deutsche Telekom and iPass launched WiFi Mobilize[1]). This solution enables transfer of some traffic from the core cellular network to WiFi at peak times. In this way users can avail of a wider service offering. However, the overall experience is still far from optimal as providing high quality mobile video services with QoS (Quality of Service) provisioning over resource-constrained wireless networks remains a challenge. Moreover user mobility, as well as the heterogeneity of mobile devices (e.g., different operating systems, display size, CPU capabilities, battery limitations, etc.), and the wide range of the video-centric applications (e.g., VoD (Video On Demand), video games, live video streaming, video conferences, surveillance, etc.) opens up the demand for user-centric solutions that adapt the application to the underlying network conditions and device characteristics.

Mobile users want to be connected to the best value network that best satisfies their preferences for their current application(s). On the other hand, the network operators want to maximize their revenue by efficiently using their networks to satisfy and retain the most users possible.

Challenges for the operators include network optimization especially for video traffic, if it is to represent two-thirds of the overall wireless traffic. Uninterrupted, continuous, and smooth video streaming, minimal delay, jitter, and packet loss, must be provided in order to avoid degradation in video quality and user experience. The main challenge for the users is to select the best available Radio Access Network (RAN). There is a need for an efficient solution for selecting the best value network for the user, considering the user preferences, application

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[1] WiFi Mobilize - http://www.telekom-icss.com/dtag/cms/content/ICSS/en/1508330

requirements, and network conditions. The network selection decision is a complex one, with the challenge of trading-off different decision criteria, (e.g. service class type, user's preferences, mobile device being used, battery level, network load, time of day, price, etc.). This is further complicated by the combination of static and dynamic information involved, the accuracy of the information available, and the effort in collecting all of this information with a battery, memory, and processor limited device. This selection decision needs to be made once for connection initiation and subsequently as part of all handover decisions.

Another challenge is the multimedia service delivery with QoS provisioning over wireless networks. This is due to the constraints of wireless links, and the user mobility. In this context, it is essential to provide QoS mechanisms to cater for multimedia throughput, delay, and jitter constraints, especially within the wireless environment where connections are prone to interference, high data loss rates, and/or disconnection. The aim of these mechanisms is to maintain an acceptable user perceived quality and make efficient use of the wireless network resources.

The battery life of the mobile device is another key component that consumers care highly about. Handsets are used as mobile work and entertainment centres, e.g. for communications, listening to music/radio, taking photos, GPS services, playing games, using any of the available 500,000 mobile apps[2] on the market, and for multimedia playback/streaming. It is known that real-time applications, and in particular those which are based on multimedia, have strict Quality of Service (QoS) requirements, but they are also the most power-consuming. In this context, one of the impediments of progress is the battery lifetime of the mobile device. With advances in technology, the mobile user has now a wide choice of high capability mobile devices, from laptop computers and netbooks to Personal Digital Assistants (PDA) and smart phones. However the batteries have not evolved as much as processors and memory, and their capability is very much limited. This deficiency in battery power and the need for reduced energy consumption provides motivation for the development of more energy efficient solutions while enabling always best connectivity to mobile users.

1.3. Solution Overview

This thesis introduces a novel **reputation-based system** for the heterogeneous wireless environment. The proposed solution, models the user-network interaction as a repeated cooperative game from Game Theory. The outcome of the repeated game is a network reputation factor computed by the user for that particular network. The reputation-based system makes use of an ***Adapt-or-Handover solution*** that combines this novel adaptive multimedia delivery and the network selection mechanisms in order to improve the energy efficiency at the

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[2] Mobile Applications - www.appmodo.com

end-user mobile device. These solution novel mechanisms are: (1) the ***Power-Friendly Access Network Selection Mechanism (PoFANS)*** that enables the selection of the best value network based on: user preferences, the quality of the multimedia stream, the energy consumption of the mobile device, the monetary cost of the wireless network, and the user mobility; (2) the ***Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy)*** which adapts the multimedia content based on network conditions.

The network reputation factor is further integrated in PoFANS, and will be considered in the decision mechanism when the next network selection process takes place. The reputation-based system is based on the idea that repeated interaction leads to cooperation. The network operators are better off cooperating, by offering and maintaining an acceptable quality of service to the end-users. By doing so they will increase the value of their reputation factor and consequently, they will increase their chance of being selected again by the user. This repeated user-network interaction can be seen as an ongoing relationship in which by using cooperative game theory it is shown that cooperation can be sustained without a contract.

1.4. Thesis Contributions

The research work presented in this thesis provides the following contributions to the advancement of the current state of the art:

- Proposal of PoFANS, a novel Power-Friendly Access Network Selection Mechanism which:
    - uses the multiplicative exponential weighted method (MEW) in order to score each candidate network. The selection is based on three key-parameters: the quality of the multimedia stream, the energy consumption of the mobile device, and the monetary cost of the network. The parameters are weighted based on the user preferences. Each parameter is scaled with the help of utility functions;
    - defines a zone-based sigmoid utility function, for the quality parameter, which maps the received bandwidth to the user satisfaction. The choice of the quality utility function is validated through subjective tests;
    - integrates a mathematical model of the energy consumption pattern which is then used in the definition of the utility function for the energy parameter. The mathematical energy consumption pattern was modeled for a Google Nexus One Android device, based on real experimental measurements on the Android device;
    - provides a flexible energy-quality-cost trade-off.
- A study of the battery energy usage for streaming adaptive video to a Google Nexus One Android device for WLAN IEEE802.11g and HSDPA networks.

  - Studies the impact of the WLAN traffic load and the distance from the access point on the Google Nexus One energy consumption for streaming a multimedia clip at five different quality levels. Including subjective testing to understand the corresponding user-perceived quality values.
  - Studies the impact of transport protocol on the energy consumption: UDP and TCP
- Proposal of SAMMy, a novel Signal Strength-based Multimedia Delivery Mechanism which:
  - adapts the multimedia content based on received signal strength and packet loss;
  - makes efficient use of the wireless network resources;
  - maintains good user estimated perceived quality levels.
- Proposal of Adapt-or-Handover solution which:
  - represents a hybrid multimedia delivery solution which combines the adaptive multimedia delivery mechanism (SAMMy) with the network selection solution (PoFANS);
  - decides when to adapt the multimedia stream and when to handover to a new network;
  - acts in the user’s best interest and achieves important power savings.
- Proposal of a Reputation-based Network Selection Mechanism which:
  - represents an extension of PoFANS by making use of Game Theory and defining a network reputation factor in the network selection decision;
  - models the user-network interaction as a repeated cooperative game, and it is shown that by defining incentives for cooperation and disincentives against cheating or selfish behavior, repeated interaction leads to cooperation;
  - builds a reputation-based systems which incorporates the Adapt-or-Handover mechanism which in turn integrates the two proposed mechanisms: PoFANS and SAMMy.
- A comprehensive survey of the current research on the game theoretic approaches used in the literature to model the network selection process, which:
  - provides a useful categorization based on the players’ interactions: Users vs. Users, Networks vs. Users, and Networks vs. Networks. Different types of games (e.g., cooperative or non-cooperative);
  - The major findings from these game models and the main challenges that surround the network selection problem are addressed and summarized;
  - outlines the problems faced by the next generation of wireless networks;

1.5 Thesis Structure

The thesis was structured in eight chapters as follows:

- ***Chapter 1* -** introduces the motivation of the research work conducted, identifies the problem and presents a brief overview of the solution. The chapter details the main contributions of the research work presented in this thesis.
- ***Chapter 2*** – introduces the technical background for the work presented in this thesis.
- ***Chapter 3* -** presents a comprehensive survey of the current research on the following topics: network selection strategies, reputation-based systems for heterogeneous environment, adaptive multimedia solutions, and energy efficient content delivery solutions.
- ***Chapter 4*** – presents the proposed system architecture and details the algorithms for the four major contributions: PoFANS, SAMMy, Adapt-or-Handover, and Reputation-based Network Selection Mechanism.
- ***Chapter 5*** - presents the experimental test set-up: environment, scenarios, and results analysis.
- ***Chapter 6*** – presents the simulation-based testing environment and the modeling and validation of the score function, quality utility, and energy consumption pattern.
- ***Chapter 7* –** presents the testing results and results analysis for the main four contributions presented in this thesis.
- ***Chapter 8* -** concludes the thesis and presents possible future work directions.

Chapter 2

Technical Background

This chapter introduces the technical background for the work presented in this thesis. It starts with a presentation of the evolution of cellular and wireless networks. The roadmap of the evolution of cellular and wireless technologies that leads towards a converged heterogeneous wireless environment is described in details. The need for an efficient mobility management solution is introduced, providing motivation for researchers to propose and develop efficient network selection solutions. The network selection concept and the decision making process are further described. The basic game theory models and their mapping to network selection problem are addressed. As multimedia traffic is the main traffic considered in this work, the main techniques for multimedia content delivery over the heterogeneous environment are presented as well as the Quality of Service provisioning and the main approaches for measuring end-user perceived quality. The chapter is concluded with a short summary.

2.1. Evolution of Cellular and Wireless Networks

Wireless technologies had a spectacular evolution over the past years, and the present trend is to adopt a global network of shared standards which comes to meet user applications' requirements.

2.1.1. Roadmap for Cellular Networks

Figure 2.1 illustrates the evolution of the cellular communication area from the first generation (1G) towards the 4G mobile networking. Each of the cellular generation system will be described in details in this section.

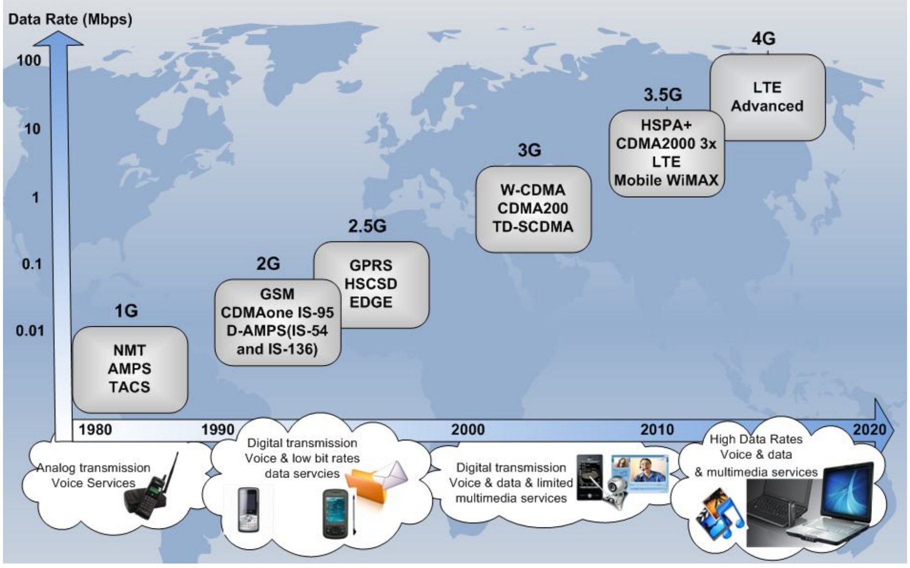

Figure 2.1 Wireless Networks Roadmap

a) First Generation (1G)

The wireless cellular communications epoch started in the 1980s when the first mobile telephones (analogue phones) appeared. This first wireless cellular communication system was referred to as **first generation (1G)**. A good representation for this generation is the brick-sized analog phone intended to offer simple voice communication services to customers. Some examples of 1G systems deployed are [2]: Nordic Mobile Telephone 450 (NMT - 450) operated in the 450MHz frequency range in Denmark, Sweden, Finland, and Norway; Total Access Communication System (TACS) at 900MHz frequency range in United Kingdom; Advanced Mobile Phone System (AMPS) operating within the 800 to 900 MHz frequency range in United States.

b) Second Generation (2G)

In the 1990s, the **second generation (2G)** of cellular systems emerged. Unlike 1G which used analog transmission for speech service, 2G used digital transmission. The second generation introduced, apart from the simple voice communication services, the low bit rate data services (e.g., Short Messaging Services (SMS)). Some of the 2G systems deployed are [2]: Global System for Mobile Communications (GSM) operating in the 900MHz frequency range in Europe; Digital AMPS (D-AMPS) in United States; Code Division Multiple Access one (CDMAone) – based digital IS-95 in United States.

GSM provided for interoperability of mobile devices between different operators leading to an easy and fast deployment of GSM all over the world. The GSM network is decentralized and consists of three separate subsystems [3]: Mobile Station (MS), Base Station Subsystem (BSS), and Network Switching Subsystem (NSS), as illustrated in Figure 2.2.

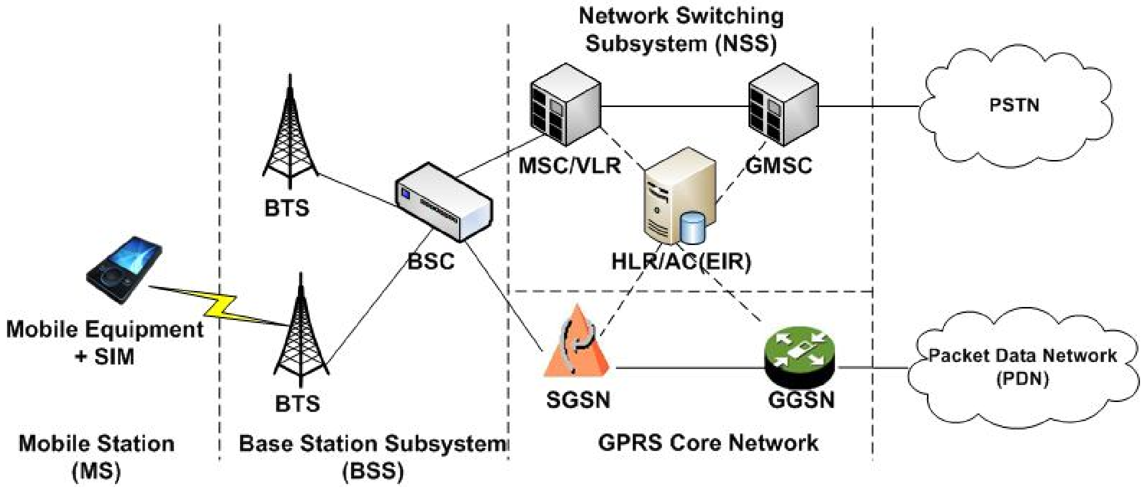

Figure 2.2 GSM/GPRS Architecture

The Mobile Station is composed of the Mobile Equipment and the Subscriber Identity Module (SIM) card. The SIM card stores the subscriber's data. In the GSM network the SIM card is used to identify the user.

The Base Station Subsystem (BSS) is responsible for the radio network management and consists of two elements: Base Transceiver Station (BTS) and Base Station Controller (BSC). The BTS is in charge of maintaining the air interface which is used for communication with the MS. The BSC is the main element of the BSS, and it is responsible to control the radio network. One BSC can control a number of BTSs, and it is responsible with the mobility management of the MS (e.g., handover initiation).

The Network Switching Subsystem (NSS) consists of five elements: Mobile Services Switching Center (MSC), Visitor Location Register (VLR), Home Location Register (HLR), Authentication Center (AC), and Equipment Identity Register (EIR).

The main role of the MSC is to control the calls in the mobile network. The MSC can control several BSSs, and one BSS can cover a large geographical area consisting of many cells. *A cell refers to the geographical covered by one BTS.* When the MSC acts as bridge between the mobile network and the fixed network (e.g., Public Switching Telephony Network (PSTN)) it is referred to as Gateway MSC (GMSC). The VLR can be represented as an independent unit or it can be integrated within the MSC (MSC/VLR). VLR is a temporary database which holds information about the users (e.g., identity numbers, security information, subscribed services, originate HLR) as long as they are within the service area. HLR contains permanent information about the subscribers (e.g., identity numbers and subscribed services) along with the current location. EIR is used for security reasons, storing information about valid mobile equipment while AUC is responsible for the authentication and encryption parameters. Both entities, EIR and AUC, can be located in the HLR.

c) 2.5 Generation (2.5G)

Based on the GSM system, new and more advanced technologies were developed [4]: *(1) High Speed Circuit Switched Data (HSCSD)* offers higher data transmission rates, the theoretical maximum data rate being 57.6Kbps; *(2) General Packet Radio Service (GPRS)* which introduces a higher theoretical data rate of 160Kbps; *(3) Enhanced Data rates for GSM Evolution (EDGE) or Enhanced GPRS (EGPRS)* brings further increases in data rates being able to handle multimedia services (e.g., video phone, video conference, etc) at a theoretical rate of 384Kbps.

GPRS adds support for packet switched data by integrating into the GPRS Core Network two main and new entities, as illustrated in Figure 2.2: the Serving GPRS Support Node (SGSN) and the Gateway GPRS Support Node (GGSN). The SGSN entity is the most important element of the GPRS network being equivalent to the MSC of the GSM network. The GGSN entity represents the gateway that connects the GPRS network to the external networks. As illustrated in Figure 2.2 the GPRS network uses and works in parallel with the GSM network.

The deployment of EDGE or EGPRS networks does not require major changes in the core network, expect for the installation of EDGE-compatible transceiver units. However, the BSS needs to be upgraded to support EDGE.

d) Third Generation (3G)

The growth of the data traffic leads to the deployment of the **third generation (3G)** of mobile networks which comes to offer higher data rates of up to 2Mbps. The 3G wireless networks were standardized as the International Mobile Telecommunications 2000 (IMT-2000). The new standard is designed for internet/data services and low bit rates multimedia services. Examples of 3G systems are [5]: Wideband CDMA (WCDMA) developed from GSM and led by the Third Generation Partnership Project (3GPP), a joint project of the standardization bodies from different European countries; CDMA2000 – developed from 2G CDMA standard IS-95 in North America and Asia Pacific; Time Division – Synchronous CDMA (TD-SCDMA) in China.

The most important 3G cellular system is Universal Mobile Telecommunications Systems (UMTS) which uses WCDMA for the air interface. UMTS keeps the concepts and solutions of the GSM network but a new infrastructure is required. The UMTS architecture is illustrated in Figure 2.3 and is composed of three main domains [3]: User Equipment (UE), UMTS Terrestrial Radio Access Network (UTRAN), and the Core Network (CN). The UE is the equivalent of the MS in GSM, with added support for UMTS. The Core Network is based on the GSM/GPRS network upgraded in order to support UMTS operation and services. The UTRAN provides the air interface for the UE, and is the equivalent of BSS in GSM, consisting of two main entities: NodeB and Radio Network Controller (RNC). NodeB is the equivalent of BTS whereas RNC is the equivalent of BSC. A RNC can control one or more NodeBs.

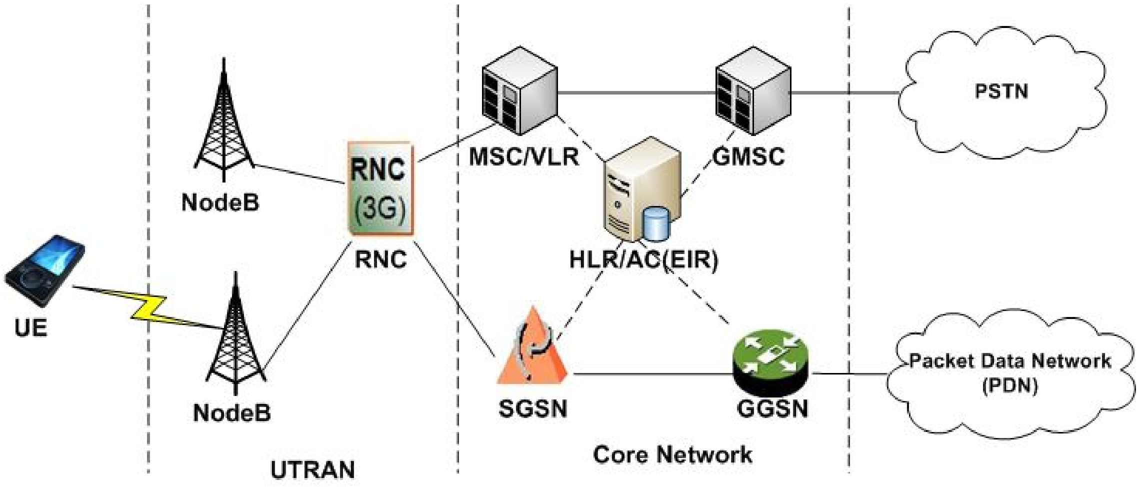

Figure 2.3 UMTS Architecture

UMTS provides peak data rates of up to 384kbps for uplink and downlink. After the NobeB functionality was upgraded to High-speed Downlink Packet Access/High-speed Uplink Packet Access (HSDPA/HSUPA) [6] the data rates could reach up to 14.4Mbps for downlink and 5.76Mbps for uplink.

e) 3.5 Generation (3.5G)

The evolution towards the **3.5 generation** of the cellular system leads to the deployment of the Evolved HSPA (HSPA+). The new HSPA+ offers improved data rates of up to 21Mbps for downlink and up to 11Mbps for uplink. This is because the NodeBs may be directly connected to the GGSN over a standard Gigabit Ethernet.

The next step in the GSM/UMTS evolution line is the 3GPP Long-term Evolution (LTE) [7]. LTE uses the Orthogonal Frequency-Division Multiple Access (OFDMA) and Single-Carrier FDMA (SC-FDMA) transmission schemes for downlink and uplink, respectively, instead of WCDMA. Moreover Multiple-Input, Multiple-Output (MIMO) technology is used for the LTE antennas, providing data rates of up to 100Mbps for downlink and up to 50Mbps for uplink. The LTE system requires a new infrastructure that is incompatible with GSM or UMTS network, as illustrated in Figure 2.4. LTE consists of three main domains [3]: User Equipment (UE), Evolved-UTRAN (E-UTRAN), and Evolved Packet Core (EPC). The UE requires to be upgraded for LTE compatibility. The E-UTRAN consists only of eNB (evolved NodeB) and is responsible for all the functionalities of the radio interface. EPC consists of three main entities: the Mobility Management Entity (MME) which handles the mobility, security, and UE identity provided by Home Subscriber Server (HSS); the Serving Gateway (S-GW), and the Packet Data Network (PDN) Gateway (P-GW).

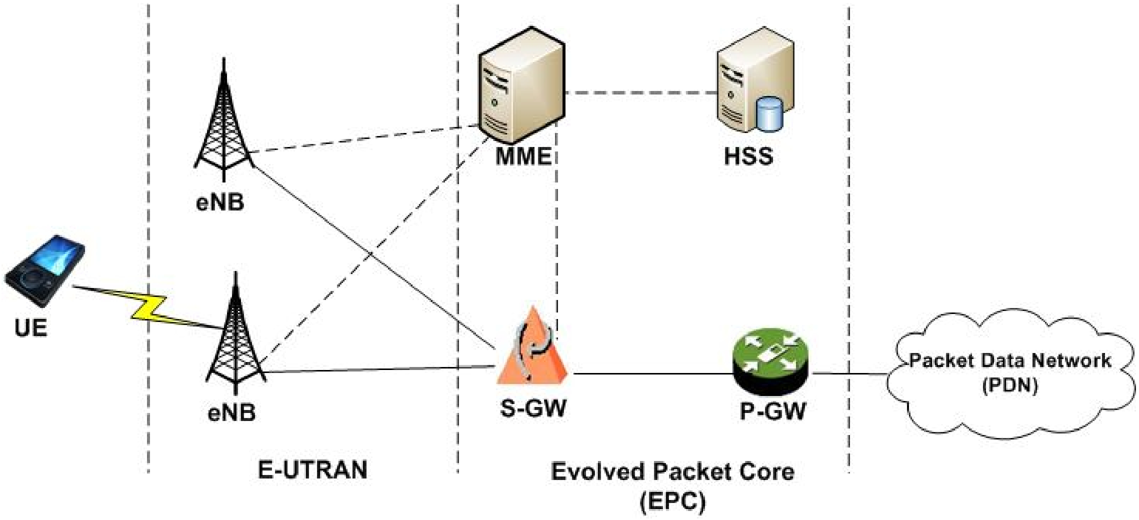

Figure 2.4 LTE Architecture

Parallel to the GSM/UMTS evolution line, the 3GPP2 Ultra Mobile Broadband (UMB) is the next successor of CDMA2000 [8]. UMB is based on OFDMA, MIMO and Space Division Multiple Access (SDMA) advanced antenna techniques, providing data rates up to 280Mbps for downlink and over 75Mbps for uplink transmission (this can be obtained by using 4x4 MIMO configuration).

f) Fourth Generation (4G)

As mobile devices became a must on the market and also with the emerging of new multimedia applications, the deployment of **fourth generation (4G)** wireless networks attracts more and more interests. The 4G system comes to bring advanced QoS capabilities, improved latency reduction, broader bandwidth, wider coverage area, smooth handover, etc. The new LTE Advanced is considered to be a 4G solution with data rates of 1Gbps for stationary users, and up to 100Mbps for mobile users.

Figure 2.5 reveals the download times for different applications over WCDMA, HSPA, and LTE according to one of the GSA reports[1]. The following peak speed rates for each network were assumed: 384kbps for WCDMA, 14Mbps HSPA, and 100Mbps LTE. Looking at the download time for one-hour High Definition (HD) Movie, it can be seen that LTE brings significant improvements in comparison with WCDMA and HSPA.

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[1] General Services Administration Reports http://www.gsa.gov/portal/content/104553

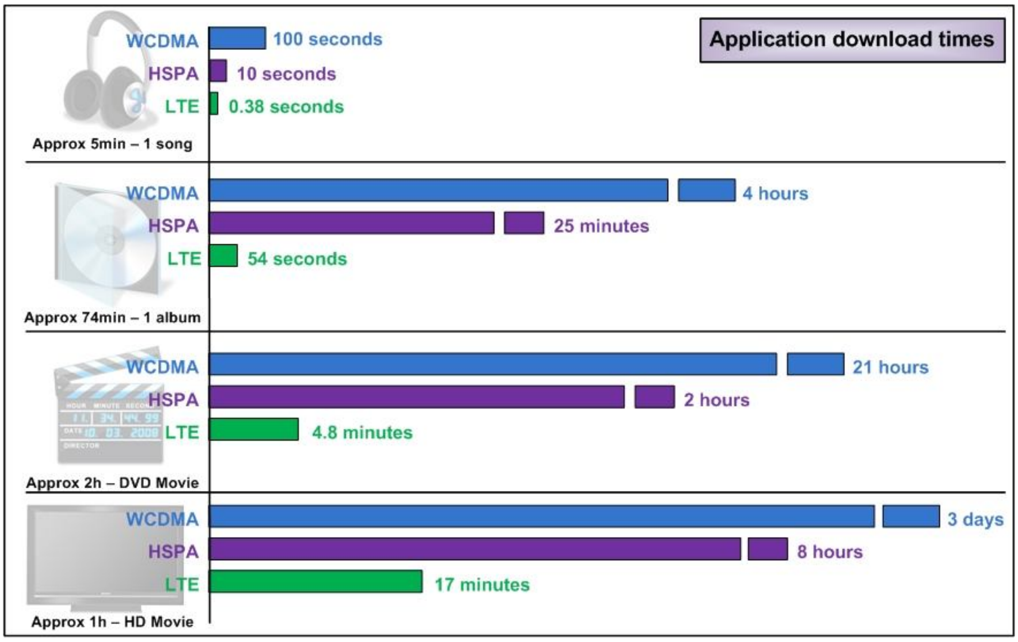

Figure 2.5. Application download times over WCDMA, HSPA, and LTE

2.1.2. Wireless Technologies Evolution

a) WLAN

Wi-Fi (Wireless Fidelity) or the Institute for Electrical and Electronics Engineers (IEEE) standard **802.11** [9], was introduced for the first time in 1997. The standard was initially able to provide 1 or 2 Mbps bit rate, using the 2.4GHz frequency. Over the years the technology evolved and there were several amendments made to the original standard. The first improved version of the original standard was **802.11a** [10] which could offer an increase in throughput up to 54Mbps using the 5GHz frequency. Because of the low number of devices operating at 5GHz, at that time, the new amendment provided less interference but the biggest disadvantage was the short coverage area and the quick degradation of the signal. 802.11a supports multiple data rates of 6, 9, 12, 18, 24, 36, 48, and 54Mbps using Orthogonal Frequency Division Multiplexing (OFDM) modulation technique. Even though the standard provides theoretical data rate of up to 54Mbps, in a real scenario, the approximate received throughput is 25Mbps [11].

Another well-known amendment and probably the most deployed was **802.11b** [12], operating at 2.4GHz frequency and providing data rates up to 11Mbps using Complementary Code Keying (CCK) modulation. The standard provides four theoretical data rates of 1, 2, 5.5, and 11Mbps. In practice, for 802.11b the approximate received throughput is 6Mbps [11].

As 802.11b, the next ratified amendment, **802.11g** [13], also gained widespread adoption because of the increase in throughput, which could go up to 54Mbps while operating at 2.4GHz frequency. It provides backwards compatibility with 802.11b devices. The standard uses OFDM and CCK modulation techniques and provides data rates of 1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48, and 54Mbps. The approximate received throughput in a real scenario is 22Mbps when there are only 802.11g clients in the network [11].

The latest amendment **802.11n** [14] brings improved reliability, more predictable coverage, improved immunity to noise, compatibility with **802.11a/b/g**, and a higher throughput which can achieve performance parity with 100Mbps fast Ethernet. The new amendment works with MIMO leading to an increased data rate.

The IEEE 802.11 standard adds two types of networks: **(1) infrastructure networks** or **non-ad-hoc networks** – meaning that the communication between mobile clients is done through a central component (e.g., AP (Access Point). This type of network offers the advantage of scalability and centralized management; **(2) ad-hoc networks** –where the communication between mobile clients is done through other mobile clients used by the routing mechanism for data forwarding. This type of network is decentralized and it does not rely on pre-existing infrastructure. Its advantage is that it eliminates the cost of adding a central component.

The basic architecture of an infrastructure 802.11-based network is illustrated in Figure 2.6. The typical 802.11 network is built up of one or more stations (STAs) and one AP, referred to as the Basic Service Set (BSS). The STAs are represented by the user equipment, such as: laptops, Personal Digital Assistant (PDAs), smartphones, or any device equipped with a WLAN interface. Nowadays most of the smartphones have both cellular and WLAN interfaces included. The APs can be connected to the same distributed system (DS) or wired network, this configuration being called the Extended Service Set (ESS). The 802.11 standard allows the stations to roam within the ESS.

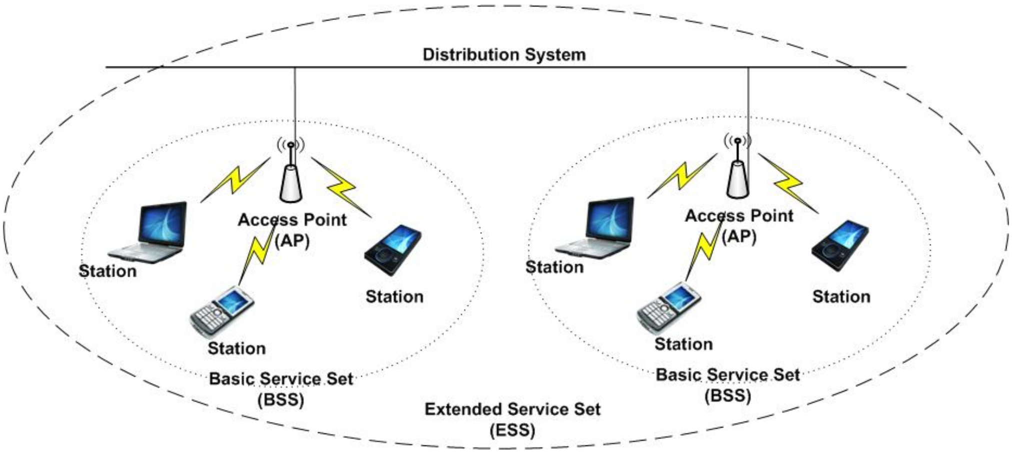

Figure 2.6. WLAN Basic Architecture

Table 2.1 presents a list of the most important (released or in progress of being released), amendments and supplements of the IEEE 802.11 family. Off all the listed standards, **IEEE 802.11a/b/g** and **IEEE 802.11k** [15] are of particular interest in the scope of this work.

TABLE 2.1. OVERVIEW OF 802.11 SUPPLEMENTS AND AMENDMENTS

Standard	Description
802.11	Data rates: 1Mbps and 2Mbps Frequency: 2.4GHz Modulation: FHSS, DSSS and IR-Phy
802.11a	Data rate: up to 54Mbps Frequency: 5GHz Modulation: OFDM (Orthogonal Frequency Division Multiplexing)
802.11b	Data rate: up to 11Mbps Frequency: 2.4GHz Modulation: extension of DSSS
802.11c	Ensures wireless bridging between APs
802.11d	Specification for operation in additional regulatory domains
802.11e	Provides QoS Enhancements and prioritization of data packets
802.11F	Inter-Access Point Protocol, provides interoperability between multi-vendor APs
802.11g	Data rate: up to 54Mbps Frequency: 2.4GHz compatible with 802.11b Modulation: OFDM
802.11h	Radio Resource Management
802.11i	Enhanced Security
802.11j	Designed only for Japanese market, operating in 4.9 to 5GHz
802.11k	Radio Resource Measurements
802.11m	Performs maintenance, technical and editorial corrections and improvements
802.11n	Provides higher throughput improvements by using MIMO technology. Data rates between 108Mbps – 320Mbps.
802.11p	Support for Vehicular Environment
802.11r	Permits continuous connectivity by providing fast BSS transition.
802.11s	Support for mesh networking.
802.11t	Provides test methods and metrics.
802.11u	Interworking with non-802 networks such as cellular networks.

The IEEE 802.11 Task Group “k” has recently developed an important extension of the IEEE 802.11 wireless LAN standard, which is referred to as **802.11k** [15] (ratified in 2008). This extension is defined for the provisioning of the radio resource measurement, in order to allow radio stations to request and exchange information about the usage of the wireless medium. The IEEE 802.11k standard defines basic structures for requesting and reporting measurements information, but only for IEEE 802 networks [16]. There are *no interoperability* methods between heterogeneous networks defined in **IEEE 802.11k**, and *no inter-RAT measurements procedures*.

The IEEE 802.11k standard defines different types of measurements [17]**,** including: the *beacon report* which provides information on signal strength and signal to noise ratio; the *frame report*, with information on all received frames; the *channel load report* that returns the channel utilization measurement (as observed by a measuring station); *noise histogram report* that provides the expected value of noise collected in a specific number of channels in the measurement duration; *statistic report* with information related to link quality and network performance; *location report* that contains the current location formatted based on the IETF

RFC 3825 standard [18]**,** in terms of latitude, longitude and altitude; *neighbor report* that provides information about the neighbors of the associated AP; and *link measurement report* that provides the instantaneous quality of a link.

In this work the main focus is on the **link quality** information obtained via *beacon report, frame report* and *link measurements report*, and information about the **current location** obtained via *location report.*

IEEE 802.11k does not include any radio resource management; the objective is to provide radio resource measurements. The standard contains two main message types: *request* and *report* messages. Radio stations can exchange messages in two ways: *station-to-station* or *station-to-AP*. These messages can be sent in unicast, broadcast or multicast nodes. Each request/report message is included in an action frame with the category field set to radio measurement, and has information about the requested measurement settings (channels, duration, start time, etc). The frame contains the *measurement information* (in request) or the *measurement results* (in reports). The action frame is then carried by a MAC management frame. The standard does not specify the default measurement duration and allows each radio station to specify duration along with a measurement request. The requested radio station can decide on the measurement duration and also whether or not to repeat the measurements after a certain time.

The **IEEE 802.11k** standard allows the inclusion of multiple measurement elements in one measurement request or report. The standard provides information about the current location but the acquisition mechanism for positioning itself is not included in the standard.

b) WiMAX

The IEEE 802.16 [19] standard referred to as Worldwide Interoperability for Microwave Access (WiMAX) is a connection-oriented long range network (up to 30 miles) that uses both the licensed and unlicensed spectrum in order to provide broadband wireless access. WiMAX is placed on the equal position with the 3G technologies. The IEEE 802.16-2004 version of the standard provides broadband wireless connectivity to fixed users with data rates of up to 75Mbps. The newer version of the standard is IEEE 802.16e, referred to as Mobile WiMAX adds mobility support and data rates up to 30Mbps. The goal of the IEEE 802.16m supplement is to meet the 4G requirements and achieve data rates up to 1Gbps for stationary usage and 100Mbps for mobile users. IEEE 802.16m is positioned on the same place with LTE and UMB in terms of technology, capacity, and services.

The basic architecture of a WiMAX network is illustrated in Figure 2.7 and it is composed of three main components [3]: Subscriber Station, Access Service Network (ASN), and Connectivity Service Network (CSN). An ASN consists of one or more Base Stations and one or more ASN Gateways. The role of the ASN Gateway is to interconnect the ASNs with the CSN. The ASNs and CSNs can appertain to different network service providers which can have roaming agreements between them.

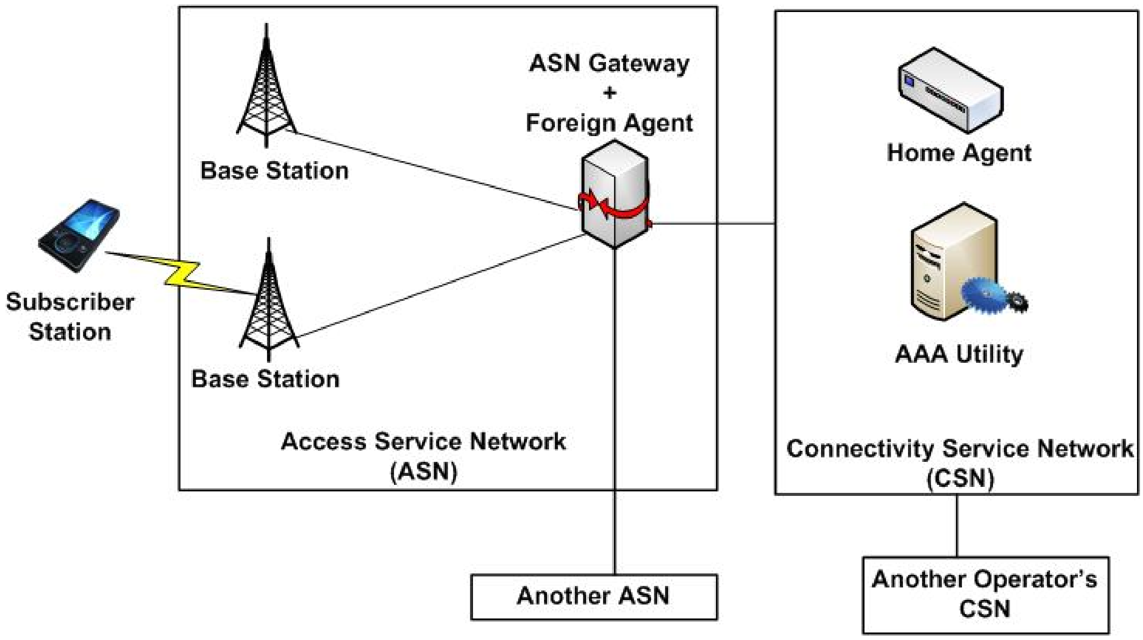

Figure 2.7. WiMAX Architecture

c) Broadband Networks (IEEE 802.20)

The IEEE 802.20 standard referred to as Mobile Broadband Wireless Access (MBWA) [20] is dedicated for vehicular mobility with speed up to 250km/h. The standard occupies the same position with the 3G cellular network being able to deliver data rates up to 4Mbps in downlink and up to 1.2Mbps in uplink. IEEE 802.20 adds support for high-speed handover and Quality of Service (QoS) preservation.

2.2. Heterogeneous Wireless Environment

Table 2.2 presents an overview of the previously introduced wireless access technologies (existing and under development). By observing the growing demand of the mobile users and the quantity of information with which they are confronted on a daily basis, it can be predicted that the coexistence of multiple access technologies (e.g., cellular networks, Wireless Local Area Networks (WLANs), Wireless Metropolitan Area Networks (WMANs), or Wireless Wide Area networks (WWANs)) deployed by different operators is fundamental for the next generation of wireless networks. In this context, the new objective is to keep the mobile user 'always best connected (ABC)' [21] anywhere and anytime.

TABLE 2.2. OVERVIEW OF WIRELESS ACCESS NETWORK TECHNOLOGIES

Technology	Category	Data Rate	Mobility Support
GSM	Cellular	9.6 Kbps	Yes
GPRS	Cellular	114 Kbps	Yes
EDGE	Cellular	400 Kbps	Yes
UMTS	Cellular	2 Mbps	Yes
CDMA 2000	Cellular	2.4 Mbps	Yes
LTE	Cellular	250 Mbps	Yes
UMB	Cellular	288 Mbps	Yes
IEEE 802.11	WLAN	2Mbps	No
IEEE 802.11b	WLAN	11 Mbps	No
IEEE 802.11a/g	WLAN	54 Mbps	No
IEEE 802.16 (WiMAX)	WMAN	75Mbps (120Mbps)	No
IEEE 802.16e	WMAN	30Mbps	Yes
IEEE 802.20	WWAN	16Mbps	Yes

This heterogeneous wireless environment, as illustrated in Figure 2.8, can be defined as a multi-technology multi-terminal multi-application and multi-user environment within which mobile users can roam freely. Some of the advantages of such an environment are as follows: it makes use of existing infrastructure, eliminating the cost of new technology deployments; it provides increased wireless capacity ensuring seamless mobility; it provides backward capability; adds support for high data rates and low latency.

The always best connected vision emphasis the scenario of a variety of radio access technologies that work together in order to form a global wireless infrastructure in which the end-users will benefit from an optimum service delivery via the most suitable available wireless network that satisfies their interests.

In order to achieve seamless connectivity within the heterogeneous wireless environment a suitable interworking solution is needed. All the existing solutions are built on the vision of all-IP based infrastructure, having the IP as the common network layer protocol. The variety of applications (e.g., voice, video, data, etc.) using different transport protocols (e.g., TCP, UDP) are running on top of the IP layer, which in turn is running over a number of access technologies (cellular, WLAN, Ethernet, etc.).

The Media Independent Handover Working Group IEEE 802.21 [22] has considered the interoperability aspects between heterogeneous networks, and developed a new standard referred to as IEEE 802.21. The new standard enables the optimization of handover between heterogeneous IEEE 802 networks and facilitates handover between IEEE 802 networks and cellular networks by providing methods and procedures to gather useful information from both the mobile device and the network [23]. This information can contain: user profile, application requirements, network policy and type, link quality, etc.

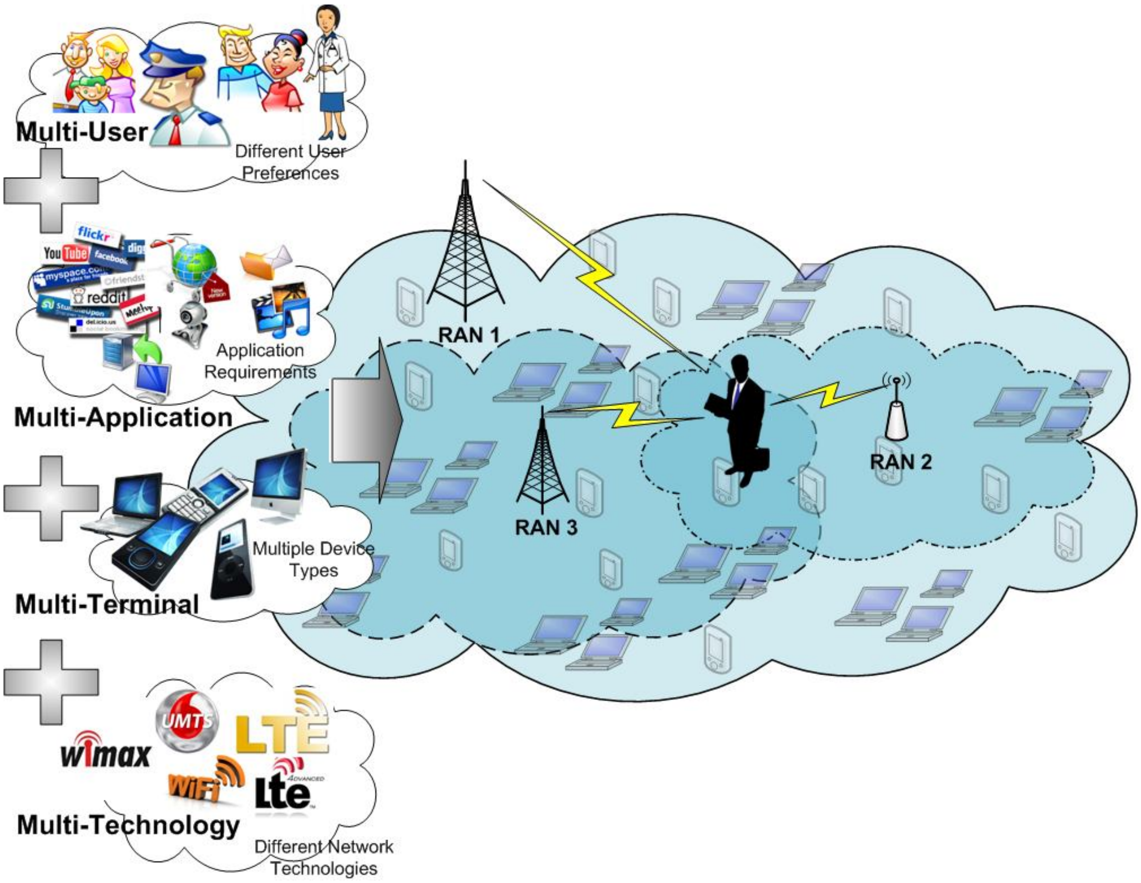

Figure 2.8. Heterogeneous Wireless Environment

The standard provides a Media Independent Handover Function (MIHF) which enables the communication between the upper and lower layers entities. MIHF integrates three services: Media Independent Event Service (MIES), Media Independent Command Service (MICS), and Media Independent Information Service (MIIS).

The work on this thesis is based on the use of the IEEE 802.21 standard which will be detailed later on this thesis.

2.3. Mobility Management

The next generation of wireless networks is represented as a heterogeneous wireless environment with a number of overlapping RANs. These RANs may differ in terms of technology, protocols, coverage, bandwidth, latency, or service providers. In this context, one of the current challenges is the design of intelligent mobility management techniques that aim at achieving global roaming within the heterogeneous wireless environment.

The mobility in the wireless environment can be classified by considering the following aspects [24]: *(1) Terminal mobility* – the user's mobile device can change the point of attachment (the connection between the mobile device and the network) without interrupting the service; *(2) User mobility* – the user can access the service under the same identity, independent of the point of attachment, or mobile device (e.g., personalized SIM cards used for mapping the user to multiple devices); *(3) Service mobility* – the user can use a particular service regardless the mobile device used and the user location.

Efficient mobility management techniques are critical for the next generation wireless networks as they need to provide some basic requirements [25]: support for all forms of mobility; mobility support for real-time and non-real-time applications; seamless user mobility support – enabling the user to move within the heterogeneous wireless environment appertaining to different or the same service provider; the support for user's mobile device to change the point of attachment while moving without interruptions of the current session; the support for global roaming. In the next-generation wireless systems, there are two types of roaming for mobile devices defined [26]: (1) intra-system/intra-domain roaming which refers to the mobile device mobility between different cells of the same system (similar network interfaces and protocols); and (2) inter-system/inter-domain roaming which means that the mobile device can move between different technologies, protocols, or service providers. Some of the mobility protocols that can be used in order to enable the mobility at a global level are: Mobile IP version 4 (MIPv4) [27], Mobile IP version 6 (MIPv6) [28], and the newest Proxy Mobile IPv6 (PMIPv6) [29]. PMIP was released in 2008 and is a *network-based mobility management protocol* which enables IP mobility without requiring the participation of the mobile device in the signaling process. The network handles the entire mobility process instead of the mobile device.

The mobility management contains two components, as illustrated in Figure 2.9 [30]: location management and handover (handoff) management.

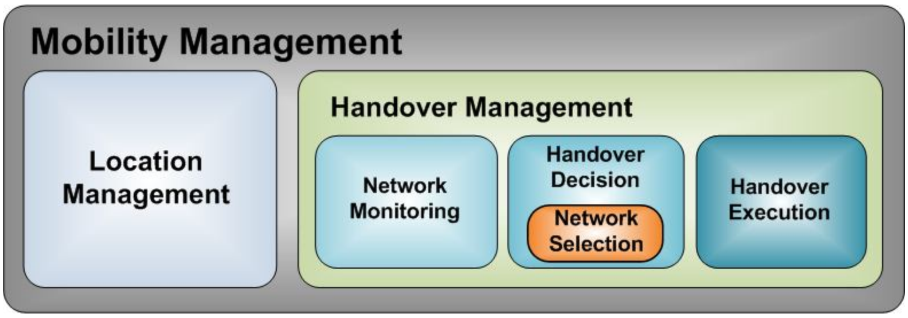

Figure 2.9. Mobility Management Components

2.3.1. Location Management

The location management keeps track of the mobile device movement, in order to locate it for data delivery. This service includes two main tasks [26]: *(1) location registration* or *location update* – the mobile device periodically informs the system about its current location, which in turn, maintains an updated location information database; *(2) call delivery* – in which case, when a communication request for the mobile device is initiated, the system has to determine the current location of the mobile device, based on the existing information in the databases.

2.3.2. Handover Management

The link between communication and mobility is enabled by the handover process [31]. A good definition of handover is given by ETSI and 3GPP [32] which define handover as being the process by which the mobile device keeps its connection when changing the point of attachment (base station or access point). In terms of technologies, if both the source and target systems employ the same radio access technology (RAT) and rely on the same specifications, then the handover process is referred to as **Horizontal Handover** (HHO) [31]. If the target system employs a different RAT, the handover process is called **Vertical Handover** (VHO) [33]. The main objective of the handover process is to minimize the service disruption, which can be due to data loss and delay during the session transfer.

Figure 2.10 presents an example of the basic handover process: as a mobile terminal, on an ongoing call, gets further from the base station (BS), its signal quality degrades due to mobility. As the mobile nears the cell edge or border, it will leave the original coverage area and enter a new cell. When the signal strength of the new cell is significantly stronger than that of the original cell, the handover process is triggered, and the mobile terminal handovers to the new cell.

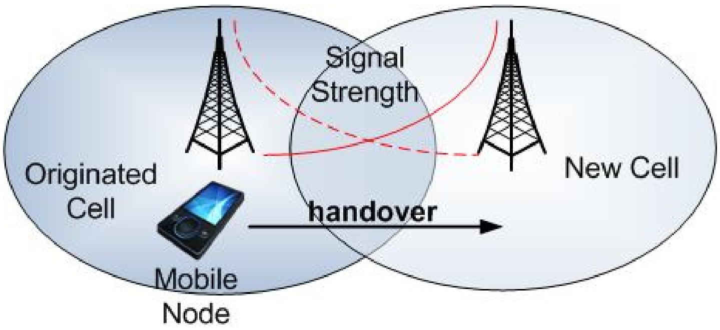

Figure 2.10. Handover process - example

Several types of handover have been identified in the literature, based on the mobile device's point of attachment:

- **Intra-cell Handover** – within the same current cell the mobile terminal can switch to another frequency, slot, code, or sector.
- **Inter-cell Handover** – handover from the current cell to another cell. This can be further split in two categories depending of the logical attachment involved:
    - *Intra-BSC/RNC Handover* – when the BTS/Node B of both original and the target cells are controlled by the same BSC/RNC;

  - *Inter-BSC/RNC Handover* – when the new target cell is attached to a different BSC/RNC than that of the current cell;
- **Inter-system Handover** – handover between different radio access technologies (e.g., UMTS to WLAN), also called **Vertical Handover**.

In addition to the handover process can be either: *(1) Hard Handover (Break-before-Make)* - all the radio links for the old original link are removed before the new radio link(s) is established. This approach requires fast handover signaling mechanisms in order to make the process transparent; *(2) Soft Handover (Make-before-Break)* – the new target link is set-up first before the old original link is torn down.

Additionally the mobile device may support multiple simultaneous connections to be used for communications. In such conditions a mobile terminal may be connected to several base stations simultaneously and use the multiple radio links for wide bandwidth communications.

Handover Management consists of three major sub-services, as illustrated in Figure 2.11: Network Monitoring, Handover Decision, and Handover Execution.

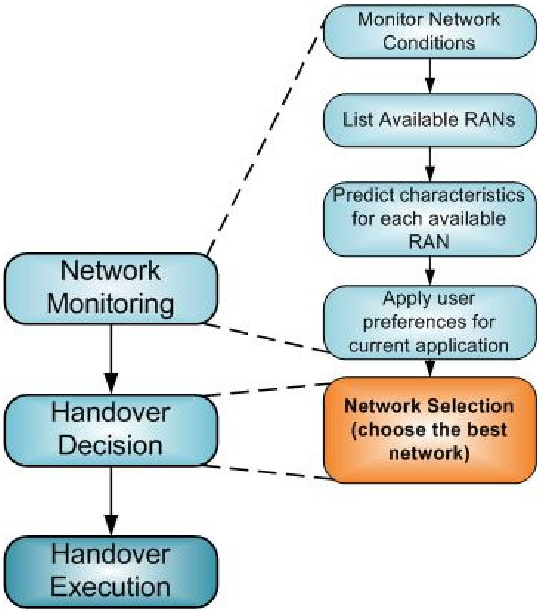

Figure 2.11. Handover process – block diagram

Network Monitoring monitors the current network conditions as well as network availability. This service is responsible for gathering the data related to the network conditions, in order to trigger the handover execution when the service quality drops below the required QoS level. Network Monitoring has to provide this gathered data, together with information related to the user preferences, current running applications on the user's mobile device and their QoS requirements, to the Handover Decision Module.

The **Handover Decision** handles the ***Network Selection*** process and is initiated either by an automatic trigger for a handover for an existing call or by a request for a new connection on the mobile device. The selection of the best network is decided based on the **decision criteria** provided by the device, the user inputs (if any), the application, and the monitoring process. After the target network is selected the Handover Execution is triggered and the call is set up on the target candidate network. Traditionally, this network selection decision was made by network operators both for mobility and load balancing reasons, and was mainly based on a single parameter (Received Signal Strength (RSS)).

Handover Execution – after the target network is selected, the connection is set up on the target candidate network. In the case of an existing connection, the handover is executed, the original connection is torn down and the call data is re-routed to the new connection. If the first choice network is unavailable, then the next listed candidate is chosen as the target network. Connection setup (and teardown in the case of handover) will be handled by a mobility management protocol such as MobileIPv6.

In order to provide good connectivity to the user the handover process has to be smooth, fast, seamless, and transparent. The main challenge in this process is to ensure the data does not get lost during the handover execution.

The main focus of this work is on **Network Selection** process, being part of the Handover Decision module, consequently the Network Monitoring and Handover Execution will not be further addressed. However existing ways and protocols on how the information is gathered by the Network Monitoring are defined.

2.4. Network Selection Decision

The ‘Always Best Connected’ vision emphasis the scenario of a mobile user seamlessly roaming in a heterogeneous wireless environment. In this context, the user will be facing the problem of selecting from a number of RANs that differ in technology, coverage, pricing scheme, bandwidth, latency, etc., belonging to the same or different service providers.

Figure 2.12 illustrates an example scenario of a heterogeneous wireless environment, where a mobile user, located in an area of overlapping RANs coverage, has a choice of RANs to use. Because of the heterogeneity of the applications and their requirements (e.g., voice, video, data, etc.), multiple device types (e.g., smartphones, netbooks, laptops, etc) with different capabilities, multiple overlapping network technologies (e.g., WLAN, UMTS, LTE), and different user preferences, the mobile user will be facing a complex decision when selecting the best network to connect to, that will satisfy his/her interests. Ideally his mobile device should auto-detect this and dynamically and seamlessly select and connect to the best available network dependent on his current needs. This multi-user multi-technology multi-application multi-provider environment requires the development of new technologies and standards that seek to provide dynamic automatic network selection decision.

In general the network selection problem is modeled using either a *centralized* or a *decentralized* approach. Most centralized approaches are *network-centric*, and consist of a centralized, operator-controlled policy that decides the users' distribution among the networks. These *network-centric* approaches are based on the cooperation of subscribed user devices in obeying the decision made by the controller. For the decentralized approach the decision is made at the user side either by the user or automatically by the user's device. This automation may be based on policies/rules set by the user or downloaded to the device from an operator or service provider. Many of the considered decentralized *user-centric* approaches consider the case of users who are not solely subscribed to one network, but instead have multiple subscriptions/agreements in place and wish their device to choose the most suitable available RAN. For example an enterprise user who uses the same mobile device for personal and business use, may have access to home and work WLANs, and minutes/data from a number of operators.

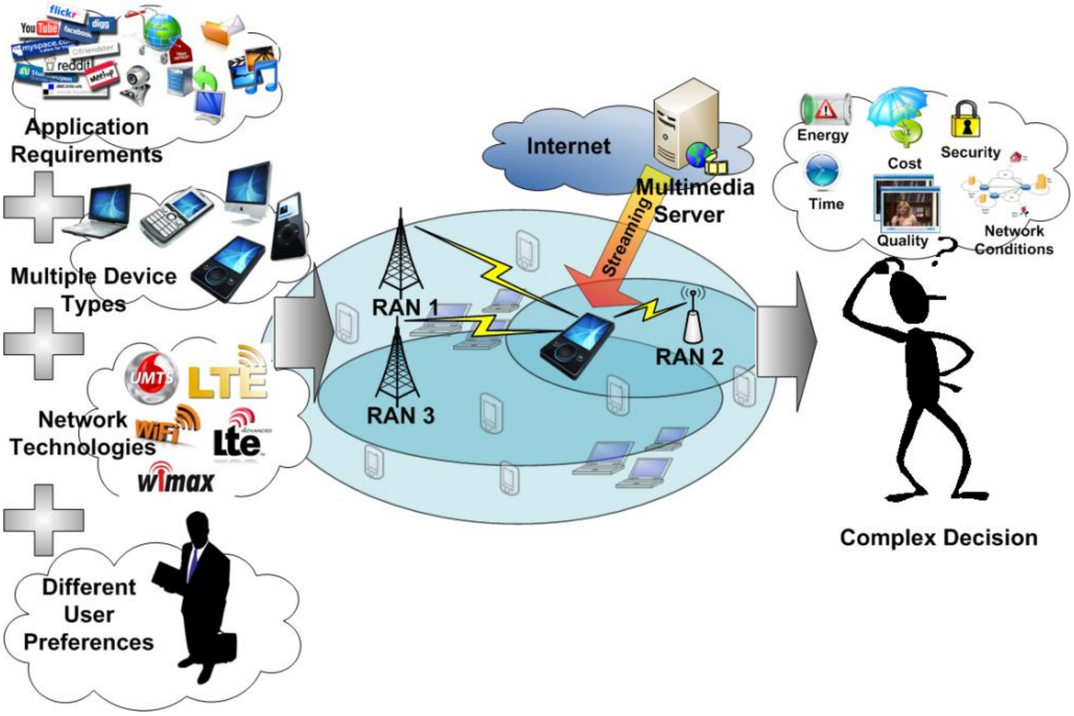

Figure 2.12. Heterogeneous Wireless Networks Environment – Example Scenario

In this work a decentralized network selection approach is considered. The network selection problem is considered to be a complex problem, because of the multiple mix of static and dynamic, and sometimes conflicting *parameters/criteria* involved in the process. An illustration of the **decision making** process is illustrated in Figure 2.13.

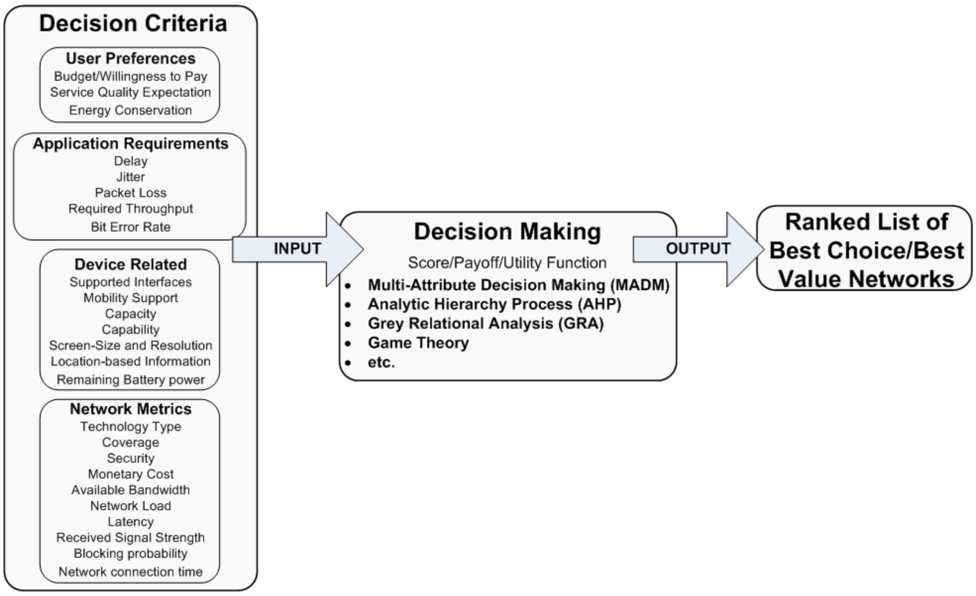

Figure 2.13. Decision Making Process

2.4.1. Decision Criteria

Every decision making mechanism requires essential and relevant input information in order to choose the best value network. The decision criteria that may be used in the network selection process can be classified into four categories depending on their nature:

- **Network metrics** – include information about the technical characteristics or performance of the access networks, such as: technology type, coverage, security, pricing scheme, monetary cost, available bandwidth, network load, latency, received signal strength, blocking probability, network connection time, etc.
- **Device-related metrics** – include information about the end-users' terminal device characteristics, like: supported interfaces, mobility support, capacity, capability, screen-size and resolution, location-based information, remaining battery power, etc.
- **Application requirements** – include information about the requirements (minimum and maximum thresholds) needed in order to provide a certain service to the end-user: delay, jitter, packet loss, required throughput, Bit Error Rate, etc.
- **User Preferences** – include information related to the end-users' satisfaction: budget (willingness to pay), service quality expectations, energy conservation needs, etc.

An important aspect to consider is what information is readily available to the decision maker and how accurate and/or dynamic that information is. For example, because of the dynamics of the wireless environment the received signal strength or the available bandwidth can present major fluctuations for short periods; while coverage and pricing schemes are less dynamic as in they do not present changes on a daily basis; and technology type, security level and application requirements are more static parameters.

Note that the parameters presented above do not represent an exhaustive list and are possible choices that can be used as input information for the **decision mechanism**. Some may use only a subset of the parameters, or may include additional parameters. Because the parameters present different ranges and units of measurement, they are normalized. The aim of the normalization process is to bring all the parameter into dimensionless units within [0,1] and make them comparable. The normalization process is done through the use of so called utility functions (normalization functions). The utility functions for the parameters may vary. For example some works consider normalized parameters based on the user and application requirements for the minimum and maximum value, while others consider normalization based on the ranges of values available from the different candidate networks. Other works consider using individual utility functions to model different parameters.

Depending on the type of architecture, and protocol in use, and whether it is a centralized or decentralized decision, different information will be available in different forms and accuracy levels. For example, for a decentralized approach, the mobile device could collect the network state information as statistics, usually represented by mean values of previous sessions, or could estimate network bandwidth, for example, through the use of *IEEE 802.21* Hello packets. A mobile station can collect authentication, routing, and network condition (e.g., available throughput, average delay, average packet loss, etc.) information through advertisement Hello packets sent by a gateway node. This information can be collected from the link layer by using the *IEEE 802.21* reference model [22]. Another option would be to predict the future network state based on past history. For example, based on location (e.g., home/office/airport/coffee bars, etc.), time of day (e.g., peak/off-peak hours), day of week (e.g., working days/weekends), year periods (e.g., holidays) many QoS parameters (e.g., availability, utilization, etc.) for different hot-spots can be predicted depending on their usage pattern statistics. The accuracy in collecting network state information is very important as the selection of the best value network depends on it. However, a trade-off between accuracy and overhead needs to be taken, as keeping accurate estimates for the more dynamic parameters depends on their frequency of change and can be data intensive, adding to signaling, processor and memory burden.

The **user preferences** play an important role in the decision mechanism and they may be used to *weight* the other parameters involved. There are many ways of collecting data from the user. Some of the existing *weighted solutions* obtain the weights through questionnaires on user and service requirements. Other solutions integrate a GUI in the user’s mobile terminal in order to collect the user preferences. An important aspect is to find a trade-off between the cost of involving the user and the decision mechanism. One solution for minimizing the user interaction may be implementing an intelligent learning mechanism that could predict the user preferences over time.

2.4.2. Decision Making

Due to the different possible strategies and the numerous parameters involved in the process, researchers have tried many different techniques in order to find the most suitable network selection solution. The mathematical background of the more formal techniques used in the literature is outlined below.

a) The Simple Additive Weighting Method (SAW)

The *SAW* method [34] (also known as the weighted sum method) is one of the most widely used Multi Attribute Decision Making (MADM) methods used in the network selection literature. The basic logic of SAW in this context is to obtain a weighted sum of the normalized form of each parameter over all candidate networks. Normalization is required in order to have a comparable scale among all parameters. Depending on the formulation of the problem, the network which has the highest/lowest score is selected as the target network. For example if a list of candidate networks is considered with each network having a list of n parameters, then for each candidate network i a score is obtained by using equation (2.1).

$$SAW_i = \sum_{j=1}^{n} w_j r_{ij} \qquad (2.1)$$

where r_{ij} is defined as the normalized performance rating of parameter j on network i, and w_j is the weight of parameter j. Usually, the greater the score value the more preferred the candidate network.

b) The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The *TOPSIS* method [34] is based on the concept that the selected candidate network is the closest to the ideal possible solution and the farthest from the worst possible solution. The ideal solution is obtained by giving the best possible values to each parameter whereas the worst possible solution is obtained with the worst value of each parameter. For each candidate network i, a score ($TOPSIS_i$) is obtained by using equation (2.2). The greater the score value, the more preferred the candidate network.

$$TOPSIS_i = \frac{D_{w,i}}{D_{b,i} + D_{w,i}} \qquad (2.2)$$

where $D_{w,i}$ and $D_{b,i}$ are given in equations (2.3) and (2.4), respectively, and they represent the Euclidian distance of a network i from the worst and from the best reference network, respectively.

$$D_{w,i} = \sqrt{\sum_{j=1}^{n} w_j^2 (r_{ij} - r_j^w)^2} \qquad (2.3)$$

$$D_{b,i} = \sqrt{\sum_{j=1}^{n} w_j^2 (r_{ij} - r_j^b)^2} \qquad (2.4)$$

where r_{ij} is defined as the normalized performance rating of parameter *j* on network *i*, r_j^w and r_j^b are the worst and the best, normalized ratings of parameter j within the candidate networks, respectively.

c) Multiplicative Exponential Weighting Method (MEW)

The *MEW* method [34] (also known as the weighted product (WP) method) uses multiplication for connecting network parameters ratings. For example, for each candidate network *i* a score is obtained by using equation (2.5).

$$MEW_i = \prod_{j=1}^{n} r_{ij}^{w_j} \qquad (2.5)$$

where r_{ij} is defined as the normalized performance rating of parameter *j* on network *i*, and w_j is the weight of parameter *j*. The greater the score value the more preferred the candidate network.

d) Elimination and Choice Expressing Reality (ELECTRE)

The *ELECTRE* method [35] is based on a pair-wise comparison amongst the parameters of the candidate networks. The concepts of concordance and discordance are used in order to measure the satisfaction and dissatisfaction of the decision maker when comparing the candidate networks.

e) Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA)

- *Analytic Hierarchy Process (AHP)*

The idea behind *AHP* is to decompose a complicated problem into a hierarchy of simple and easy to solve sub-problems. According to [36] there are four steps involved in the process: *(1) decomposition* – the problem is structured as a hierarchy of multiple criteria, where the top level is the problem to be resolved, the subsequent levels are the decision factors, and the solution alternatives are located at the lowest level; *(2) pair wise comparison* – at each level the elements within the same parent are compared to each other, the results are translated into numerical values on a scale from 1 to 9 and presented in a square matrix, referred to as the AHP matrix; *(3) local weight calculation* – the weights of the decision factors are computed by calculating the eigenvector of the AHP matrix; *(4) weight synthesis* – the overall weights of the decision factors are computed by multiplying the local weights from each level.

- *Grey Relational Analysis (GRA)*

The *GRA* method is used to rank candidate networks and select the one which has the highest rank. There are three steps involved in the process: *(1) normalization of data* – is performed considering three situations: larger-the-better, smaller-the-better, and nominal-the-best; *(2) definition of the ideal sequence* – the ideal sequence will contain the upper bound, lower bound and moderate bound respectively in the three considered situations; *(3) computing the grey relational coefficient (GRC)* as given in equation (2.6) – the larger the GRC is, the more preferable the sequence is.

$$GRC_i = \frac{1}{\sum_{j=1}^{n} w_j \, | r_{ij} - R_j | + 1} \qquad (2.6)$$

where r_{ij} is defined as the normalized performance rating of parameter j on network i, w_j is the weight of parameter j, R_j represents the ideal value of parameter j.

2.5. Game Theory and Network Selection

Game theory is a mathematical tool used in understanding and modeling competitive situations which imply the interaction of rational decision makers with mutual and possibly conflicting interests. It was originally adopted in economics, in order to model the competition between companies. Nowadays game theory is widely applied to other areas, such as: biology, sociology, politics, computer science, and engineering. Game theory has been adopted in the telecommunication environment, especially in *wireless sensor networks* [37], *cognitive radio networks* [38], and *ad-hoc networks* [39]. Game theory is used as a tool for studying, modeling, and analyzing the interactions between individuals strategically. In the wireless environment, game theory has been used in order to solve many *distributed power control* [40], *resource management* and *allocation*, and *dynamic pricing* [41] related problems. A more comprehensive survey on general game theory application in wireless networks is offered by Charilas et al. in [42]. They present a categorization, under the corresponding OSI Layer (e.g., Physical, Data link, Network, and Transport), of a collection of game theoretic approaches applicable to various telecommunication fields (e.g., power control, spectrum allocation, MIMO systems, medium access control, routing, load control, etc.). The aim of their survey is to show that game theory can be used to solve problems in all aspects of telecommunications. The recently released book [43] presents a collection of fundamental issues and solutions in applying game theory in different wireless communications and networking domains (e.g., wireless sensor networks, vehicular networks, power control games, economic approaches, and radio resource management).

2.5.1. Basic Concepts of Game Theory

The main components of a game are: the **set of players**, the **set of actions**, and the **set of payoffs**. The players seek to *maximize* their payoffs by choosing strategies that deploy actions depending on the available information at a certain moment. Each player chooses strategies which can *maximize* their payoff. The combination of best strategies for each player is known as **equilibrium**. The payoff for each player can be represented as the actual or expected *utility* a player receives by playing the current strategy. When the game is viewed from the point of view of an outside observer, a **Pareto Optimal** solution can be defined. The game is said to have reached a **Pareto Optimal** when the payoffs cannot be further enhanced with any other combination of strategies that can make at least one player better off without making any other player worse off. In other words, there is no change that can be made to increase the common goal of all the players.

- *Pareto Optimality Definition*

Let N be the number of players in a game and i be an index of a player such that $0 < i \leq N$. Let S_i denote a set of available mixed strategies for player i with $s_i \in S_i$ being any possible strategy of player i. The strategy profile s_p is Pareto Optimal if it satisfies the condition given in equation (2.7) [44]:

$$\pi_i(s_p) \geq \pi_i(s) \quad \forall 0 < i \leq N, \forall s \in S \tag{2.7}$$

where $\pi_i()$ is the payoff function of player i, and s_p denotes the Pareto Optimal strategy.

When the game is viewed from the point of view of an individual player, then the solution concept of Nash equilibrium can be defined. When each player cannot benefit anymore by changing his strategy while keeping the other players' strategies unchanged, then it is said that the solution of the game represents **Nash Equilibrium**. In other words, each player makes the best individual strategy choice based on the choices of the other players.

- *Nash Equilibrium Definition*

Let N be the number of players in a game and i be an index of a player such that $0 < i \leq N$. Let S_i denote a set of available mixed strategies for player i with $s_i \in S_i$ being any possible strategy of player i and s_{-i} is the strategy profile s without player i's strategy, so that $s=(s_i, s_{-i})$. The strategy profile s^* is a Nash equilibrium if it satisfies the condition given in equation (2.8) [44]:

$$\pi_i(s_i^*, s_{-i}) \geq \pi_i(s_i, s_{-i}) \quad \forall 0 < i \leq N, \forall s_i \in S_i \tag{2.8}$$

where $\pi_i()$ is the payoff function of player i, s_i^* denotes a Nash Equilibrium strategy of player i, and s_{-i} denotes the strategy profile of all players other than player i. However, some games might not have a Nash Equilibrium or they can have more than one Nash Equilibrium.

2.5.2 Game Theory to Network Selection Mapping

A mapping of game theory components to network selection environment is given in Table 2.3. The players in the game are the mobile users and/or the networks. Players seeking to maximize their payoffs can choose between different strategies, such as: available bandwidth, subscription plan, or available APs. The payoffs can be estimated using *utility functions* based on various *decision criteria*: monetary cost, energy conservation, network load, availability, etc. The games can be formulated so that they can target different objectives, such as maximizing or minimizing different resources -bandwidth, power, etc.

TABLE 2.3. MAPPING OF GAME COMPONENTS TO NETWORK SELECTION ENVIRONMENT

Game Component	Network Selection Environment Correspondent
Players	The agents who are playing the game: users or/and networks
Strategies	A plan of actions to be taken by the player during the game: available/requested bandwidth, subscription plan, offered prices, available APs, etc.
Payoffs	The motivation of players represented by profit and estimated using utility functions based on various parameters: monetary cost, quality, network load, QoS, etc.
Resources	The resources for which the players involved in the game are competing: bandwidth, power, etc.

Different categorizations of the various game types are possible. In this work the solutions are classified firstly by the players involved **(Users vs. Users**, **Users vs. Networks**, **Networks vs. Networks**) with a further sub-classification under two broad major game theoretic approaches:

- ***cooperative** approaches* – which implies the joint considerations of the other players.
- ***non-cooperative** approaches* – in which each player selects his/her strategy individually.

TABLE 2.4. GAME THEORETIC APPROACHES FOR NETWORK SELECTION

Players' Interaction	Game theoretic approach	Objective
Users vs. Users	**Non-cooperative**	users compete against each other seeking to maximize their own utility
	Cooperative	users cooperate in order to obtain mutual advantage (maximize social welfare)
Networks vs. Users	**Non-cooperative**	users compete against networks, each seeking to maximize their own utility. On one side the users try to maximize their cost-benefit performance. On the other side the networks aim to maximize the profit for the provided services.
	Cooperative	both sides cooperate in order to achieve mutual satisfaction
Networks vs. Networks	**Non-cooperative**	the networks compete against each other seeking to maximize their individual revenues
	Cooperative	networks cooperate in order to achieve global welfare maximization

In this context, game theory is used to model and analyze cooperative or non-cooperative behaviors of **users and networks** during their interaction in a *heterogeneous wireless environment*. For example consider a group of users that are located in an area with a number of available networks. Each user is seeking to select the best network that will maximize its utility. In this particular case six different game theoretic approaches can be identified, as illustrated in Table 2.4.

2.5.3. Game Theoretic Models

Different types of games are used to model various cooperative or competitive situations between rational decision makers. Some of the most widely used game theoretic models are outlined below.

a) Strategic Game: Prisoner's Dilemma

A *Strategic Game* is an event that occurs only once, with each player being unaware of the other player's action. The players choose their action simultaneously and independently. One of the most well-known strategic games is Prisoner's Dilemma [44]. Prisoner's Dilemma models a situation in which two suspects in a major crime are held in separate cells. The payoffs of each player for this game are illustrated in Table 2.5. The idea is that the players are seeking to minimize their jail sentence (minimizing the payoff). If they both remain silent (*Cooperate* with each other), each will be sentenced to 1 year in prison, getting a payoff of 1 each: payoffs (1,1). If they both confess (*Defect*), each will be sentenced to 3 years in prison and both getting a payoff of 3: payoffs (3,3). If only one player confesses, he/she will be freed by getting 0 payoff, and used as a witness against the other player, who will be sentenced to 4 years in prison with a payoff of 4: payoffs (0,4) or (4,0). The best outcome for the players is if they both cooperate (payoffs (1,1)), meaning that neither confesses, but each of them has an incentive to "free ride" (*Defect*) seeking to get out of jail. In isolation both players will prefer *Defect* to *Cooperate*, leading to the game's unique **Nash equilibrium** (*Defect*, *Defect*) and the payoffs (3,3).

TABLE 2.5. PAYOFF TABLE FOR THE PRISONER'S DILEMMA

		Player 1	
		Cooperate	**Defect**
Player 2	**Cooperate**	(1,1)	(4,0)
	Defect	(0,4)	(3,3)

Payoffs: (Player2, Player1)

b) Repeated Game

The main idea of the *Repeated Game* is to examine the logic of long-term relationships and show that repeated interaction leads to cooperation [44]. Usually in repeated games, a set of players will repeatedly play the same strategic game taking into account the history of the past behavior. Let us consider the repeated Prisoner's Dilemma game with the same payoff table as illustrated in Table 2.5. For each player, playing *Defect* strictly dominates playing *Cooperate*, despite the fact that both players are better off cooperating. Therefore, the game has a unique **Nash equilibrium** when each player Defects. When the game is played repeatedly, the mutual desirable outcome is when they both *cooperate* in every period (**long-term gain**). This becomes stable if each player believes that by *Defecting* they will cause the *Cooperation* to end, which results in **short-term gain** but **long-term loss**.

c) Bargaining Game

The *Bargaining Game* [45] is a game theoretic approach in which players bargain for an object or service. The most common example is where one of two players splits a pie of a certain size. The first player proposes a division of the pie and the second player has two options: to accept – in which case he might end up with no pie if player 1's division is selfish (i.e., he leaves no pie for player 2) leading to a unique **subgame perfect equilibrium**, or to refuse the division – in which case neither player gets any pie. In the extended game where the players alternate the offers over many periods, the player who makes the offer in the last period will end up with the entire pie considering the case of subgame perfect equilibrium.

d) Trading Market

The *Trading Market* game [44] models the scenario in which a single seller can negotiate to trade a certain good with multiple buyers. The basic idea behind this game is to analyze how the presence of a second buyer affects the negotiated price. The buyers know that by rejecting the seller's offer there is a 50% probability that another buyer will be trading in the next period.

e) Auction Game

The *Auction Game* [45] is a game theoretic approach that models the situation in which bidders submit bids to an auctioneer in order to obtain a certain object or service. The good is sold to the bidder that submits the highest bid. There are two main auction games: *(1) the first-price auction game* - in which the winning bidder will pay an amount equal to his bid; *(2) second-price sealed-bid auction game* - in which the bidder with the highest bid wins but pays an amount equal to the second highest bid.

f) Cournot Game

The *Cournot Game* [44] models the competition among firms for the business of consumers. It considers the case where a good is produced by multiple firms. Each firm has a cost of producing a certain amount of good units. More output means more cost to produce. The profit of each firm is computed as the difference between the firm’s revenue and the cost incurred. The price decreases as the total output among the firms increases. The aim is to analyze the impact of several factors (i.e., market demand, the nature of the firms’ cost functions, or the number of firms) on the outcome of competition among firms.

g) Bankruptcy Game

The *Bankruptcy Game* [44] is a game theoretic approach used to model distribution problems. This usually involves the scenario in which a perfectly divisible good has to be allocated among a group of agents. The bankruptcy game considers the case in which the amount is insufficient to satisfy all parties’ demands.

h) Stackelberg Game / Leader-Follower Game

The *Stackelberg Game* [46] is a strategic game also known as the *Leader-Follower Game* in which the player acting as the leader moves first and then the follower players move sequentially. It is assumed that the followers are rational and they will try to optimize their outcome given the leader’s actions. Given this, the aim is to find an optimal strategy for the leader.

i) Bayesian Game

Bayesian Games [44] represent a combination of game theory and probability theory, offering the possibility to take into account incomplete information. Each player involved in the game can have some private information which is unknown by the other players but it can affect the overall game play. In these situations the players act optimally according to their private information and their beliefs which are represented through probability distributions.

j) Coalition Game

Usually cooperative games explore the formation of coalitions between various players [44]. For example considering a N-player cooperative game, where $N = \{1, ..., n\}$ is the set of n players, the coalition form would be given by the pair (N,v) where v is the characteristic function. The characteristic function assigns the maximum expected total income of the coalition. The core represents the solution concept of the cooperative game, and is usually used in order to obtain the stability region. It gives the set of all feasible outcomes that cannot be improved by the coalition members when acting independently. Another concept which represents a measure of efficiency is **Pareto Optimality**. By definition, an agreement is said to be **Pareto efficient** if and only if there is no other feasible agreement that all the players prefer.

k) Evolutionary Games

The *Evolutionary Game* [47] is a game theoretic approach that has been applied most widely in the area of evolutionary biology. The main idea behind evolutionary game theory is that many behaviors are involved in the interaction of multiple entities/organisms in a population and the success of any of them depends on how their behavior interacts with that of the others. In these types of games, an individual entities/organism has to be evaluated considering the context of the entire population in which it is living.

l) Mechanism Design

Mechanism Design [48] is an area of Game Theory that concerns defining incentive mechanisms which will induce desirable equilibrium. The incentives can be defined through the use of utility functions or by using pricing or virtual currency mechanisms.

2.6. Multimedia Content Delivery over Heterogeneous Wireless Networks

Current and future wireless environments are based on the coexistence of multiple networks supported by various access technologies deployed by different operators. In this heterogeneous multi-technology multi-application multi-terminal multi-user environment, as illustrated in Figure 2.14, there is a general goal to keep mobile users "always best connected" anywhere and anytime.

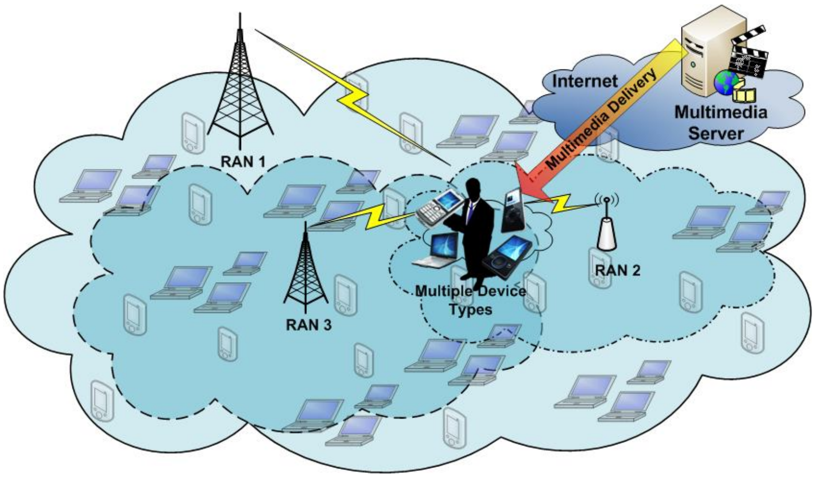

Figure 2.14. Multimedia Delivery over a Heterogeneous Wireless Environment

As wireless network deployments increase, their usage is also experiencing a significant growth. Due to advances in technologies and the mass-market adoption of the new multi-mode high-end devices - smartphones, iPhones, netbooks, and laptops, with improved CPU, graphics, and display, the mobile users' demands have increased significantly, users expecting a better multimedia experience on their devices. But due to the fluctuating behavior and constraints of the wireless networks, and also user mobility, delivering high quality streaming video over wireless networks is more challenging than over wired networks. The main challenge for this high volume and real time service is to provide low latency data connectivity and negligible data loss.

Multimedia content delivery refers to the process of delivery of media (e.g., movies, video clips, and live presentations) over a network in real or non-real time. Two distinct methods can be identified, for multimedia content delivery: downloading and streaming. Each of the two methods will be further detailed.

2.6.1. Multimedia Delivery Method - Downloading

The downloading method is considered to be the simplest form of multimedia delivery on the web. This method can be further divided into two categories: traditional download and progressive download [49].

a) Traditional Download

In order to deliver multimedia content over a network, a web server is used for storing the video files. The *traditional download* method implies that the user downloads the video file on the mobile device. The download can be done by using a file transfer mechanism such as File Transfer Protocol[2] (FTP) or BitTorrent[3]. Only after the video file was fully downloaded the user can locally watch the multimedia content. This method has the advantage that there is no expectation of real-time performance. However the main drawback is that the user has to wait for the file to be fully downloaded before watching the content, which can be a potentially long wait.

b) Progressive Download

Another downloading method for multimedia content delivery is *progressive download* which like in the case of traditional downloading method, the video content is downloaded from standard web and FTP servers. This method makes use of common protocols, such as Hypertext Transport Protocol[4] (HTTP) or FTP which are based on the Transmission Control Protocol[5]

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[2] File Transfer Protocol - http://www.ietf.org/rfc/rfc959.txt
[3] BitTorrent - www.bittorrent.com
[4] Hypertext Transport Protocol - http://www.ietf.org/rfc/rfc2616.txt

(TCP)[5] [49]. TCP is a reliable transport protocol designed to always deliver the data packets to the destination. The main difference between traditional downloading and progressive downloading is that by using the second method the user will be able to locally watch the multimedia content as it is received by the mobile device. This means that the user has to wait less in order to be able to watch the multimedia content. As for the traditional downloading, in the case of progressive download, the HTTP server will send the data packets until the download is completed. The service providers can encode the multimedia content at higher rates, but they have to maintain a trade-off between quality (higher rates) and waiting time (users' willingness to wait until the download is finished).

2.6.2. Multimedia Delivery Method - Streaming

The second multimedia delivery method is streaming, which unlike the downloading method, it requires a specialized multimedia streaming server. The streaming server delivers, on request, the exact amount of data required by the client, which plays the media content as it is delivered. With the streaming method, the video file is not downloaded on the user's mobile device. Two categories can be identified here [49]: traditional streaming and adaptive streaming.

a) Traditional Streaming

A well-known traditional streaming protocol is Real-Time Streaming Protocol[6] (RTSP). By using RTSP the client connects to the streaming server, which starts sending the multimedia stream as a series of small packets (1452 bytes for typical Real-Time Transport Protocol[7] (RTP)/RTP Control Protocol[8] (RTCP) packet size) at only one real-time rate, usually it represents the bit rate at which the multimedia stream was encoded. An illustrative example of traditional streaming is presented in Figure 2.15 [49].

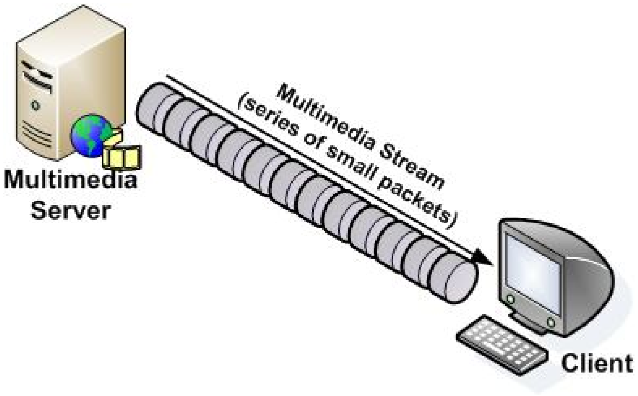

Figure 2.15. Traditional Streaming Example

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[5] Transmission Control Protocol - http://tools.ietf.org/html/rfc4614
[6] Real Time Streaming Protocol - http://www6.ietf.org/rfc/rfc2326.txt
[7] Real-Time Transport Protocol - http://www.ietf.org/rfc/rfc1889.txt
[8] RTP Control Protocol - http://tools.ietf.org/html/rfc4961

The server monitors the client's state (e.g., Play, Seek, and Pause) during the entire connection time, and only sends enough data packets to fill the client buffer. Usually the service providers using this technique need to encode the multimedia content at a certain data rate based on the available bandwidth so that it can be streamed to the client without problems.

b) Adaptive Streaming

Adaptive streaming is considered to be a hybrid delivery method that combines streaming and progressive download. An example of adaptive streaming technique is illustrated in Figure 2.16 [49]. The video content is stored on the server, encoded at different encoding rates (quality levels) and divided into small chunks. The client will switch between the chunks of different quality levels based on different parameters (e.g., estimated user bandwidth, CPU, resolution, etc.). In this way the users that have a good connection can avail of high quality multimedia stream (high data rate) whereas the users with poor connection will receive a lower data rate stream, meaning lower quality.

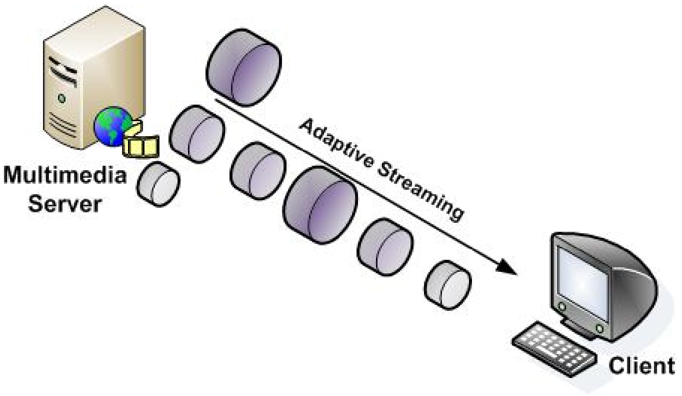

Figure 2.16. Adaptive Streaming Example

2.6.3. Transport Protocols for Multimedia Delivery

The aim of the Internet Protocol (IP) is to get the packet across the network, from the source to destination. In order to communicate over the Internet the IP is used together with the Transmission Control Protocol (TCP). TCP is a connection-oriented protocol that guarantees the correct reception of the packets to the client [50]. TCP handles the transmission problems by reordering out-of-order packets and by requesting the retransmission of the lost packets. While this is essential for reliable file transmissions across the Internet (e.g., downloading a file), when it comes to video playback the retransmissions can lead to increase latency (e.g., stalling the playback so that TCP receives the retransmitted packet).

In case of real-time services RTP mostly uses the User Datagram Protocol (UDP). In comparison with TCP, UDP is a connectionless protocol, meaning that it discards the lost packets and does not attempt any retransmission or error correction [50]. This makes RTP one of the most popular protocols for streaming applications, mainly used on managed internal networks. As UDP does not have any inherent transport layer-based rate-control mechanism, unlike TCP, makes it easier the implementation of an application layer–based adaptive mechanism suitable for low-latency and best-effort multimedia transmissions. The main disadvantage of using RTP/UDP is that it cannot traverse Internet firewalls and NAT devices as most of them are configured to restrict the UDP traffic.

In order to overtake this problem the Hyper Text Transfer Protocol (HTTP) is used, as it is the most common communication protocol used on the Internet being allowed by the majority of firewalls. HTTP uses TCP as the underlying transport protocol. This is the main reason for which the majority of the deployed adaptive multimedia solutions are based on HTTP, and hence TCP.

2.6.4. QoS and QoE in Wireless Multimedia Networks

When dealing with multimedia content delivery, two important concepts that need to be defined are *Quality of Service* (QoS) and *Quality of Experience* (QoE). Figure 2.17 illustrates the main difference between the two.

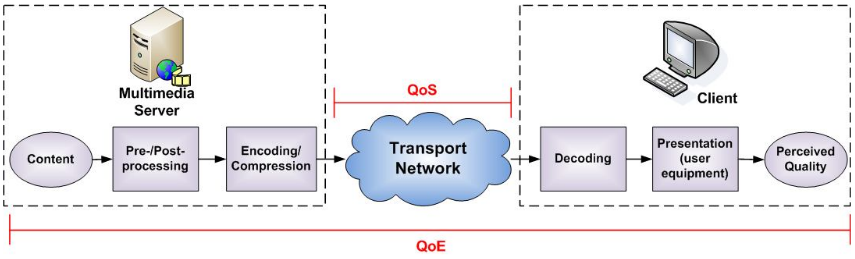

Figure 2.17. QoS vs. QoE in Multimedia Content Delivery

In general, QoS is related to the underlying data transport network and measures network-related parameters (e.g., delay, jitter, packet loss, Round Trip Time (RTT), etc.). Whereas QoE is related to the service quality as perceived by the end-user. Starting from the content provisioning, as illustrated in Figure 2.17, each stage within the content delivery process will add complexity to the QoE measurements.

Moreover, with the dynamics of the wireless environment, that is changing dynamically as people or objects move through the coverage area, QoS provisioning over heterogeneous wireless networks for multimedia streaming, presents great challenges.

The Recommendation G.1010 ‘*End-user Multimedia QoS Categories*’ [51] defines *user-centric QoS classes* for a range of services and applications. Eight QoS classes are defined for different multimedia applications based on the delay range and loss sensitivities, as illustrated in Table 2.6.

As QoS looks more at measuring the performance from a network perspective, it does not have a direct impact in guaranteeing the end-user satisfaction. That is why when talking about video quality and user satisfaction the **Quality of Experience (QoE)** needs to be addressed. QoE defines the overall performance as being perceived subjectively by the end-user. In this case taking the scenario of a roaming mobile user, the main parameters that have an impact on the mobile user experience are identified, as illustrated in Figure 2.18.

TABLE 2.6. THE G.1010 MODEL FOR USER-CENTRIC QOS CATEGORIES [51]

	Error tolerant	**Error intolerant**
Interactive (delay < 1 sec)	Conversational voice and video	Command/control (e.g., Telnet, interactive games)
Responsive (delay ~ 2 sec)	Voice and video messaging	Transactions (e.g., eCommerce, Web browsing, e-mail access)
Timely (delay ~ 10 sec)	Streaming audio and video	Messaging and downloads (e.g., FTP, still images)
Non-critical (delay > 10 sec)	Fax	Background (e.g., Usenet)

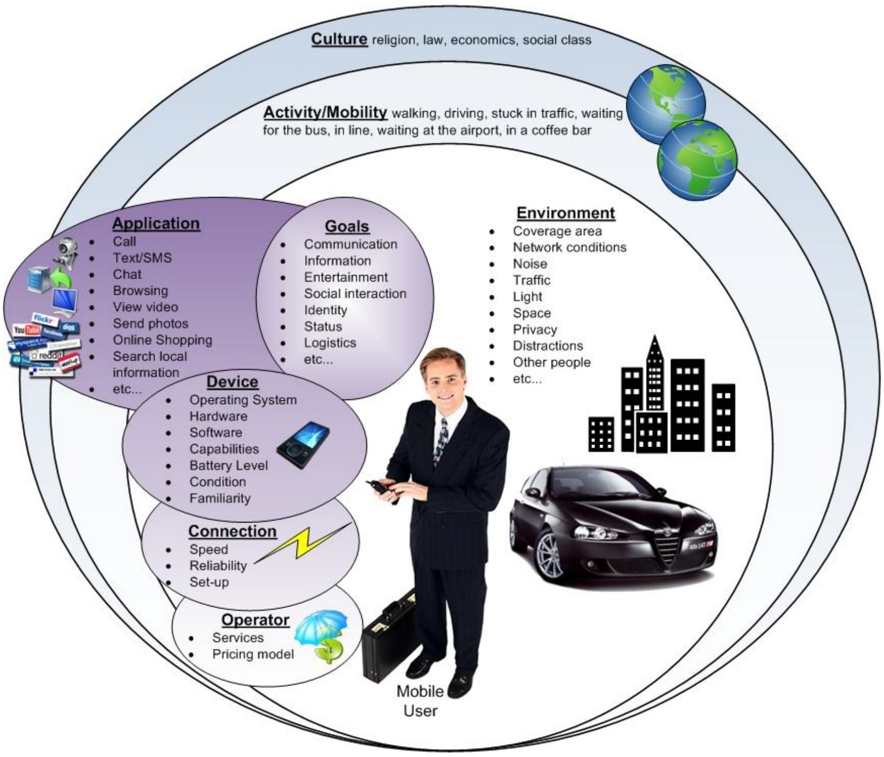

Figure 2.18. Parameters that impact the mobile user experience

The overall user experience may be affected by a wide range of factors, like: *Operator* (e.g., different pricing models for various class of services, etc.); *Connection* (e.g., the set-up of the connection, signal strength, reliability, speed, etc.); *Device* (e.g., various ranges of OS (Operating Systems), hardware, software, capabilities, battery level, condition, familiarity, etc.); *Application* (e.g., video call, text/SMS, chat, browsing, online shopping, streaming, etc.); *Goals* (e.g., social interaction, entertainment, information, communication, etc.); *Environment* (e.g., coverage area, network conditions, noise, traffic, space, light, privacy, etc.); *Activity/Mobility* (e.g., walking, driving, stuck in traffic, etc.); *Culture* (e.g., religion, economics, social class, etc.).

As it can be seen, the overall acceptability of the end-user is influenced by the entire end-to-end system effects, user expectations and context.

2.6.5. QoS Provisioning for Multimedia Delivery

It is known that multimedia applications have strict QoS requirements in terms of packet loss ratio, delay, jitter (delay variations) and bandwidth.

There are two main reasons for which **packet loss** can happen in case of multimedia content delivery: **(1) congestion** – can happen at a certain node in the network because of its limited-queue-exhaustion which leads to packet drop. In this case the packet loss ratio can be either *distributed* (the network is congested for a period of time) or *bursty* (the network presents a sudden congestion because of a short increase in traffic); **(2) network errors** – can happen on the transmission path, the packet can be marked as corrupted and discarded because of various reasons, such as nosy links or link-errors which are very common in the wireless environment (drop in signal strength, wireless link disconnections, etc.).

The **delay** can be categorized as:

- **end-point application delay** which represents the time difference between the arrival of the media content and the drain of media content.
- **network delay** the time needed for the media content to travel from the source to the destination.

The network delay can also be divided into three parts, such as: transmission delay – the time needed to transmit the packet; packet processing delay – time needed to process a packet, e.g., queuing; and propagation delay – time needed for the signal to reach the destination.

The end-to-end delay is very important in case of interactive multimedia applications (e.g., video-conference) as very large delay has a significant impact on the interactive human conversations. However in case of Video on Demand (VoD) the end-to-end delay does not affect the end-user perceived quality level because the data packets can get relatively offset on the network transport path regardless of the delay conditions [52].

The **jitter** represents the delay variation caused by network congestion, queuing delays, processing delays, signal drop, path changes or other reasons. Usually, to avoid the delay variation, a buffer is implemented at the receiver which collects a number of packets and afterwards sends them to the decoder. Packet drops may appear if the buffer is full, or if the packets arrive slowly, then the buffer will not have enough media data to send to the decoder which can cause degradation in the user perceived quality level. However, nowadays the buffers in video applications have grown so that the direct impact of the jitter can be neglected.

The **available bandwidth** could also be a factor in determine the performance of the end user’s application. Different applications have different requirements. For example for a file transfer, knowing the available bandwidth, a completion time of the transfer could easily be estimated.

This shows that the video quality is dependent on a various range of parameters: the mobile device capabilities and characteristics, the type of RAT, the application requirements, and network conditions.

2.6.6. Approaches for Measuring the Video Quality

Different methodologies were developed in order to achieve the assessment of end-user perceived quality levels. These methodologies can be classified in two main categories: subjective methods and objective methods.

Subjective methods are more reliable because they are performed on human subjects, and there is a direct measurement of the user experience. On the other hand these methods have a high cost of implementation and they are time consuming, making them useless in case of real time assessment.

Objective methods can be classified into three main subgroups [53]: *full reference methods*, *reduced reference methods*, and *no reference methods*.

The **full reference** methods are based on the comparison of two sequence of signal: the *original video* and the *distorted* one. Usually these methods are more correlated with the subjective methods than the non-reference ones. This makes them more precise but the computational complexity involved is higher as they are based on pre-pixel processing and synchronization between the original video and the distorted one. According to the ITU-T recommendation P.910 [54], some of the typically used metrics in the full reference methods are: blockiness, blur, brightness, contrast, jerkiness, frame skips, and freezes, etc. The main disadvantage of these methods is the need of both signals and also the high complexity makes them time and resource consuming.

The **reduced reference** methods represent a variation of the full reference methods. These methods are based on extracting specific features from the *original video* which are then transmitted to the receiver. At the receiver side, the same information is extracted from the *distorted video* and then compared with the ones of the original video.

The **no reference methods** are not dependent on the reference signal (*original video*), some complex algorithms are applied only to the distorted signal. This makes them more applicable as they present less computational complexity and can be used in analyzing live streams.

One of the most important metrics used in the video quality assessment of both subjective and objective methods is the Mean Opinion Score (MOS) [54]. Typically there are five MOS levels used for describing the quality and impairment of a multimedia stream as illustrated in Table 2.7 [54], starting with Level 1 representing bad quality and ending with Level 5 representing excellent quality.

TABLE 2.7. MEAN OPINION SCORE LEVELS

MOS	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

The most common and the most widely used objective method for video quality assessment is Peak Signal to Noise Ratio (PSNR), and it is given by the following equation (2.9):

$$PSNR_{dB} = 20\log_{10}\frac{255}{\sqrt{MSE}} \qquad (2.9)$$

where, *MSE* represents the Mean Square Error and it can be defined as the cumulative squared error between the original and the processed video. The main advantage of PSNR is that it is very easy to compute. Various different approaches in defining PSNR appear in the literature. In this thesis the PSNR metric proposed by Lee in [55] is used. The PSNR defined by the authors is given in equation (2.10):

$$PSNR_{dB} = 20\log_{10}\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)^2}} \qquad (2.10)$$

where *MAX_Bitrate* represents the bitrate of the multimedia stream after the encoding process, *EXP_Thr* represents the expected average throughput for the delivery of the multimedia stream over the network, and *CRT_Thr* represents the actual average received throughput for the multimedia delivery over the network. For the case when *EXP_Thr* equals *CRT_Thr*, PSNR is undefined ($\sqrt{(0)^2}$). Instead of leaving PSNR undefined for this case it is set to 100dB. When no data is lost, there is no significant difference between the processed video and the original one and very high quality of the original video is used, the result is excellent in terms of user perceived quality levels, associated with 100dB.

Some examples of no reference models are: Video Streaming Quality Index (VSQI) [56], Mobile TV Quality Index[9] (MTQI), Video Telephony Quality Index[10] (VTQI), and Perceptual Evaluation of Video Quality[11] (PEVQ). The main disadvantage is that they are not open-source, being proprietary solutions. For example, VSQI takes the entire streamed video and assigns a MOS score to it based on various parameters: video codec used, total bit rate, duration of initial buffering, number and duration of re-buffering periods, and packet loss.

Nowadays, when delivering multimedia content over the Internet, one important parameter that has to be taken into account and that has a significant impact on the quality degradation as perceived by the user, is the buffering effect (initial buffering and the re-buffering periods). The biggest impediment for the research community is that all the video quality assessment solutions that consider the effect of re-buffering periods are proprietary.

2.7. Chapter Summary

This chapter presents the evolution of the **cellular** and **wireless networks** which leads towards a multi-technology **multi-terminal multi-application multi-user heterogeneous wireless environment** representing the next generation of wireless networks. The basic architecture of the main cellular and wireless technologies is described in details. In this context, the **Always Best Connected** vision emphasis the scenario of a variety of radio access technologies that work together in order to provide a global wireless infrastructure in which the end-users will benefit from an optimum service delivery via the most suitable available wireless network that satisfies their interests.

In order to achieve seamless connectivity within the heterogeneous wireless environment an efficient **mobility management** is needed. Part of the mobility management is the network selection process, which represents the core of this thesis. An overview of the **network selection concept** and of the main steps involved in the **decision making process** is presented. The chapter also introduces the **basic game theory models** and their **mapping** to the **network selection** problem.

In terms of multimedia delivery, the chapter presents the **main techniques** used in **multimedia content delivery over the heterogeneous wireless environment**: *downloading (traditional download* and *progressive download)* and *streaming (traditional streaming* and *adaptive streaming)*. The choice of the transport protocol (**UDP vs. TCP**), **QoS provisioning**, and the main approaches for **measuring the video quality** as perceived by the end-user are discussed.

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[9] Mobile TV Quality Index - http://www.scribd.com/doc/53306459/10/Mobile-TV-Quality-Index-%E2%80%93-MTQI
[10] Video Telephony Quality Index - http://www.ascom.com/en/evaluating-mobile-video-service-quality-with-tems-solutions.pdf
[11] Perceptual Evaluation of Video Quality - http://www.pevq.org/

Chapter 3

Related Work

This chapter presents a comprehensive survey of the current research on the following topics: network selection strategies, reputation-based system for heterogeneous environment, adaptive multimedia solutions, and energy efficient content delivery solutions. The existing standards, industry solutions, and solution approaches in the research literature are presented, categorized, and compared. The main challenges and open issues that need to be addressed in the evolution towards a heterogeneous mobile wireless environment are outlined.

3.1. Network Selection Strategies

3.1.1. Standards which Support Network Selection

The "optimally connected anywhere, anytime" vision was introduced by ITU in Recommendation ***ITU-R M.1645*** [57] in June 2003 and relies on different radio access networks connected via flexible core networks. The aim is to provide seamless, transparent and QoS-enabled connectivity to the user by taking into account the limitations of the underlying wireless access technology and user preferences.

The IEEE 802.21 ***Media Independent Handover (MIH)*** Working Group [22] (Jan 2009) considers the interoperability aspects between heterogeneous networks, and has developed a standard referred to as IEEE 802.21. This standard enables the optimization of handover between heterogeneous IEEE 802 networks and facilitates handover between IEEE 802 networks and cellular networks by providing a media-independent framework and associated services. The standard provides three services:

(1) *Media Independent Event Service* – triggered when changes occur at the physical layer (i.e., link parameters change, new networks available, interrupted/established session);

(2) *Media Independent Command Service* – enables the higher layers to control the link layer by reconfiguring or select an appropriate link;

(3) *Media Independent Information Service* – provides an interface for the handover policy in order to gather information about the available networks. However IEEE 802.21 only

facilitates handover and does not specify the network selection algorithm, which is a major part of the handover process. As a result many proprietary algorithms exist.

The third-Generation Partnership Project (3GPP) defines a novel entity for access network discovery and selection referred to as ***Access Network Discovery and Selection Function (ANDSF)*** [58] which enables the interworking of 3GPP (e.g., GSM, UMTS, LTE) and non-3GPP networks (e.g., CDMA, WiFi, WiMAX). ANDSF provides information about the neighbouring access networks to the mobile device through Access Network Discovery Information (e.g., location data, SSID in case of WLAN, Area/cell identities in case of 3GPP access, Network Access provider ID in case of WiMAX, etc.) and assists the device in the handover process through rule based network selection policies. Two categories of policies are defined: *Inter-System Mobility Policy (ISMP)*, which guides the selection decision for devices with single links, and the *Inter-System Routing Policy (ISRP)*, which directs the distribution of traffic for devices with multiple simultaneous links.

A study on the network selection requirements for non-3GPP access types (e.g., Bluetooth, WLAN, and wired networks) is provided in ***3GPP TR 22.912*** specifications [59]. The study identifies the potential requirements for automatic and manual selection as well as operator and end-user management requirements. The aim of the study is to ensure predictable behaviour and enable the user or application to select the best type of access that fulfils the requested service requirements.

3.1.2. Industry Solutions for Network Selection

In the current environment network operators are trying to cope with the significant increase in data traffic by adopting different solutions to expand the capacity of their network capacity. One category of network selection solution includes those employed by operators with multiple converged networks (i.e. multiple radio access technologies (RATs)) - ***which expand their network capacity by adding next generation wireless networks*** (e.g., HSDPA, LTE, WiMAX). Many of these upgrades involve closely interworking the existing 2G/2.5G/3G network with the new next generation network in terms of handover and network selection. For example Verizon upgraded their wireless network to offer commercial LTE-based services in the United States[1].

Another category of commercial network selection solutions are used by the operators who ***offload the mobile data traffic onto WLAN networks***. This solution category enables transfer of some traffic from the core cellular network to WLAN at peak times. AT&T adopted this solution and launched the Wi-Fi Hotzone project[2] which aims to supplement their macro cellular coverage with additional Wi-Fi capacity (over 24,000 WiFi hotspots) in areas with high

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[1] Verizon - www.network4g.verizonwireless.com
[2] AT&T, WI-FI Hotzone project - www.fiercewireless.com

3G traffic and mobile data usage. The Wi-Fi offload solution is already adopted by many other service providers including: Swisscom with its “Mobile Unlimited”[3] service which provides automatic connection to the fastest available mobile broadband (on Swisscoms EDGE/HSPA networks which are supplemented with more than 1,200 WLAN hotspots); T-Mobile’s “Hotspot@Home”[4] solution which offers connectivity on the home WiFi, on all T-Mobile hotspots and on the T-Mobile cellular network; the British Telecom “BT Fusion”[5] service which works on the user’s home wireless network, BT Openzone WiFi hotspots, and on the BT cellular network; Deutsche Telekom and iPass WiFi Mobilize[6] solution; and Wi-Fi network database provider WeFi[7] who launched WeANDFS, an offload solution (to over 80 million hot-spots worldwide) which is ANDSF 3GPP compliant.

In the Enterprise Fixed Mobile Convergence (FMC) service space, the advantages of fixed mobile convergence for business are well established, with one mobile device using a single number, mailbox, address book and ***always the lowest cost network for connectivity***, all without burdening the user with the responsibly to choose the appropriate network. Solutions in this area, include: Siemens with its “Highpath MobileConnect”[8] solution and AT&T with its “Global Network Client”[9].

Another player category in this space is softphone service providers, such as CiceroPhone[10] whose software (which works over Session Initiation Protocol (SIP) and IP Multimedia Subsystem (IMS)) allows ***roaming between WLAN and cellular networks***.

Many existing commercial solutions are proprietary and involve rudimentary static network selection decisions (e.g., always select the WLAN, always select the cheapest or the fastest network). They do not account for the varying network characteristics or for the various user context-based preferences and may often result in lower quality of service. User mobility, as well as the heterogeneity of mobile devices (e.g., different operating systems, display size, CPU capabilities, battery limitations, etc.), and the wide range of the video-centric applications (e.g., VoD (Video On Demand), video games, live video streaming, video conferences, surveillance, etc.) opens up the demand for user-centric solutions that adapt the application to the underlying network conditions and device characteristics.

3.1.3. Network Selection Research Area

In order to strengthen the ***Always Best Connected*** vision, various network selection mechanisms have been proposed in the research literature. Due to the different possible

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[3] Swisscom ‘Mobile Unlimited’ Service - http://www.swisscom.ch/solutions/Solutions-products/Mobile-Unlimited
[4] T-Mobile ‘Hotspot@Home’ - https://content.hotspot.t-mobile.com/AssetProcess.asp?asset=com.default.main.001
[5] Britich Telecom ‘BT Fusion’ - http://www2.bt.com/static/i/btretail/consumer/btbenefits/fns/fusion.html
[6] Deutsche Telekom and iPass ‘WiFi Mobilize’ - http://www.telekom-icss.com/dtag/cms/content/ICSS/en/1508330
[7] Wi-Fi Network Database Provider – WeFi ‘WeANDFS’- http://www.wefi.com/carriers/weandsf/
[8] Siemens ‘Highpath MobileConnect’ - http://www.midlandtelecom.co.uk/SiemensHiPathMobileConnect.aspx
[9] AT&T ‘Global Network Client’ - http://attnetclient.com/
[10] CiceroPhone - http://www.electronista.com/articles/06/11/02/cicero.cell.wifi.roaming/

strategies and the numerous parameters involved in the process, researchers have tried many different techniques in order to find the most suitable network selection solution. The existing solutions were divided into two wide categories: (1) Multi Attribute Decision Making (MADM) – based network selection solutions – in which the decision making is based on one or more MADM methods; (2) Game Theory-based network selection solutions –in which game theory is used to model the user network interaction. Next these areas are described in details.

3.1.3.1. MADM-based Network Selection Solutions

One of the first researchers to apply the SAW method in the area of network selection strategy was Wang et al. in 1999 [60]. They describe a policy-enabled handover system used to select the “best” wireless system at any moment. They define a score function as the cost of using a network at a certain time as a function of several parameters: the bandwidth it can offer, the power consumption of the network access, and the monetary cost of this network. The score function is the sum of a weighted normalized form of the three parameters. The weights may be modified by the user or the system at run-time. The monetary cost is limited by the maximum sum of money a user is willing to spend for a period of time and the power consumption is limited by the battery lifetime. The network that has the lowest value for the score function is chosen as the target network.

Since 1999 a number of other papers offering variations of this SAW method, have been produced, e.g., Adamopoulou et al. [61]. In order to scale different characteristics of different units to a comparable numerical representation, different normalized functions have been used, such as: exponential, logarithmic and linear piecewise functions [62]. One of the main drawbacks with SAW is that a poor value for one parameter can be heavily outweighed by a very good value for another parameter, so, for example, if a network has a low throughput, but a very good price, it may be selected over a slightly more expensive network with a much better throughput rate.

Bakmaz et al. [63] propose a network selection algorithm based on the TOPSIS method. The networks are ranked based on the closeness to the ideal solution using TOPSIS method. The proposed solution is evaluated using numerical examples. The parameters considered in the decision matrix are: available bandwidth, QoS level, security level, and cost. The results show that TOPSIS is sensitive to user preference and the parameter values.

In [62] Nguyen-Vuong et al. examine the disadvantages of previously proposed SAW algorithms and instead they propose the use of a weighted multiplicative method in the decision making mechanism. Their results show the inaccuracy of the SAW method and the benefits of using their proposed utility function together with a weighted multiplicative method.

Bari et al. propose in [64] a modified version of ELECTRE in order to solve the network selection problem. They compute a concordance set (CSet) which consists of a list of parameters indicating that the current network is better than the other candidate networks. On the other hand a discordance set (DSet) is defined which provides a list of parameters for which the current network is worse than the other candidate networks. Two corresponding matrices are constructed using CSet and DSet. In order to indicate the preferred network, the elements of each matrix are compared against two thresholds: $C_{threshold}$ and $D_{threshold}$.

In [36] Song et al. propose a user-centric network selection scheme using two mathematical techniques: AHP and GRA. AHP is used in order to compute the relative weights of the various parameters used in the decision model, such as: availability, throughput, timeliness, reliability, security, and cost. GRA is used to rank the networks.

An in-depth comparison study of the MADM methods is presented by Martínez-Morales et al. in [65]. The authors analyze the performance of SAW, TOPSIS, MEW, ELECTRE and GRA through simulations considering a 4G environment with three network types (e.g., WLAN, UMTS, and WiMAX) and six decision criteria (available bandwidth, total bandwidth, packet delay, packet jitter, packet loss, and monetary cost per byte). In order to differentiate the services, the authors considered three cases with different values of the parameter weights corresponding to a specific service type: a baseline case in which all the parameters have the same associated weights, a voice connection-based case in which the delay and packet jitter weight is 70% while the rest of the parameters are considered equally important, and a data connection-based case in which the available and total bandwidth have the highest importance (70%). The results show that SAW and TOPSIS are suitable for voice connections resulting in low jitter and packet delay, while GRA, MEW, and ELECTRE are suitable for data connections obtaining high throughput. A summary of the advantages and disadvantages of each of the MADM methods, as identified in this section, is illustrated in Table 3.1.

TABLE 3.1. MADM METHODS –SUMMARY

MADM Method	Advantages		Disadvantages	
SAW	- easy to use and understand - good performance for voice connections [65]	- can accommodate multiple criteria - easy to implement - accurate result and scalability - high efficiency - high flexibility - medium implementation complexity - integrate subjective judgments with numerical data	- poor value parameter can be outweighed by a very good value of another one	- imprecise data cannot be handled - normalization issues
TOPSIS	- the concept is simple and comprehensive - good performance for voice connections [65]		- most sensitive to user preferences and parameter value [63]	
MEW	- the least sensitive method [62] - good performance with data connections [65]		- penalizes alternatives with poor attribute values more heavily [62]	
ELECTRE	- good performance with data connections [65]		- complicated, uses pair-wise comparison	
AHP & GRA	- can handle many parameters, giving a precise solution -good performance for data connections [65]		- complicated - length of the process increases with the number of levels and pair-wise decisions	

3.1.3.2. Game Theory-based Network Selection Solutions

The network selection problem can be a very complex problem, and various game theoretic approaches that try to solve the network selection problem are proposed in the literature.

Different game models are used to model the problem as non-cooperative or cooperative game between users and/or networks. Figure 3.1 illustrates a classification of the existing approaches into three broad categories based on the interaction between players: **users vs. users** (*non-cooperative* [66-72] and *cooperative* [73]), **networks vs. users** (*non-cooperative* [74-78] and *cooperative* [79]), and **networks vs. networks** (*non-cooperative* [80-86] and *cooperative* [87-91]). As it can be seen from Figure 3.1, most of the related works formulate the network selection problem as non-cooperative games. Few of the works look at cooperative behavior, and of those that do, most are based on cooperation between networks.

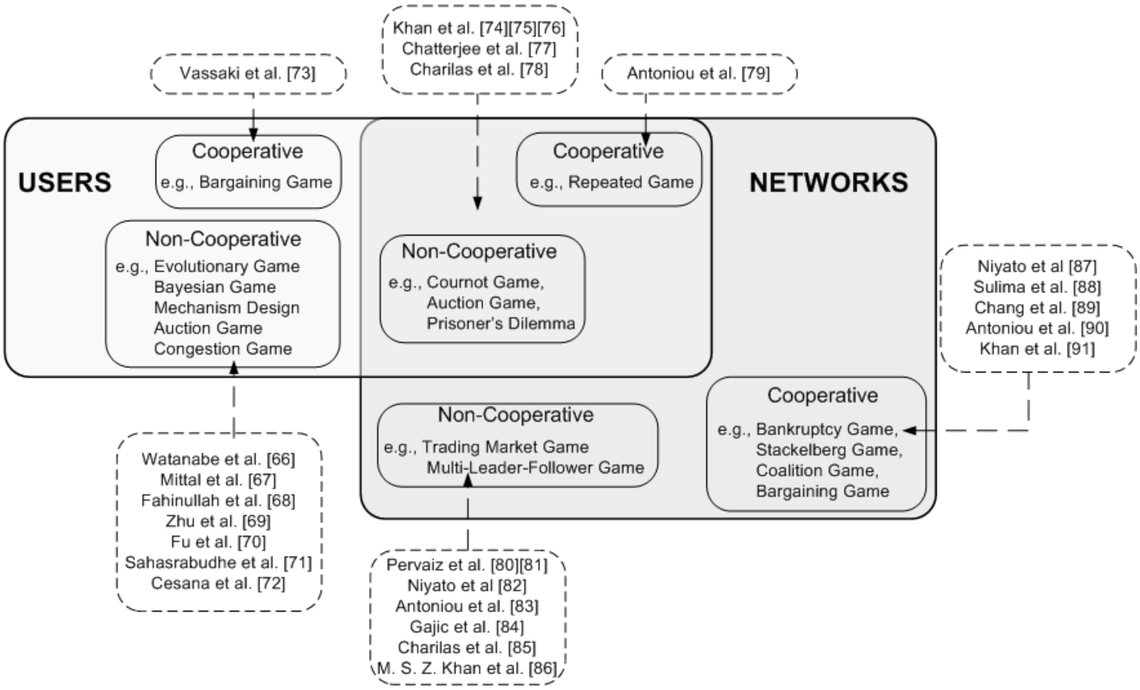


Figure 3.1. Classification of Related Works Based on Players Interactions

The approaches presented in the literature, differ in terms of: game model (Evolutionary Game, Auction Game, Bargain Game, Repeated Game, etc.), players (users and/or networks), strategies (transmission rates, available APs, service requests, etc.), pool of parameters (delay, jitter, throughput, packet loss, monetary cost, etc.), single or multiple operators, use of single or multiple simultaneous RAN connections, pricing scheme (dynamic or flat rate pricing), used RATs (WLAN, WiMAX, Cellular), etc. However, the main objective of the games is more or less the same: network selection, which is in fact a resource allocation problem.

Table 3.2 provides a comparative summary of the latest proposed game theoretic solutions in terms of related category, game type, game model, objective, strategy set, payoffs, considered parameters, resource, Radio Access Technology (RAT), and number of operators. The next section categorizes and describes these solutions in details.

TABLE 3.2. SUMMARY OF THE SURVEYED APPROACHES

Category	Game type	Game Model	Objective	Strategy Set	Payoffs	Parameters	Resource	RAT	Op.	Ref.
Users vs. Users	**Non-Cooperative**	*Evolutionary Game*	*resource sharing* -study the behavior of selfish users who compete for medium access in a WLAN.	available transmission rates	utility function	Loss rate, mean burst size, delay, jitter	bandwidth	WLAN	single	[66]
		Evolutionary Game	*network selection* - fair users' distribution among the APs.	all available APs in the network	utility function	distance from AP and network load (number of connected users)	bandwidth	WLAN	single	[67]
		Evolutionary Game	*network selection* - fair users' distribution among the APs.	all available APs in the network	utility function	distance from AP, network load (number of connected users), price	bandwidth	WLAN	multiple	[68]
		Bayesian Game	*network selection* – choosing the best value network	the probability of choosing one of the available networks	utility function	Bandwidth, price	bandwidth	WLAN, CDMA, WiMAX	multiple	[69]
		Mechanism Design	*resource management* – fair resource distribution among users.	requested bandwidth	utility function	Signal to Noise Ratio, video source characteristics, price	bandwidth	WLAN	single	[70]
		Auction Game	*resource allocation* – resource distribution among users	bids representing the willingness to pay	utility function	Bandwidth, user's budget	bandwidth	not specified	multiple	[71]
		Congestion Game	*network selection* – select the network that minimizes the selection cost	available APs in the network	cost function	congestion of the AP (number of interferences)	bandwidth	WLAN	single	[72]
	Cooperative	*Bargaining Game*	*resource allocation* – optimal bandwidth distribution.	requested bandwidth	utility function	bandwidth, transmitted power, path gain, noise spectral density	bandwidth	Cellular	single	[73]
Users vs. Networks	**Non-Cooperative**	*Auction Game*	*network selection* - select the network which fulfils the user requirements.	requested bandwidth with associated attributes	utility function	Bandwidth, Mean Opinion Score, Delivery Response Time, Application Requirements	bandwidth	HSDPA, WLAN	multiple	[74] [75] [76]
		Cournot Game	*resource allocation* - allocate the available resources among users within user classes.	subscription plan (Premium, Gold, or Silver)	utility function	Cost per byte, cost for up time per unit time, cost of coverage of services	power	CDMA	single	[77]
		Prisoner's Dilemma	*resource management* - admission and load control.	**network:** admit or reject; **user:** stay or leave;	utility function	delay, jitter, throughput, packet loss, cost	bandwidth	not specified	multiple	[78]
	Cooperative	*Repeated Game*	*network selection* - achieve a user-satisfying and network-satisfying solution.	**network**: tit-for-tat or cheat-and-return; **user:** Grim, Cheat-and-Leave, Leave-and-Return, or Adaptive return	utility function	perceived quality, price (not defined)	bandwidth	not specified	multiple	[79]
Networks vs. Networks	**Non-Cooperative**	*Strategic Game*	*network selection* - select the network which fulfils the user requirements.	offered prices	utility function	Reputation, degradation, price and availability	bandwidth	WiMAX, WLAN	multiple	[80] [81]
		Trading Market	*resource allocation* - allocate bandwidth from each available RAN to an incoming connection in a fair manner.	amount of offered bandwidth	utility function	bandwidth, number of ongoing connections	bandwidth	WLAN, CDMA, WMAN	single	[82]
		Strategic Game	*network selection* – select the best network to satisfy a service request	the service requests	utility function	delay, jitter	bandwidth	4G system	multiple	[83]
		Two Stage Multi-Leader-Follower Game	*network selection* – select the best value network for the user	offered prices	utility function	spectral efficiency, allocated time fraction, and the willingness to pay	bandwidth	not specified	multiple	[84]
		Non-Zero-Sum	*admission control* – service requests distribution among the available access networks	the service requests	utility function	network efficiency and network congestion	bandwidth	WLAN	multiple	[85]
		Strategic Game	*network selection* – select the best access network	the service requests	utility function	service type, user preferences, signal strength, mobility, battery level	bandwidth	WCDMA, WLAN, WiMAX	multiple	[86]
	Cooperative	*Bankruptcy Game*	*admission control* - guarantee the total transmission rate requested by the new connection; *bandwidth allocation* - allocate bandwidth from each network in a fair manner.	coalition form	characteristic function	available bandwidth	bandwidth	WLAN, CDMA, WMAN	single	[87]
		Stackelberg Game	*resource allocation* - allocate resources by splitting the user's application over the available networks.	coalition form	characteristic function	congestion factor, available bandwidth	bandwidth	not specified	single	[88]
		Strategic Game	*network selection* - compute the preference value from the network point of view, seeking to decrease the number of handoffs and achieve load balancing.	preference value for each network	utility function	network load, call holding time, the dwell time, mobility	bandwidth	not specified	single	[89]
		Coalition Game	*resource allocation* - allow individual access networks components to cooperate and share resources.	coalitions	characteristic function	available bandwidth	bandwidth	not specified	multiple	[90]
		Bargaining Game	*resource allocation* - allocate bandwidth from each network in a fair manner.	offered bandwidth	utility function	available bandwidth	bandwidth	not specified	multiple	[91]

3.1.3.2.1. Game players: Users vs. Users

In the Users vs. Users scenarios, the players are the mobile subscribers/clients. Two types of games are identified: **(1) non-cooperative** – in which the users compete for resources; **(2) cooperative** – in which the users cooperate in order to maximize the social welfare.

A) Users vs. Users - Non-Cooperative Approach

In the non-cooperative users vs. users scenarios, users compete against each other while seeking to maximize their own utility.

The behavior of selfish users who compete for access in a WLAN is studied by Watanabe et al. in [66]. The authors make use of ***evolutionary game-theory*** in order to model the interaction between users. The players are the mobile users and the available transmission rates represent the set of strategies. The payoff for each user is modeled as a utility function which determines the voice quality received by each user in each state. The role of the utility function is to map the wireless characteristics, such as delay and loss rate into a Mean Opinion Score (MOS) which represents a measure for voice quality. The authors show that by having free users, equilibrium close to optimal, from the system perspective, can be reached, but the equilibrium is very unfair.

Another approach which studies the interaction between selfish users, is proposed in [67] by Mittal et al. The authors look at the problem faced by mobile users selecting the least congested Access Point (AP) when they are located in an area with a number of deployed WLANs. The aim is to find the best trade-off between the bandwidth gained and the effort incurred by the user when travelling to the new location. The AP selection system is modeled as a non-cooperative game between selfish users. The set of strategies for the user is represented by the set of available APs in the network and involves physically relocating to within close range of the chosen AP. The authors show that the stability of the system is high when user arrivals and exits are evenly intermingled. The necessary condition to attain a ***Nash Equilibrium*** is examined and the Nash condition is used in order to evaluate the stability of the distribution. The outcome of the game is user distribution among the APs.

Fahimullah et al. in [68] extended the work proposed in [67] by considering the case of multiple operators. The authors define a weighted sum score function based on the AP's load, the price and the distance that the user must travel to reach the new AP. The authors argue that the results prove the existence of the ***Nash Equilibrium***.

A *Bayesian game* is used by Zhu et al in [69] in order to model the network selection problem. The players are the users, and their action set is represented by the selection of an available access network. Each user has partial information about the preferences of other users.

The authors show that Bayesian ***Nash Equilibrium*** can be reached in an environment with incomplete information.

Fu et al. [70] model the wireless resource allocation problem as a non-cooperative game between rational and selfish users. The users compete against each other in order to stream real-time video traffic. The authors make use of ***mechanism design*** in order to ensure that the players declare their resource requirements truthfully and the resources are fairly allocated.

An ***auctioning game*** is used by Sahasrabudhe et al. in [71] to model the resource allocation problem between the wireless users. Considering the scenario of multiple wireless users located in the coverage area of a number of base stations (BSs), each user is interested in *buying* a certain amount of bandwidth owned by the BS. Every user has a total amount (budget) that he can spend, and from which he bids for a BS allocation. Each BS will allocate its available bandwidth among the wireless users in a proportionally fair manner, based on the users' bids. The authors argue the existence of ***Nash Equilibrium*** for the case where each user can access all BSs. However, in the case of constrained users (users that can access only a subset of all BSs) the existence of Nash Equilibrium is not guaranteed.

In [72] Cesana et al. consider the scenario where there is only one WiFi network with multiple APs and the users within the system can choose the AP to connect to. In this scenario the users are the players of a non-cooperative game and their actions are the selection of an AP within their area. For every user, a cost function is defined based on the AP the user will connect to and on the congestion level of that AP. The solution of the game is the existence of the ***Nash Equilibrium***.

B) Users vs. Users - Cooperative Approach

In cooperative users vs. users situations, users cooperate in order to obtain mutual advantage and maximize the global welfare of the group.

Vassaki et al. [73] look at the scenario of a single cell network with one base station (BS) and multiple users having certain capacity demands. The authors model the bandwidth sharing problem using two different approaches. The first approach models the allocation problem as a ***cooperative N-person bargaining problem*** and the Nash bargaining solution (NBS) is found. The users' strategies are the bandwidth demands, and users are assumed to be free to bargain in order to achieve mutual advantage. The second approach models the problem as a ***bankruptcy game***, solved using three different division rules: Constrained Equal Awards (CEA) rule – assigns awards as equal as possible, Random Arrival (RA) rule – follows the first-come first-served principle, and Talmud rule – if the amount to divide (bandwidth) is smaller than the sum of the half-claims then the CEA rule is used and applied to the half-claims, else, if it is greater, the Constrained Equal Losses (CEL) rule is used – equalizes the losses. The results show that the maximization of total capacity is reached by using CEA or NBS, but in terms of maximum fairness the RA and Talmud rules act better.

3.1.3.2.2. Game players: Networks vs. Users

In the Networks vs. Users scenarios, the players are the network operators and the mobile subscribers/clients. Two types of games are identified: **(1) non-cooperative** – in which the networks compete against the users, each seeking to maximize its own benefit; **(2) cooperative** – in which the networks and the users cooperate in order to achieve mutual satisfaction.

A) Networks vs. Users - Non-Cooperative Approach

In non-cooperative networks vs. users situations, users compete against networks, each seeking to maximize their own utility. On one side, the users try to maximize their benefits from the service for the price they pay. On the other side, the networks try to maximize the profit for the provided services.

The interaction between networks and users is studied by Khan et al. in [74-76]. The authors model the network selection problem as a non-cooperative ***auction game*** which has three components: bidders, sellers, and an auctioneer. The buyers are represented by the users, sellers/bidders are analogous to available network operators and the auction item is represented by the requested bandwidth with associated attributes. The winning bid is computed such as it will maximize the user’s utility.

A non-cooperative game is also used in [77] for service differentiation in CDMA systems. In order to define the utility function for the provider, the authors use the ***Cournot game*** played between a provider and their customers. The dominant strategies for the provider and customer are defined as: the provider is looking to serve only customers who bring high revenue, while the customers will opt to leave the network if the received service quality does not fulfill their expectations. Users are accepted into the network if the provider’s utility value is less than the value of the new utility computed for each of the service classes when a new customer arrives. The authors categorized the users into three classes: Premium, Gold, and Silver. The resource allocation is done in two steps: (1) at the macro level, where the available resources are split between different user classes by the admission control algorithm which meets the Nash equilibrium; (2) at the micro level, where the resources are split between active users within the same class. Using a variant of the Cobb-Douglas utility function, the authors find the equilibrium for resource distribution.

Charilas et al. [78] propose a congestion avoidance control mechanism which models the competitive customer-provider scenario as a non-cooperative two-player game. The proposed framework consists of two games, namely the Admission Control (AC) game and the Load

Control (LC) game. The AC game is modeled using the classical ***Prisoner's Dilemma*** game and is played between each user-provider combination. Each service request represents an instance of the game with both players having two strategies. The provider either admits or rejects the service request, while the customer can decide to leave or to stay with the service provider. The authors argue the existence of a pure strategy ***Nash Equilibrium***. The LC game is similar to the AC game and is played periodically while the sessions are running. In this way, users can decide to leave the network even though their session is still running, or providers can decide to terminate a session, if that session is causing QoS degradation to the on-going sessions. The authors show that when both proposed mechanisms are used the provider achieves the best revenue.

B) Networks vs. Users - Cooperative Approach

In cooperative networks vs. users situations, users and networks cooperate in order to achieve mutual satisfaction.

Antoniou et al. in [79] look at the network selection problem and model the user-networks interaction as a cooperative ***repeated game*** where the user has four strategies: *Grim strategy* dictating that the user is participating in the relationship but if dissatisfied he will leave the relationship forever, *Cheat-and-Leave strategy* gives the user the option to cheat and then leave the network after cheating, *Leave-and-Return strategy* dictates that in case the network cheats the user leaves for only one period and returns in the subsequent interaction, and *Adaptive Return strategy* in which the user returning is dictated by the normalized weight of network's past degradation behavior. The network can choose between two strategies: *Tit-for-Tat strategy* which mimics the action of the user, and *Cheat-and-Return* strategy which gives the option to the network to cheat and return accepting the user's punishment. The authors show that employing the proposed Adaptive Return strategy can motivate cooperation, resulting in higher payoffs for both players.

3.1.3.2.3. Game players: Networks vs. Networks

In the Networks vs. Networks scenarios, the players are the network operators. Two types of games are identified: **(1) non-cooperative** – in which the networks compete, each seeking to maximize its own revenue; **(2) cooperative** – in which the networks cooperate in order to maximize the social welfare.

A) Networks vs. Networks - Non-Cooperative Approach

In non-cooperative networks vs. networks situations the networks compete against each other, seeking to maximize their individual revenues.

Pervaiz et al. in [80][81] use a non-cooperative game approach in order to formulate the network selection problem as an interaction game between network service providers aiming to maximize their rewards. Dynamic pricing is used and the prices set are considered to be the players' strategies. The payoff for each provider represents the gain from users selecting that provider's network.

Another study which looks at the interaction between networks is presented by Niyato et al. in [82]. The authors propose a radio resource management framework based on non-cooperative game theory and composed of four main components: network level allocation, capacity reservation, admission control and connection-level allocation. The bandwidth allocation problem is modeled as a non-cooperative game between different access networks and the solution is obtained from the Nash equilibrium showing that the total network utility is maximized. A ***bargaining game*** is used in order to model the capacity reservation problem. The connection level allocation is modeled as a ***trading market*** game and a ***Nash Equilibrium*** is found as the solution of the game.

Antoniou et al. [83] model the network selection problem as a non-cooperative game between the networks which compete against each other in order to maximize their own payoff. The payoffs are defined based on a utility function which models the user preferences. The utility function follows a three zone-based structure, which was previously proposed in [97], that defines the user's level of satisfaction relative to delay: satisfied, tolerant, and frustrated. The authors argue the existence of ***Nash Equilibrium*** and observe that under Nash Equilibrium the networks' payoffs are maximized when the users with higher preferences for the specific network are selected.

In [84] Gajić et al. propose a provider competition game that makes use of a two-stage multi-leader-follower game, where networks are the leaders and users are the followers. The game consists of two stages. In the first stage the providers announce their prices per resources and in the second stage the users announce their resource demands. The users are allowed to have simultaneously connections with different providers. The authors consider a social welfare optimization problem (SWO) which aims at maximizing the sum of payoffs of the users and providers. They demonstrate the existence of an unique equilibrium corresponding to the unique social optimal solution of the SWO problem.

Charilas et al. in [85] propose a non-cooperative multi-stage game between two independent WLANs to model the admission control problem. The players in the game are the two networks and their strategy set is the users' service requests. The outcome of the game is the distribution of the service requests among the networks, so that each network gains the maximum payoff.

Another study that models the network selection as a non-cooperative multi-stage game is provided by Khan et al. in [86]. The players are three wireless access networks: WCDMA, WLAN, and WiMAX. The set of strategies is represented by the users' service requests, and the payoffs for each network are computed based on the type of service (streaming video, internet surfing, or voice call), user preferences (cost and quality), traffic state and signal strength of the network (bad, medium, or good), speed of the user (high, low, or stable), and drainage rate of the battery. The outcome of the game is the distribution of the service requests among the networks while each network tries to maximize its own payoff.

B) Networks vs. Networks - Cooperative Approach

In the cooperative networks vs. networks case, networks cooperate in order to achieve global welfare maximization.

A cooperative approach which looks at the interaction between networks was proposed by Niyato et al. in [87]. The authors look at the scenario where a wireless multi-mode terminal can be served simultaneously by three different access networks owned by different cooperating network operators. In this context, the bandwidth allocation and admission control problems are modeled using a ***bankruptcy game***. In this game the mobile user who initiates a connection request is seen as the bankrupt company, the bandwidth requirement is the money that has to be distributed among different networks. The access networks involved cooperate in order to provide the required bandwidth to the mobile user by using a coalition form and a characteristic function which is used to express the payoff of the coalition. The solution of the bandwidth allocation problem is computed by using the Shapley Value and the core concept is used in order to analyze the stability of the allocation.

Another cooperative approach that models the problem of resource allocation in heterogeneous wireless networks as a ***cooperative Stackelberg game***, using coalitions between individual wireless networks is studied by Sulima et al in [88]. When a user cannot be served by a single network, the proposed model will enable the user to split its application traffic between the coalition members. The authors define the characteristic function which is used to express the payoff of the coalition, and the core concept is used in order to analyze the stability of the allocation.

A combination of utility and game-theory network selection scheme is proposed by Chang et al. in [89]. Considering the scenario of a mobile user located in a area with a number of available wireless networks, the authors propose the use of a cooperative game modeled between the candidate networks in order to achieve load balancing and reduce the handoff occurrence frequency. The strategies in the game are the set of preference values for each network. The payoff for each candidate network is a function of the current load intensity before accepting the call request, the predefined load intensity threshold and the penalty weight of the network. The goal of the game is to maximize the payoff function for each candidate network.

Antoniou et al. in [90] explore the formation of a coalition between individual access networks which is done based on the available resources and the payoffs' allocation method. The authors propose the use of two types of payoffs: *transferable payoffs*, where a network can transfer a certain amount from its own payoff to other members of the coalition, as long as its final payoff is greater than zero; and *non-transferable payoffs* which are the payoffs obtained for each member's resource contribution. The authors study the stability of coalitions for the two types of payoffs, using the core concept. Using analysis they have shown that when considering transferable payoffs only winning coalitions, which are minimal in size for at least one player, are in the core. On the other side, the coalitions which are by-least winning for at least one player, are located in the core when considering the non-transferable payoffs.

Another approach, which considers cooperation between networks, was proposed by Khan et al. in [91]. The authors considered a multi-operator environment where a network sharing agreement has been established between the operators. The interaction between networks is modeled by defining two games: intra-operator and inter-operator games. In the case of the intra-operator game, the networks within a single operator play a ***bargaining game*** in order to share the bandwidth requested by an application. If that single operator cannot satisfy the requirements, then a second game is played (this time an inter-operator game). The inter-operator game is played between operators who are willing to share extra bandwidth.

3.1.4. Reputation-based Systems

Reputation systems have been studied and deployed to the wireless environment [92], especially in mobile ad-hoc networks, wireless mesh networks, and Internet-based peer-to-peer, being useful in cooperation scenarios and decision making problems. For example, reputation systems are used in order to help peers decide with whom to cooperate or not. Peers with good reputation are favoured.

Seigneur et al. in [93] use a reputation system in a telecommunication environment where the users share their QoE information in a peer-to-peer fashion. The authors consider the possible attack from the telecommunication operator that might want to try to influence their QoE levels in order to maintain market position. In this context they present their work in progress towards an attack-resistant computational reputation model by introducing a trust engine for reputation-based network selection. The trust engine is used to manage trust and reputation of different entities. Trust values are computed by the trust engine and assigned to potential networks before the network selection is done. Any mobile terminal can have its own integrated local trust engine that communicates in a peer-to-peer fashion with other trust engines. The main objective is to avoid false information propagation and to facilitate the choice of the best network available,

Salem et al. in [94] look at the problem of selecting a Wireless Internet Service Provider (WISP) when multiple providers are available. The authors propose the integration of a Trusted Central Authority (TCA) into a Wi-Fi environment. All the WISPs will be registered with the TCA which will periodically collect feedback about each WISP in order to update the reputation records. The authors also provide a detailed threat analysis. They have identified eight specific attacks: Publicity, Selective Publicity, Denigration, Flattering, Report Dropping, Service Interruption, Refusal to Pay and Repudiation attacks. They have considered also several general attacks such as: Packet Dropping, Filtering and Replay attacks.

In [95] Zekri et al. propose a reputation system to speed up vertical handover in a complex wireless environment. The proposed reputation system is denoted by the Overlay Reputation Manager (ORM) and is based on the analysis of past connections between mobile terminals and available access networks. The ORM collects information about the individual scores given by users and computes a global rating which represents the network reputation. In the case of a handover the mobile terminal will send a request to the ORM for the available networks' reputations.

Satsiou et al. in [96] propose the use of a reputation based system in the context of neighbourhood wireless communities. The main objective of a neighbourhood wireless community is to provide free internet access to its members. The internet sharing community is formed with a number of APs whose owners are members of the community willing to share their available capacity. Any user who is a member of the community can access the internet as he/she passes through the neighbourhood. The authors propose a reputation-based allocation framework that based on the reputation of the visiting users decides on how to allocate the available resources. The reputation is computed based on the offered quality of the internet connection and the past ten transactions. In this way cooperation is induced inside the internet sharing community and members can enjoy free Internet access.

Most of the reputation-based systems compute a global reputation based on the information gathered from multiple entities. In this context the trust level of each entity is addressed in order to avoid fraudulent behaviour, by providing false information which could increase or decrease the reputation of an entity. In our case, considering the fact that different users have different preferences, different device requirements, different application requirements; each mobile terminal will store its own list of reputations for the visited networks, avoiding, in this way, possible fraudulent behaviour.

3.1.5. Challenges and Open Issues

When using game theory in the heterogeneous wireless environment, several challenges and issues can be identified as illustrated in Figure 3.2 and highlighted in this section.

- **Cooperative or Non-cooperative Approach**

The 4G environment aims to provide a combination of network and terminal heterogeneity as well as heterogeneous services. In this multi-user multi-provider heterogeneous environment, users equipped with multi-mode wireless mobile devices will have the option to connect to one or more access networks, which differ in technology, coverage range, available bandwidth, service provider, monetary cost, etc. In this context, game theory approaches have been used in order to model and analyze the cooperative or competitive interaction between rational decision makers, which represent users and/or network operators.

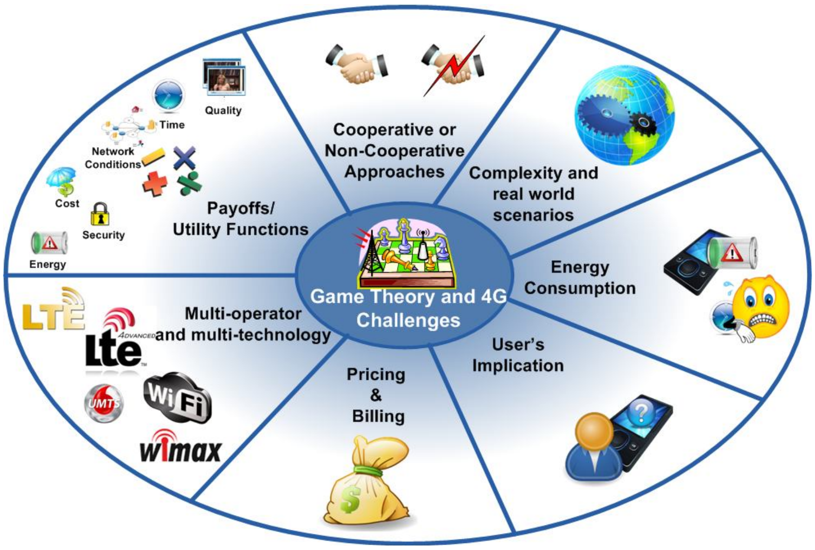


Figure 3.2. Challenges in Game Theory and 4G

One of the first challenges is to identify the players and model the problem with the appropriate cooperative or non-cooperative game. The players, the strategies available to each player and their objectives must be clearly defined as they represent the main components with crucial roles in the game. The existing approaches were classified based on players' interaction as: users vs. users, users vs. networks, and networks vs. networks. Game theory works on the assumption of rationality, meaning that it is assumed that players are rational individuals who act based on their best interest. While the service providers' main interest is in trying to increase their revenues by increasing their number of customers, the users expect to get the service quality they are paying for. When considering the heterogeneous wireless environment, the players are represented by entities in the networks or by user terminals, which are assumed to be rational. However, it cannot be always guaranteed that these entities will act in a rational manner.

As it could be seen in this section, various **game models** (strategic games, bargain game, auction game, etc.) have been considered under different scenarios (users vs. users, network vs. users, networks vs. networks). Most of the presented solutions used non-cooperative game theory in order to define the interaction between players. Users compete against each other by adopting different strategies, such as: available transmission rates [66], available APs [67-69][72], requested bandwidth [70] or by submitting bids representing the willingness to pay [71]. The cooperative approach is modeled as a bargain game [73] where users are free to bargain in order to obtain mutual advantage. Networks compete against each other in order to increase their individual revenue by employing different strategies, such as: offered prices [80][81][84], offered bandwidth [82], and service requests [83][85][86]. Most of the related works that explore the cooperation between networks look at the scenario in which a number of different access networks form coalitions [87][88][90][91] in order to handle the service requests when a single access network cannot. In this scenario, the cooperation is built on the assumption that the wireless networks may cooperate either because their service demand overwhelms the network capacity or because they can reduce some of their cost by cooperation.

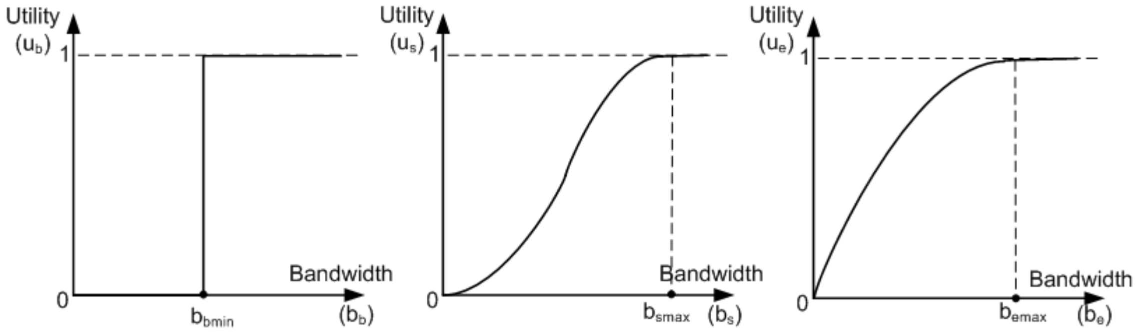
By using game theory realistic scenarios can be modeled in which players compete against each other, all of them seeking to maximize their own profit. In the cooperative games, players are assumed to be collaborating in order to maximize their payoffs, but in some cases they may act selfishly and refuse to cooperate in order to optimize their own profit or to conserve their own limited resources (e.g., energy). In these situations, in order to avoid an overall QoS degradation, incentive mechanisms can be adopted. The aim of using incentive mechanisms is to motivate the players to cooperate for the social welfare maximization. An important aspect that appears, due to the dynamics of the wireless environment, is that some of the cooperative players can be perceived as selfish because of random wireless errors, interference, or packet collisions. This situation can lead to players ending their cooperation thus decreasing the overall network performance.

The cooperative approach was adopted by Centonza et al. in [98] with respect to the differentiated service delivery. By analyzing real users demand data from TV-like Internet multimedia services, the authors have seen that the service demand follows a well defined periodic pattern. Consequently, they proposed the use of a pre-scheduling mechanism for cooperative IP-based broadcast and mobile telecommunications networks. So that, when there is high service demand the broadcast network will be used for service delivery, whereas during low service demand the mobile telecommunication network is used. The authors argue the economic efficiency of such platform.

Another important aspect is the way the players make their decisions: **distributed or centralized manner**. The centralized approach is rarely used in solving the problem of multiple access networks. This may be due to the computational expense increasing with increase in network size, increasing the network control overhead as well. In general, game theory is more suitable for distributive approaches with self-configuration features and a lower communication overhead. The common aim of these game theoretic approaches is to improve the overall system performance (e.g., efficient resource utilization, throughput maximization, QoS guarantee).

- **Payoffs/Utility Functions**

The choice of payoff or utility function is another challenge as it impacts on how the players will choose their actions. Utility functions have been introduced to describe the player's perception of performance and satisfaction. They usually express the trade-off the user is willing to accept between acquiring more resources (e.g., bandwidth) and saving resources (e.g., money, energy, etc.). All the existing approaches have a common goal of optimizing the network performance by maximizing the utility function. Because of the traffic heterogeneity, that brings a huge number of different applications with different requirements, a precise definition of a utility function becomes very complicated.



a) Brittle Traffic Class b) Stream Traffic Class c) Elastic Traffic Class

Figure 3.3. Utility Functions for Different Traffic Classes

An example of some popular utility function shapes are those defined by Rakocevic et al. in [99]. They differentiate the traffic into three broad classes (brittle, stream and elastic traffic) and propose the use of a utility function for each traffic class, as illustrated in Figure 3.3.

The traffic in the brittle class is real-time traffic with strict performance requirements and includes applications like: video telephony, telemedicine, highly secure data transactions, etc. This type of traffic flow is not allowed to enter the network if any basic requirements are not met. The mathematical representation of the utility function is simple, given in equation (3.1). Usually the users of this type of traffic are interested only in high level QoS, in which case the utility will be 1. If the network cannot fulfill the requirements, the utility will be 0.

$$u_b(b_b) = \begin{cases} 1, if\ b_b \geq b_{b\,min} \\ 0, if\ b_b < b_{b\,min} \end{cases} \qquad (3.1)$$

where b_b represents the allocated bandwidth and $b_{b\ min}$ represents the minimum required bandwidth.

The stream traffic class represents real-time traffic that is adaptable to the network conditions and includes audio and video applications that requires a minimum level of network performance guarantee. The shape of the utility function is illustrated in Figure 5b and the mathematical representation is given in equation (3.2).

$$u_s(b_s) = 1 - e^{-a_{s2}\frac{b_s^2}{a_{s1}+b_s}} \qquad (3.2)$$

where b_s is the allocated bandwidth, a_{s1} and a_{s2} are constants that determine the shape of the utility function.

The elastic traffic class represents non-real-time, elastic traffic and includes applications like data transfer (files, pictures, etc.). These type of applications have loose response time requirements and they do not need a minimum level of bandwidth requirement. The shape of this utility is illustrated in Figure 5c and the mathematical representation is given in equation (3.3).

$$u_e(b_e) = 1 - e^{-\frac{a_e b_e}{b_{e\,max}}} \qquad (3.3)$$

where b_e denotes the allocated bandwidth, $b_{e\ max}$ represents the peak rate of the elastic flow, and a_e is a scaling constant.

Several other approaches exist that try to quantify the utility in practice. For example, the authors in [97] explore the trade-off between user’s willingness to pay and file download completion time for FTP downloads. A zone-based utility function is proposed. Depending on the transfer completion time, three zones are defined: satisfaction zone, tolerance zone, and frustration zone, as illustrated in Figure 3.4. The zone-based utility function represents a trade-off between the user’s willingness to pay and the willingness to wait for a particular data service transfer. This concept is based on the idea that a user is willing to pay a minimum amount (U_{min}) if the data is transferred within a maximum transfer completion time (T_2), going above this threshold the data will worth nothing to the user. On the other side, each user has a preferred delay time, within which he will be willing to pay a maximum amount (U_{max}), this denotes the satisfaction zone.

Depending on the type of service, utility functions are defined to describe the user satisfaction with certain QoS parameters. When multiple parameters are involved in the network selection process, an overall score function based on a combination of these utility functions is defined. The overall utility can be defined by using one of the multi-attribute decision making (MADM) methods, previously described. For example the authors in [68] define a score function as a simple additive weighted (SAW) function of several parameters: AP’s load, price, and distance. Similarly, the authors in [86] define a SAW function considering the service type, user preferences, signal strength, mobility, and battery level. The authors in [70] introduce a pricing function (transfer) in order to prevent the users from exaggerating their resource requirements and misusing the available resources. In [78] the user's payoff is defined based on Consumer Surplus, expressed as the difference between the monetary value of the provided QoS to the user for the running service, and the actual charged price.

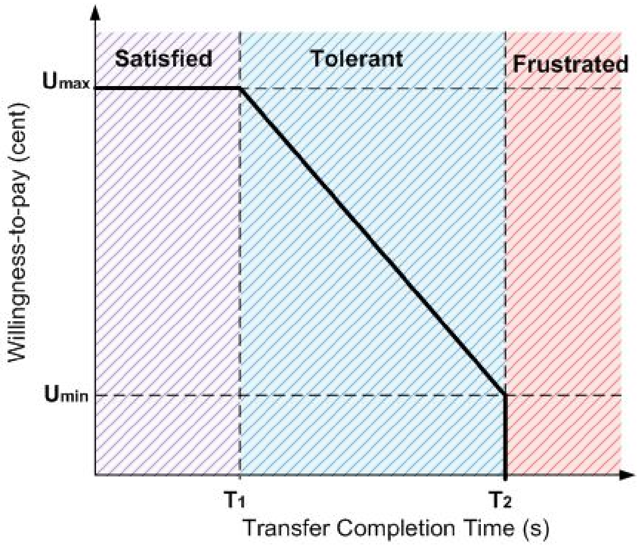


Figure 3.4. User utility function for non-real-time applications

- **Multi-Operator and Multi-Technology**

Another challenge, when designing a cooperative or a non-cooperative game, comes when considering a single or multiple operators. Some of the cooperative games in the literature explore the formation of coalitions between various network operators. In [90] the authors envision a unified environment where network operators would cooperate in order to combine and share their resources and provide global connectivity and transparency to the end-user. The individual access networks form a coalition and offer their available resources in return for some benefit, defined by a payoff function. In [91] the authors assume that different network operators are in contractual agreements with each other in order to share resources. A user is considered to have a contractual agreement with a home operator that handles a number of RATs. The operator will first allocate the service requests among its own RATs, if the demand exceeds the offer then he will request additional bandwidth from foreign operators that have RATs in the same area. The feasibility of such a scenario in the real regulated telecoms world, where competition among operators is intense, is questionable. Moreover, coverage range and operational characteristic information is considered to be highly confidential to the operators. For example, in [67][68] the authors assume the existence of an information service deployed in the system which provides information about the available APs and their associated users. It would be unusual for operators to be willing to provide such information.

The existing solutions can be applied to single or multiple types of access network technologies. For example, the research results published in [66-68][70][72][85] apply to WLAN networks only, those from [73] apply to cellular, the ones from [77] apply to CDMA networks only, while the rest can be used by two or even three different technologies.

- **Pricing and Billing**

The multi-technology multi-terminal multi-user multi-application multi-provider environment brings increasing demands for the charging systems towards flexibility, scalability and efficiency. In today’s mobile telecommunication networks, charging and billing models are relatively simple: time-based and/or volume-based charging. Considering the competitive market, the wireless operators followed the ‘all you can eat’ model by adopting flat rate pricing schemes. Flat rate pricing works well as long as the usage on the network is reasonable. Nowadays, with the exponential increase in data traffic, more wireless operators have started to re-adopt a usage-based pricing scheme (e.g., AT&T moved to a tiered model). If more and more wireless operators adopt the usage-based model, then all the flat rate wireless operators will attract the heaviest data users which will lead to a heavy traffic load on their networks. Looking at the wide pool of QoS parameters (e.g., bandwidth, packet loss, delay, jitter, etc.), bandwidth only is considered to be charge-relevant, even though other parameters could be significant as well. For example, with the increasing popularity of real-time applications, delay could be considered of relevant importance. Moving towards the 4G system brings important challenges for the pricing mechanisms in terms of:

- **Multiple service providers -** In the 4G vision, users will be able to roam freely between different service providers. This situation requires a more complex pricing and billing mechanism. As it has been seen several works explore the formation of coalitions between service providers in order to share resources. In [90] the authors propose two cases for allocating the payoffs between the members of the coalitions. In the first case they propose the use of non-transferable payoffs meaning that the access network operators, members of the coalition, get a fixed payoff based on their resource contribution. In the second case, they make use of the transferable payoffs in which the members of a coalition can make side payments to other members in order to attract other players into the coalition.
- **Multiple RATs -** The coexistence of multiple RATs within the same service provider represents another challenge when it comes to pricing models. This is because the RATs differ in coverage area, capacity, QoS, offered data rate, mobility support, etc. Moreover

users equipped with a multi-mode terminal will be able to connect simultaneously to different RATs.

The authors in [70] make use of the ***Vickrey-Clarke-Groves (VCG)*** mechanism in order to incentivize the mobile users to play truthfully. As mobile users are considered to be self-interested and rational players, it is natural to take into account the fact that they could also lie about their service requirements in order to maximize their own utilities. This could lead to decreasing the overall performance of the entire system. By using the VCG mechanism, which is a simple pricing mechanism, they introduce the cost associated with using one network which will encourage the mobile users to send the real values of the service requirements.

In [71] the authors modeled an auction-based scheme where users periodically send bids representing their willingness to pay for the radio resources. The service provider will then make a decision on resource allocation which will maximize its revenue.

Most of the works consider a flat rate pricing scheme [68][74][80][84] and a few consider differentiated pricing as in [77]. The approach in [77] is based on service differentiation considering the expected QoS from the service provider and the price they are willing to pay. Three classes are defined: Premium, Gold, and Silver. The Premium class gets the highest priority but pays the most while the Silver class has the lowest priority and pays the least.

- **User Implication**

Involving the user in the decision mechanism is based on the idea that in order to provide a useful solution, if not the best one to the customer, service providers should know what each customer really needs and where the real problem lies. As the user preferences play an important role in the decision mechanism another important aspect is the degree of the user’s implication. There are many ways of collecting data from the user. Some of the proposed solutions probe the user for some required settings that are transformed afterwards into weightings for the networks parameters [80]. The solution proposed in [74] integrates a GUI in the user’s mobile terminal in order to collect the user preferences on the following inputs: Service request class (Data, Video, Voice); Service preferred quality (Excellent, Good, Fair); and Service price preferences (Always Cheapest, Maximum service price). Asking the user for data can be annoying or even invasive to the user as the decision mechanism is no longer transparent. It is very important to find a trade-off between the cost of involving the user and the decision mechanism. One solution for minimizing the user interaction may be implementing an intelligent learning mechanism that could predict the user preferences over time.

- **Energy Consumption**

When considering the energy consumption of a multi-interface mobile device, an important aspect is the connectivity. For example, in [84][87][88][91] the authors consider that the multi-interface mobile device has simultaneous connections, with the bandwidth requirements split among multiple networks. In terms of energy consumption, simultaneous connections will drain the battery of the mobile device even faster than a single connection. In terms of monetary cost, simultaneous connections involve more complicated pricing schemes for the operators.

A concept of cooperation that aims to extend the coverage and minimize the power consumption is proposed in [100]. The authors present a distributed clustering protocol named Cooperative Network protocol (CONET). The protocol exploits the use of two interfaces of the mobile device: the WLAN interface and the Bluetooth interface. The aim is to form clusters as a Bluetooth Personal Area Network (WPAN). Each cluster consists of a cluster head which acts as a gateway between the WPAN and WLAN, and several regular nodes (mobile devices). The cluster head enables the regular nodes within the cluster to access the WLAN via Bluetooth with their WLAN interface switched off, conserving in this way the energy of the mobile device. The basic idea behind the protocol is illustrated in Figure 3.5. The clustering and the selection of the cluster head is done periodically in a distributed manner based on the application requirements and the energy consumption of each node.

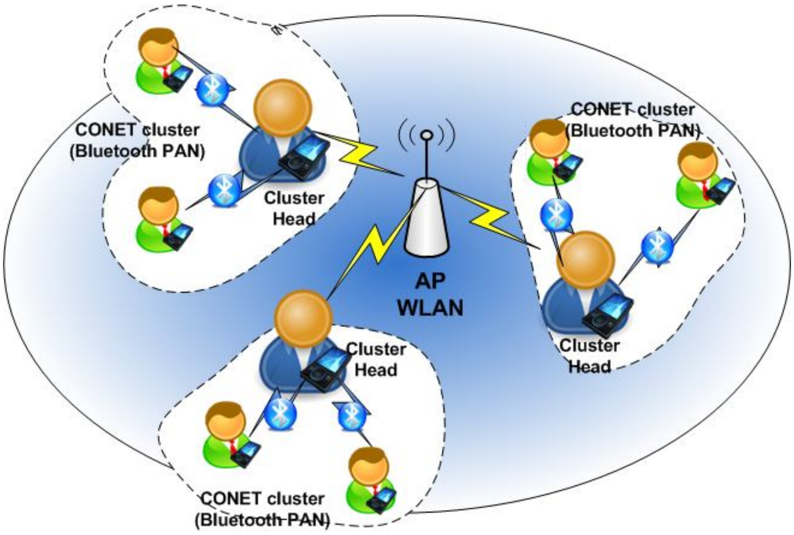


Figure 3.5. Clustering example using CONET

An important aspect in this type of environment is the motivation for cooperation. To this extent the authors consider two cases:

- Group networking - in which the nodes within the cluster have a common goal, to prolong the group lifetime. Considering the case of a group of friends playing network games together, their aim would be to play as much as possible. The constraint in this situation would be the node with the lowest battery level. CONET could prolong the group lifetime by rotating the cluster head role between the nodes with higher battery level.

- Individual networking - consisting of unrelated individuals without any common goal. An important aspect in this situation is defining the benefits a cluster head user may gain by spending more of his energy just to help some unrelated users. In this situation CONET distributes the gain within the cluster in a fair manner.

- **Complexity and Real World Scenarios**

Generally the proposed solutions were tested through intensive numerical analysis or simulations that imply the simplification of the wireless environment. No real-world test-bed scenarios were proposed. The implementation in a real-world scenario is disputable. Some solutions require the deployment of external entities. For example, in [60] the deployment of a Central Spectrum Moderator, in the network, is required in order to divide the available resources among competing users. In [71] a central agent is used for resource allocation based on users' bids. Adding new equipment to an already complex network may not be a good solution.

The authors in [67][68] make use of the existence of a service deployed into the system that provides information about the location and the current load of the APs. In a real world scenario, considering the competitive market, operators are not willing to provide such information without having a clear benefit from doing so. As the technology is advancing, network operators are looking towards adopting new architectures that come to simplify things, enabling quick deployment of services and applications.

Another important aspect when using game theory and dealing with such a heterogeneous and complex environment is the risk of users misbehaving, acting selfishly by trying to obtain the maximum performance over other users, leading to an overall system performance degradation. A survey on security threats for 4G networks is presented in [101]. In general, because of the mutually contradictory interests among service providers and/or users, different security requirements are needed. On one side, service providers compete against each other in order to maximize their own revenue by gaining more customers. On the other side, users compete against each other, each of them seeking to get the best value service/performance. In this scenario several threats can be identified: disclosure, destruction, loss, corruption or modification of information or other resources.

Many reputation-based systems are built based on cooperation. In these types of systems a global reputation is computed based on the information gathered from multiple entities. In this context the trust level of each entity is addressed in order to avoid a fraudulent behavior, by providing false information which could increase or decrease the reputation of an entity. Salem et al. in [94] look at the problem of selecting a Wireless Internet Service Provider (WISP) when multiple providers are available. The authors propose the integration of a Trusted Central Authority (TCA) into a Wi-Fi environment. All the WISPs will be registered with the TCA which will periodically collect feedback about each WISP in order to update the reputation records. The authors also provide a detailed threat analysis. They have identified eight specific attacks: Publicity, Selective Publicity, Denigration, Flattering, Report Dropping, Service Interruption, Refusal to Pay and Repudiation attacks. They have considered also several general attacks such as: Packet Dropping, Filtering and Replay attacks.

3.2. Adaptive Multimedia Solutions

The next generation of wireless networks is almost a reality and as multimedia applications have become widespread and mobile device capabilities have grown, users expect access to rich services at higher quality levels from their devices, even while roaming over different wireless networks. It is known that the main attributes of multimedia data traffic are the large volume and real time requirements. Delivering streaming video with QoS provisioning over wireless networks is more challenging than in wired networks due to the radio constraints of wireless links, and user mobility. It is essential to provide QoS mechanisms to cater for multimedia throughput, delay, and jitter constraints, especially within the wireless environment where connections are prone to interference, high data loss rates, and/or disconnection. The aim of these mechanisms is to maintain high user perceived quality levels and make efficient use of the wireless network resources

3.2.1. Standards which Support Adaptive Streaming

One of the hot topics in the multimedia networking environment is adaptive streaming techniques. Because of the continued growth of the video content, ensuring a seamless multimedia experience at high quality levels to the end-user has become a challenge. This has led to the definition and appearance of new standards and protocols related to adaptive streaming.

In ***TS 26.234*** [102] (PSS; Protocols and Codecs) the 3rd Generation Partnership Project (3GPP) defines a new ***Adaptive HTTP Streaming (AHS)*** protocol that enables the video content delivery from a standard HTTP server to an HTTP streaming client. The new protocol consists of dividing the entire stream into segments. It is assumed that the HTTP streaming client has access to a Media Presentation Description (MPD) which contains the metadata information required by the client to access the corresponding segment. The streaming service could be on-demand or live and the segments could differ in bitrates, languages, resolutions, etc. The streaming session is controlled by the client which can adjust the bitrate or other attributes based on the mobile device state or user preferences in order to ensure a smooth streaming experience.

Currently 3GPP is working on extending the AHS version in the TS 26.247 [103] specification, where a general framework is defined. The new version is referred to as ***3GP-DASH*** and provides support for fast initial start up, seeking, adaptive bitrate switching, on-demand and live delivery, etc. Even though the MPD syntax, the segments format and delivery protocol are specified, there is no specification for content provisioning, client behaviour, and the transport of MPD.

The Open IPTV Forum (OIPF) [104] proposed an ***HTTP Adaptive Streaming (HAS)*** solution which is based on the 3GPP AHS specifications. In the case of HAS the streaming content is provided in multiple bitrates and segmented into temporally aligned and independently encoded chunks. The terminal may be able to adapt to variations in the available bandwidth by seamlessly switching between the chunks at higher or lower bitrate. The new HAS method is an extended version of the 3GPP AHS with support for MPEG-2 transport stream encoding.

The Moving Picture Experts Group (MPEG) adopted the 3GPP AHS as a baseline specification and started working on the development of Dynamic Adaptive Streaming over HTTP referred to as ***MPEG DASH*** [105]. The MPEG DASH ad-hoc group has been working on the delivery format and on the use of MPEG-2 Transport Streams as a media format. In January 2011 the group decided to start an evaluation experiment aiming to better understand the requirements for MPEG DASH in order to add a better support for Content Delivery Network (CDN) - based delivery.

3.2.2. Industry Solutions for Adaptive Streaming

In addition to the existing standards and ongoing work progressing adaptive streaming-based standards, some of the key market players have adopted their own proprietary solutions for adaptive streaming.

Move Networks is one of the first online video providers that has been granted a patent [106] for its ***HTTP-based adaptive streaming*** technology. The technology involves receiving and segmenting the media content in order to generate multiple sequential streamlets. Each streamlet will be encoded as a separate content file having identical time indices and a unique bitrate. The patent covers the encoding and the use of multiple bitrate streamlets. The novelty of the technology is the possibility of using standard HTTP web requests with ordinary web servers without the need for a dedicated streaming server. The adaptive mechanism will switch between the different quality streams according to the available bandwidth.

Another fierce competitor in the market is *Microsoft* with its ***IIS Smooth Streaming solution***. Recently, in August 2011, Microsoft was granted a patent [107] on 'Seamless switching of scalable video bitstreams'. The patent claims the concept behind smooth streaming, which involves switching between streams of different quality levels (high and low quality) according to the network's available bandwidth.

Adobe has deployed its own ***web-based dynamic streaming service*** [108], being available on any device running a browser with Adobe Flash plug-in. The Flash Media Server stores the video content encoded at different bit rates and it can receive commands to switch between the different versions. The adaptation can be done based on the user's available bandwidth and the CPU load of the mobile device.

Apple has also released a client-side ***adaptive HTTP streaming solution*** that supports both live and on-demand H.264 video playout within the browser. The video content is segmented into chunks of different duration and bitrate and is adaptively streamed to the client. The new technology is available on the devices that run iPhone OS 3.0 or later, or on the devices with QuickTime version X or later, installed.

Hulu[11] is an online video service that offers on-demand TV shows, movies, clips, news, etc. Hulu integrated the adaptive bitrate streaming mechanism into their new Hulu player, written in ActionScript 3. The mechanism adapts to the user's available bandwidth by switching between different video bitrates and resolution. The user has the option to turn on the adaptive streaming options or to play the stream at a fixed resolution from the player's settings menu.

The worldwide leading Content Delivery Network (CDN), *Akamai*, has launched an adaptive HDTV streaming service available for Adobe Flash, Microsoft Silverlight and iPhone. The video content is encoded at different bitrates and the switching between them is done based on the feedback received from the client (e.g., available bandwidth).

Apart from these key market players there are a number of others adopting or in the process of developing an adaptive streaming solution (e.g., Netflix, Limelight, Widevine, Qualvlive, etc.). A summary of the industry solutions discussed in this section is presented in Table 3.3.

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[11] Hulu - http://www.hulu.com/about

TABLE 3.3. SUMMARY OF THE INDUSTRY SOLUTIONS

	3GP-DASH	**MPEG DASH**	**OIPF HAS**	**Move Networks**	**Microsoft Smooth Streaming**	**Adobe HTTP Dynamic Flash Streaming**	**Apple HTTP Live Streaming**	**Hulu Adaptive Streaming**	**Akamai adaptive HDTV Streaming**
Type	Standard-based	Standard-based	Standard-based	Proprietary/Patent	Proprietary/Patent	Proprietary	Proprietary	Proprietary	Proprietary
Codec	H.264 AAC	H.264 AAC	H.264 AAC	VP7	H.264, VC-1 AAC, WMA	H.264, VP6 AAC, MP3	H.264 AAC, MP3	H.264	MPEG-4, H.264,VP6 AVC
Transport	RTP/RTSP HTTP	RTP/RTSP HTTP	RTP/RTSP HTTP	HTTP	HTTP	HTTP RTMP RTMFP	HTTP	RTMP	HTTP
Playback	3GPP compliant devices	MPEG compliant devices	Open IPTV compliant services & devices	Web browser plugin, Windows, Mac OS X	Silverlight, Windows 7 phones, STB, xBox	Flash, Air, Android phones, Connected TV	iPhone, iPad, Apple TV, Apple iOS, QTx	Hulu player, Flash	Flash, iOS, Silverlight, Windows, Mac, Linux
Adaptation Logic Control	Client	Client	Client	Server	Client	Client	Client	Client	Client
Default Number of Quality Levels	Configurable	Configurable	Configurable	Five	Configurable	Configurable	Configurable	Three	Three
Default Video Resolution	Configurable	Configurable	Configurable	Configurable	up to 1080p	Configurable	Configurable	288p, 360p, 480p	180-720p
Default Bitrates range	Configurable	Configurable	Configurable	100-2200kbps	300-2400kbps	Configurable	up to 1600kbps	640-1600kbps	300-3500kbps

3.2.3. Adaptive Streaming Research Area

To date there has been extensive academic research related to adaptation techniques for video streaming over the Internet. Various solutions have been proposed in order to address this problem of streaming video over the Internet while maintain high user perceived quality levels.

In the following section, the proposed adaptive techniques from the literature are classified into four main categories: (1) **network-protocol based adaptive solutions** which relate to the actual network delivery mechanisms; (2) **scalable video coding solutions** which concern coding the video content in a scalable fashion (e.g., Multiple Description Coding (MDC), MPEG-2 scalability, Fine Grain Scalability (FGS) MPEG-4 FGS that enables adaptation by dropping selected parts of the scalable-based encoded video; (3) **transcoding-based solutions** which adapt the video content by changing the target bitrate parameter of the transcoder on the fly, and (4) **bitrate-switching solutions** which consist of storing multiple versions of the same video content pre-encoded at different formats and bitrates.

3.2.3.1. Network-Protocol based Adaptive Solutions

One of the well-known adaptive multimedia solutions is the TCP-friendly rate control protocol (TFRC) described in [109]. The proposed mechanism consists of two parts: a sender-side protocol and a receiver-side protocol. At the sender-side, a TCP-rate equation-based model is used in order to compute the sending rate considering the measured loss rate and the round trip time (RTT). The sending rate is computed at each defined time interval. The receiver sends ACK packets that contain the sequence number and timestamp for the acknowledging packets. Next the sender processes the ACK packets and computes the sending rate for the next time interval. The proposed solution does not have any built-in error recovery mechanism and when high losses occur the sending rate is reduced to very small values otherwise the rate is doubled.

Rejaie et al. [110] propose an end-to-end TCP-friendly Rate Adaptation Protocol (RAP) which is mainly implemented at the sender side and works by adjusting the sending rate based on the loss rate and the estimated RTT. The proposed protocol addresses the following aspects: the decision function, the increase/decrease algorithm and the decision frequency. The decision function is defined as: if there is no congestion than the transmission rate is increased periodically otherwise, if congestion is detected than the transmission rate is immediately decreased. The increase/decrease algorithm is an additive increase multiplicative decrease algorithm. If there is no loss than the transmission rate is increased additively in a step-like fashion. If loss is detected than the transmission rate is decreased multiplicatively. The decision frequency is an important factor as changing the rate too often can result in oscillations whereas the delay in changing the rate can lead to an unresponsive behavior. RAP adjusts the transmission rate once every round-trip time (RTT).

In [111] the authors propose an adaptive scheme referred to as the loss-delay based adaptation algorithm (LDA+), which adapts the multimedia flows based on the current network conditions (e.g., loss, delay, RTT, bandwidth capacity). The proposed algorithm makes use of the real time transport protocol (RTP) for data delivery and RTCP for feedback information about the round trip time and losses. In order to estimate the round trip time, a timestamp is included in the sender reports. Losses are estimated by counting the sequence numbers of the received data packets. LDA+ is an additive increase and multiplicative decrease (AIMD) algorithm which works as follows: if there is no loss detected than the sender computes an additive increase value which will be added to the transmission rate; if loss is detected than the sender decreases the rate in a multiplicative manner. The performance of the proposed scheme was analyzed by extensive simulations and compared with another two adaptive schemes: TFRC and RAP. The results show that LDA+ achieves similar fairness as RAP or TFRC over a wide range of parameters. The authors argue the high efficiency of the LDA+ in achieving high network utilization and avoiding losses.

In [112] Yang et al. propose a new protocol for real-time video applications in wireless networks, referred to as the Video Transport Protocol (VTP). The goal of the proposed protocol is to provide smooth rate adaptation, to be efficient and robust to errors, and friendly to legacy TCP. VTP incorporates two major components: a loss discrimination algorithm and an estimation of the Achieved Rate (AR). The receiver measures the receiving rate and sends feedback to the sender. The sender uses an Exponential Weighted Moving Average (EWMA) in order to update the AR value. The end-to-end loss discrimination algorithm, Spike, is used in order to distinguish between congestion and error losses. The concept of VTP rate control is to reduce the rate by less when loss is detected, but stay at that rate for longer. The performance of the proposed protocol was tested in NS-2 and compared with another two adaptive mechanisms, TFRC wireless and MULTFRC. The results show that VTP performs better in terms of efficiency, smoothness and adaptivity in the presence of wireless errors.

Cen et al. in [113] extended TFRC to provide better performance over wireless networks. The new proposed protocol makes use of UDP as the basic video transport protocol and of TFRC as the congestion control mechanism extended with a loss discrimination algorithm in order to distinguish between congestion losses and wireless error losses. When the receiver detects losses the loss discrimination algorithm is invoked in order to classify the losses. If congestion losses are detected then the receiver will consider them in the computation of the loss event rate, otherwise the losses are not included. If a packet is lost, it will not be retransmitted. The authors studied the performance of different loss discrimination algorithms, such as: Biaz, mBiaz, ZigZag, Spike and ZBS, and showed that the hybrid solution ZBS is the most suitable for both, wired and wireless networks.

Chen et al. [114] propose an adaptive mechanism, referred to as MULTFRC which was built for wireless video streaming. The proposed solution makes use of multiple TFRC connections in order to increase the competitiveness of the current session. The number of connections is adjusted based on the measured RTT.

In [115] the authors propose an adaptive cross-layer scheme for multimedia delivery by combining three adaptive strategies: (1) Adaptive MAC Layer Retransmission Limiting – makes use of UDP-Lite [116] in order to be able to receive packets which have a partially damaged payload; (2) Adaptive Application Layer FEC - makes use of the delay constraints of the application together with MAC layer ARQ with limited retransmissions in order to recover the errors, and (3) Adaptive Packet Size Decision – the size of the video packets is chosen adaptively based on the channel condition, delay constraint of the application, and the application FEC in order to maximize the goodput. The authors argue that the proposed cross-layer solution maximizes the achievable multimedia performance by adapting the system parameters to the varying network environment.

The authors in [117] proposed a power management cross-layer mechanism for video streaming over WLANs when using the TFRC protocol. The parameters taken into consideration are the transmission power collected at the physical layer and the packet loss information provided by the TFRC receiver’s reports to sender. The algorithm is based on thresholds which were defined by the authors after performing several experimentations using different values. The proposed mechanism was tested by simulations under NS-2 with the Evalvid-RA (Rate Adaptive) patch embedded in order to support rate-adaptive MPEG-4 multimedia transmissions. The mechanism was compared with the classical transmission without power management in terms of PSNR and energy consumption. The results show a slightly increase in PSNR leading to a slightly better user perceived quality but also an increase in energy consumption with no significant increase in performance.

3.2.3.2. Scalable Video Coding Solutions

Chen et al. in [118] propose an algorithm based on layered encoding. The proposed solution is composed of two parts: a client side and a server side. The server stores a layer-encoded version of each stream. The available bandwidth is determined using the congestion control mechanism and as the available bandwidth increases the server sends more layers of the encoding stream. The client will demultiplex the layers and send them into the buffers and from there the data is send to the display. When the available bandwidth decreases, the server will drop some of the layers that are transmitted. The performance of the proposed mechanism was tested by extensive simulations using NS-2. The results show that the mechanism can efficiently cope with short term bandwidth variations.

In [119] Ding et al. make use of cumulative layered coding (LC) and propose an adaptive scheme for video streaming. In LC, the video stream is split into multiple interconnected layers. There is a base layer which will ensure the basic quality level, and the other layers which come to increase the quality. In order to decode a higher layer, the layer must be completely received and the lower layers are also required. The authors propose a system architecture which consists of two main components: the video server and the Stream Rate Adapter (SRA) which is responsible for adjusting the bit rate of the video stream based on the available bandwidth. In order to assess the proposed solution, the authors use *spectrum*, a novel video quality metric proposed by Zink et al. in [120]. The authors in [120] have shown that using PSNR for assessing the video quality in the case of layered-encoded video is not suitable and they proposed *spectrum*, a new metric which takes the subjective assessment into consideration and also the frequency of changes of the quality levels. The authors argue that *spectrum* provides better results than PSNR when it comes to layered video streams.

Qin et al. [121] propose an adaptive media streaming strategy for MANETs (mobile ad hoc networks) which is based on the layered video encoding schemes: Scalable Video Coding (SVC) and Multiple Description Coding (MDC). Both encoding schemes have a multi-layered structure. SVC splits the video stream into a base layer which can be decoded independently and several enhancement layers which can be added to the base layer in order to improve the video quality. MDC splits the video stream into several correlated layers which can be decoded independently. The proposed adaptive algorithm increases or decreases the number of layers to be streamed based on the available buffer size and distance. In order to analyze the performance of the proposed solution, the authors run simulations using NS-2 and argue 60% increase in the streaming probability with reasonably high video quality.

In [122] Huang et al. propose a video adaptation scheme for layered multicast systems using scalable video codec. The proposed scheme bases its adaptation mechanism on channel estimation, available bandwidth and packet loss rate. The system consists of several modules such as: scalable video layer creation, packet loss classification (PLC), bandwidth probing, and adaptive FEC insertion. The PLC is integrated in order to differentiate between the losses due to congestion and losses due to the wireless channel errors. In order to determine the available bandwidth the author propose an embedded probing scheme which is done in advanced preventing in this way the congestion. The performance of the system is analyzed by simulations using NS-2 and the results show that the system rapidly adapts to the wired/wireless channel conditions.

Schaar et al. in [123] provide a solution for video transmission over WLANs, specifically IEEE 802.11a which offers theoretically bit rates up to 54Mbps enabling the transmission of delay sensitive traffic. The authors propose an integrated cross-layer approach based on the MPEG-4 fine-grained scalability (FGS) and the join of APP and MAC layers. Based on the channel conditions and application requirements, the cross-layer approach comes to provide a tradeoff between throughput, reliability, and delay enhancing in this way the robustness and efficiency of the scalable video transmission.

In [124] Piri et al. propose a cross-layer architecture for streaming adaptive real-time multimedia over heterogeneous networks by integrating at the end hosts a Triggering Engine (TRG) and an Application Controller. The TRG is build on top of the new IEEE 802.21 standard, and its role is to facilitate the information exchange between the Media Independent Handover Function (MIHF) and higher layer entities and the Application Controller. The Application Controller adapts the video transmission based on the current transmission channel state. When a vertical handover occurs the Application Controller adjusts the video parameters (e.g. data rate and frame rate) during the transmission based on the fuzzy logic. The decision is made based on the packet loss ratio (PLR), estimated received bit rate from application layer, and estimated channel signal-to-noise ratio (SNR) from the PHY or link layer. The authors describe an use case scenario, the performance of the proposed architecture being part of the future work.

Krasic et al. in [125] introduce the idea of adaptive streaming through priority-drop. The data units of the media content are prioritized and sent through the network in the priority order.

The mechanism is using a TCP-based congestion control mechanism that decides the appropriate sending rate. When the sending rate is low, the quality of the media content is reduced smoothly by dropping the low-priority data units at the sender. The authors show that by combining the scalable video compression and the adaptive streaming through priority-drop they form a very effective adaptive streaming system.

3.2.3.3. Transcoding-based Solutions

One of the first transcoding-based solutions for multimedia delivery was proposed by Yeadon et al. in [126]. The authors propose the use of filters deployed in the distribution network. The solution considers a multicast delivery environment that makes use of filters in order to match the quality level required by the clients. Even though the filtering approach seems promising it requires significant processing time.

Prangl et al. [127] propose a server-side adaptation technique for TCP-based media delivery. The authors introduce an adaptation engine that enables on-the-fly content adaptation through transcoding. The adaptation of the video stream is done based on the measured TCP throughput at the server side. The authors argue that the proposed technique leads to smooth playback at the client side.

Vijaykumar et al. in [128] propose the use of a cross-layer framework, implemented in the AP, for adaptive video streaming over an IEEE 802.11 infrastructure mode network. The framework uses the retransmission information from the data-link layer in order to estimate the channel conditions. This information is then used at the application layer in order to vary the transcoding rate of the video content based on the channel conditions. The authors argue that the proposed mechanism can reach more than 2% decrease in packet loss when compared to the non-cross-layer solution.

Hiromoto et al. [129] propose a server-side dynamic rate control for TCP-based media streaming over high-speed mobile networks. The authors make use of a transcoder at the server-side which is controlled by a rate control algorithm. The rate control algorithm determinates the target bitrate of the video content based on the transcode delay. The transcode delay is determined as the difference between the current time and the time stamp of the current transcoding frame. The authors argue that by using the transcode delay, the mechanism can achieve high-quality smooth streaming under unstable networks.

In [130] Takaoka et al. propose the use of a MPEG video transcoder located at the server side in order to dynamically adjust the video stream over the network. The dynamic rate control scheme adjusts the target birate for the transcoder based on the predicted channel bandwidth. The authors predict the channel bandwidth by using the data-processing speed information of the transcoder, such that fast data-processing speed means high throughput where as slow data-processing speed means low throughput. This information is then used to adjust the target bitrate of the video content accordingly. The authors argue the effectiveness of their mechanism through simulations.

Wang et al. [131] propose an adaptive rate control strategy suitable for video transcoding from MPEG-2 to H.264. The proposed solution dynamically adjusts the target bitrate of the transcoded video content according to the output bandwidth fluctuations. The authors argue that the mechanism can be used for video transcoding from MPEG-1. MPEG-2, MPEG-4, H.263 to H.264.

A study on adaptive video streaming through transcoding is carried out by Medagama et al. in [132]. The authors investigate the variation of the transcoding parameters (e.g., quantization factor, frame rate, data rate) with respect to low bandwidth network in order to achieve an optimum quality. The assessment of the video quality is done through objective measurements. The authors argue that transcoding can be useful in low bandwidth situations in order to efficiently use the available resources, but the video quality is affected.

Chattopadhyay et al. in [133] propose an adaptive rate control for H.264 UDP-based video conferencing over wireless networks based on bandwidth estimation. The proposed system architecture is divided into three layers such as: application layer, middleware framework, and processing layer. The adaptation mechanism consists of two stages: the first adaptation is done in the audio and video codec and the second one is done in the packetization and transmission interval of the data. The bandwidth is estimated based on the time difference of RTT for the probe packets, and used afterwards in the video rate control, audio rate control, and the transmission rate control. In order to assess the performance of the proposed mechanism the solution was compared with the H.264 reference code in terms of PSNR. The authors argue that the proposed solution achieves better performance in terms of speed and bit fluctuation.

3.2.3.4. Bitrate Switching Solutions

Mukhtar et al. in [134] propose an adaptive scheme for multimedia transmission over wireless channels which combine several techniques such as: adaptive modulation, adaptive channel coding, adaptive playback, and bit stream switching in order ensure an uninterrupted video playback. The proposed architecture consists of a server and a client. The server stores multiple versions of different quality levels of the same video sequence. When feedback is received from the client, the bitstream switching module along with adaptive modulation module and adaptive channel coding module adapt the video stream according to the channel conditions and the client buffer occupancy. The client integrates an adaptive playback module. The results show that by combining the adaptive playback with the bitstream switching mechanism, the client buffer starvation is eliminated. This implies degradation in the video quality but uninterrupted video playback.

Muntean et al [135] propose a Quality-Oriented Adaptation Scheme referred to as QOAS, which seems to provide good results when streaming over wireless networks. The proposed architecture is distributed and consists of a server side and a client side. At the client side the estimated end-user perceived quality is monitored and feedback is send to the server. The server stores multiple quality levels of the video stream and when receives the feedback from the client it adjust the quality level accordantly.

Schierl et al. [136] propose an adaptive streaming system that is 3GPP compliant. The system makes use of the client feedback information included in the Packet-switched Streaming Service (PSS) specified in the 3GPP standard. Based on the feedback received from the client, the transmission characteristics and the client buffer status are determined. The streaming server combines the bit-stream switching and the temporal scalability in order to switch between H.264 bit-streams characterized by the same encoding parameters but different quantization parameter.

Qiu et al. in [137] propose an HTTP-based adaptive video streaming mechanism referred to as Intelligent Bitrate Switching-based Adaptive Video Streaming (ISAVS). The proposed solution makes use of the real-time and historical information about the available network bandwidth in order to select the proper quality level of the video content. The authors propose an optimization algorithm for choosing the best video quality level and showed the advantages of their proposed solution in comparison with the IIS Smooth Streaming strategy in terms of total video freeze time, number of video freezing periods, and PSNR.

3.2.4. Challenges and Open Issues

As it has been seen there are a number of works offering different strategies for adaptation of the multimedia streaming. The existing approaches were classified in four wide categories: (1) network-protocol based adaptive solutions [109-117]; (2) scalable video coding solutions [118-125]; (3) transcoding-based solutions [127-133]; and (4) bitrate-switching solutions [134-137].

The first category concerns with network delivery mechanisms and mainly includes protocols for adaptive streaming solutions. The common idea among the proposed solutions included in this category is that the sending rate is dictated by the transport protocol and the congestion control mechanism used, based on various network-related parameters (e.g., loss rate, delay, round trip time, etc.).

The other three categories are mainly concerned with the representation and the coding of the video content. The scalable video coding solutions are mainly focused on creating/using scalable compression formats avoiding in this way the re-coding of the video content. By scalable compression the encoded video exposes multiple quality layers with the higher layers depending on the lower layers. In this case the adaptation can be done in bitrate, frame rate, and resolution, by dropping selected parts of the scalable video content. The main drawback of these solutions is the fact that the scalable compression cannot adapt to different codecs.

Another adaptive multimedia approach that involves non-scalable single-layer bitstreams is on-the-fly transcoding. This approach includes live encoding of the video content based on the fluctuating behavior of the available bandwidth. The main advantage of this solution is the immediate response time and the very fine granularity. On the other hand, this approach requires computing overhead being very computationally intensive relative to the other solutions. This makes it difficult to provide support for a large number of clients without adding a computational cost on the server.

The fourth category involves precoding the media content at multiple format and bit rates and storing them at the server side. This method is the most simple to implement and the most efficient in terms of the processing complexity. However the main drawback is the latency introduced in the response time. This latency appears because of the switching between different quality levels that has to be done at selected key frame locations.

From the OSI network protocol stack point of view a number of new protocols have been developed over the last years at different layers in the stack especially for multimedia applications:

- At the physical layer methods have been developed in order to help the data link layer to estimate the channel conditions and adjust the modulation and coding strategies [138].
- At the data link layer several strategies were defined in order to provide error control and frame scheduling [139].
- At the transport layer several methods were defined in order to provide the network condition in terms of available bandwidth, packet loss rate, and delay. Protocols such as RTP/RTCP can record, calculate and return network condition information [140-142].
- At the application layer mechanisms which provide network-adaptive video coding were defined. Some of the existing technologies, where much research has been devoted to, are: Scalable Video Coding (SVC) – [143-145]; Multiple Description Coding [146-148]; and joint source-channel coding [149].

Some of the existing adaptive solutions provide good results in wired networks, for example LDA+ described in [111] adapts very well in highly loaded networks. TFRC proposed in [109] prevents data starvation and limits the aggressiveness with competing adaptive traffic opposed to LDA+ which acts aggressive. In order to provide better QoS support for multimedia streaming, P. Zhu et al. in [150] extended the TFRC mechanism and proposed TFRCC (TCP

Friendly Rate Control with Compensation) which also provides good network fairness. All these solutions [111][109][150] and others [110][118][125][151], they all present good results in wired networks but they are not suitable when it comes to wireless networks.

In order to overcome this problem and also with the popularity of wireless networks new solutions were proposed [112][114][115][119][134][152][153]. All these solutions are trying to differentiate between congestion-based losses and random losses due to the variation of the wireless channel in order to achieve a higher throughput and a higher user perceived quality level.

Apart from these layered protocol architectures the concept of cross-layer design appeared, that aims to increase the effectiveness and the efficiency of the system as a whole by increasing the level of cooperation and communication among various network elements. In the cross-layer design, higher layers share the knowledge of lower layer conditions in order to improve the performance of the entire system.

Recently there have been various cross-layer design proposals in the literature which are focusing on multimedia transmission [115][117][123-125][154-157]. In [154] a classification of the cross-layer solution is proposed, the need of a cross-layer optimization is examined and the authors proposed a joined APP, MAC and PHY layer solution. In [123] the authors proposed a joined APP and MAC adaptation scheme for MPEG-4 transmission. The authors in [158] addressed the issue of cross-layer design in wireless networks. Because of the numerous numbers of parameters involved in the whole adaptation process, the cross-layer adaptation can be a challenging process. It has been seen that the participation of the PHY and MAC layer is very important especially when it comes to wireless networks [159-161]. Some of the existing solutions make use also of the APP layer [123][154].

Although the cross-layer approaches seem to be a good solution they exhibit different drawbacks for wireless multimedia networks in terms of complexity, limitations, used protocols, algorithms at various layers, and application requirements. Moreover, some of the cross-layer designs require implementation of new interfaces between layers, merging of two or more adjacent layers, coupling two or more layers, etc.

3.3. Energy Efficient Content Delivery Solutions

Energy conservation has become a critical issue around the world and presents motivation for researchers to propose and develop energy efficient techniques in order to manage the power consumption in next-generation wireless multimedia networks. Various studies were performed in order to determine an energy consumption pattern of different mobile devices. Researchers investigated the energy consumption in various conditions (e.g., different radio access technologies, time, device motion, etc.) trying to identify the main parameters that contribute to the energy consumption. In the research literature there are a number of different solutions that are trying to conserve the power consumption by: adaptive streaming, decoding, reception, display (brightness compensation), transmission modes (ON/OFF), and interface switching (handover/network selection). Consequently the exiting energy efficient solutions were categorized in five wide categories: *surveys and studies on energy consumption, energy efficient network selection, operation modes-based energy efficiency, cross layer solutions for energy conservation,* and *energy efficient multimedia processing and delivery.*

3.3.1. Surveys and Studies on Energy Consumption

Zhang et al. in [162] present a survey on the recent major advances in power-aware multimedia. The main focus of the survey is on video coding and video delivery. The authors identify the main challenges that come when designing energy efficient mobile multimedia communication devices, as: *(1)* ***real-time multimedia*** *is delay-sensitive and bandwidth-intense making it also* ***the most power consuming application****, (2) the radio frequency environment is changing dynamically over time and space, (3) the diversity of mobile devices and their capabilities, (4) the video quality does not present a linear increase with the increase in complexity, and (5) the battery discharge behavior is nonlinear.* The authors conclude that due to the dynamics involved, enabling power-aware mobile multimedia is extremely challenging. Many tradeoffs are involved in the process, for example using high compression techniques to reduce the amount of data to be transmitted and therefore the energy involved in data delivery, but higher compression involves higher computation both at the client and the server, and therefore increased battery usage.

A study on the energy consumption of **YouTube** in mobile devices was carried out by Xiao et al. [163]. The authors measured the energy consumption of a **Nokia S60 mobile phone** for three different use cases (*progressive download, download-and-play, and local playback*) and for two access network technologies (WCDMA and WLAN). Even though the results show that the WCDMA network consumes more energy than WLAN, they do not consider the impact of fluctuating network bandwidth nor the quality of the video.

Correia et al. in [164] address the problem of energy efficiency for mobile cellular networks (e.g., WCDMA/HSPA, LTE). The authors look at the energy efficiency of the entire system on three levels: (1) component level – looking at the efficiency of the power amplifier; (2) link level – looking at the discontinuous or continuous transmission modes of the base stations; and (3) network level – looking at the deployment paradigm of the cellular networks. The authors conclude that a potential for energy consumption reduction at the network level would be by taking into account **daily load patterns** as well as the network architecture type (e.g., multi-hop transmission, ad-hoc meshed networks, etc.).

Vallina-Rodriguez et al. [165] perform a study on collecting usage data of **18 Android OS** users during a 2 weeks period (Feb. 2010) in order to understand the resource management and **battery consumption pattern**. The information collected from the mobile devices covers a wide range of parameters, more than 20 (e.g., CPU load, battery level, network type, network traffic, GPS status, etc.) being updated at every 10 seconds. The study shows the importance of contextual information when designing energy efficient algorithms. For example, by identifying where and when some resources are in high demand (*50% of their time the users were subscribed to their top three most common base stations*) a more energy efficient resource management can be proposed that uses this information.

3.3.2. Energy Efficient Network Selection Solutions

The context information (time, history, network conditions, device motion) is also used in [166] by Rahmati et al. in order to estimate current and future network conditions and automatically **select the most energy efficient network** (802.11b or GSM/EDGE). The authors collected usage information from 14 users (**HTC Wizard Pocket PC, HTC Tornado, and HP iPAQ hw6925 phones)** during a 6 months period (Sept. 2006 – Feb. 2007). The authors argue that by using the context-based interface selection mechanism the average battery lifetime of the mobile device can reach 35% increase comparing with the case of using the cellular interface only.

Selecting the most energy efficient network in order to prolong the lifetime of the mobile device was addressed in [167-170] as well. Petander et al. [167] propose the use of traffic estimation of an **Android mobile device** in order to select between UMTS/HSDPA and WLAN. The traffic estimation is done by the Home Agent of the Mobile IPv6 protocol and sent to the mobile device which will take the handoff decision based on the estimate. The results show that the energy consumption for data transfer over UMTS can be up to three hundred times higher than over WLAN. The authors in [168] propose a network selection algorithm based on **AHP and GRA** which selects the best network between CDMA, WiBro, and WLAN. The authors consider a wide range of parameters: QoS (e.g., bandwidth, delay, jitter, and BER), the monetary cost, the Lifetime (transmission power, receiver power, and idle power) and user preferences. In [169] Liu et al. use a **SAW function** of available bandwidth, monetary cost, and power consumption to select between WiFi, WiMAX , and 3G whereas in [170] the authors **make use of TOPSIS** to solve the multi criteria (available bandwidth, RSS, velocity, load rate, and power consumption) problem and select between 802.11a, 802.11b, and UMTS networks.

3.3.3. Operation Modes-based Energy Efficiency Solutions

A state-of-the-art power management method for next-generation wireless networks with a focus on operation modes (e.g., sleep, idle, etc.) is presented by Kim et al. [171]. The authors provide a technical overview of power management in IEEE 802.16m and 3GPP LTE. 802.16m provides advanced power saving mechanisms based on enhanced versions of legacy IEEE 802.16 sleep and idle modes. Whereas, LTE adopts a **discontinuous reception mechanism** for power saving. The authors conclude that alternating available and unavailable intervals can provide an efficient and basic power saving method. However, by doing this, **extra power consumption** will be spent on **activating and deactivating components**, so the number of mode changes needs to be kept low.

Lee et al. [172] propose a Content-Aware Streaming System (CASS) that aims at improving the energy efficiency in Mobile IPTV services. CASS uses information from the network and makes use of the **Scalable Video Coding** scheme in order to reduce the transmission of unnecessary bitstreams. In order to further increase the energy efficiency, CASS **reduces the operating time** of the client **wireless NIC** by switching it **ON/OFF** based on the client buffer.

Perrucci et al. [173] investigate the energy consumption of a **Nokia N95** while performing VoIP. The authors propose the use of a lower energy consumption interface (e.g., GSM) as a signaling channel to wake up the WLAN interface and run the **VoIP service**. The authors argue that by using the **wake-up signals** the energy consumption can be reduced significantly in a VoIP scenario. The use of **sleep and wake-up schedules** is used by Namboodiri et al. [174] for energy saving during **VoIP calls**. The authors propose a GreenCall algorithm that keeps the WLAN interface of a laptop in **sleep mode** for significant periods during the VoIP calls. The maximum delay that a user can tolerate during a call is used to compute the sleep periods.

3.3.4. Cross Layer Solutions for Energy Conservation

Li et al. in [175] propose **joint optimization** of video coder parameters, channel coder, and transmit power in order to minimize the power consumption in video transmission. Their results indicate that when transmitting over a slow fading wireless channel, the solution is very efficient and effective in terms of energy-efficiency. The consideration of more realistic channel models is part of their future work.

The authors in [176] propose a power savings **cross layer solution** for an adaptive multimedia delivery mechanism based on remaining battery level, remaining video stream duration, and packet loss rate level. The mechanism decides whether or not to adapt the multimedia stream in order to achieve power saving while maintaining good user perceived quality levels.

3.3.5. Energy Efficient Multimedia Processing and Delivery

Baker et al. [177] propose a power saving mechanism at the **decoding stage**. The power-aware technique aims on reducing the decoding computation required for **H.264 streams** by using *macro-block prioritization*. This is done by allocating block priority levels in each frame of the video content, and omitting them, based on the allocated priority, at the decoder side. In this way the low priority block will be ignored by the decoder leading to decrease in computational workload.

Another technique that explores the energy saving in multimedia streaming is **brightness compensation** [178-180]. The authors in [178][179] propose the use of a proxy server that performs **on-the-fly transcoding** and **dynamic adaptation** of the video content (brightness compensation) based on the feedback from the client. The proxy server will send back the control information to the client middleware which will change its system parameters (e.g., operating backlight level) accordantly. In [180] the authors propose a similar approach and model the problem as a **dynamic backlight scaling optimization** in order to determine the appropriate video content backlight level. The authors show that when the energy consumption present a monotonic increase with the backlight level, their proposed algorithm is optimal in terms of energy saving.

3.4. Chapter Summary

This chapter aims to present the related works done in the area of network selection solutions, reputation-based systems, adaptive multimedia, and energy efficient techniques with the main emphasis on network selection and adaptive multimedia. The chapter introduces the current standards that support network selection and adaptive streaming and as well as the existing industry solutions. It presents a comprehensive survey of the current research on network selection and provides a useful categorization of the game theoretic approaches used in the literature to model the network selection problem. The categorization is done based on the players' interactions: ***Users vs. Users***, ***Networks vs. Users***, and ***Networks vs. Networks***. The existing reputation-based systems solutions for heterogeneous wireless environment are listed. The major findings from these game models and the main challenges that surround the network selection problem are addressed and summarized in Table 5.2.

In terms of adaptive multimedia solutions the chapter introduces a classification of the adaptive techniques, presented in the literature, in four main categories: (1) ***network protocol - based adaptive solutions*** which include protocols/mechanisms for video network delivery; (2) ***scalable video coding solutions*** which relate to coding the video content in a scalable manner in order to enable the adaptation process by dropping selected parts of the scalable video; (3)

transcoding-based solutions which adapt the video content by using on-the-fly transcoding; and (4) ***bitrate-switching solutions*** which consist on storing different quality levels of the same video content and switching between them when required.

The chapter concludes with an overview of the current research on the main energy efficient solutions for multimedia content delivery.

Chapter 4

Proposed System Architecture and Algorithms

This chapter presents the system architecture and the details of the four major contributions of the thesis: (1) the Power-Friendly Access Network Selection Mechanism (PoFANS) which selects the best value network for the user; (2) the Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy) which adapts the multimedia stream in order to maintain good user perceived quality levels; (3) the Adapt-or-Handover Solution which makes use of both network selection and adaptive multimedia delivery in order to achieve considerable power savings, and (4) the Reputation-based Network Selection Mechanism that makes use of Game Theory in order to model the user-network interaction.

4.1. Current Mobile Market Environment

Due to advances in technologies (e.g., improved CPU, graphics, display, etc.) and the mass-market adoption of the new multi-mode high-end devices - smartphones, iPhones, netbooks, and laptops, - the mobile operators are confronting a massive traffic growth. Because of the growing popularity of video-sharing websites such as YouTube, social networks like: Twitter, Facebook, Linkedin, MySpace, etc., entertainment services, mobile TV, etc., the use of mobile video will more than double every year by 2015 [1], representing the highest growth rate of any application category. The continuing growth of video content creates challenges for the network service providers in ensuring seamless multimedia experience at high end-user perceived quality levels, given the device characteristics and network resources. Adaptive multimedia streaming represents one possible solution that aims at maintaining acceptable user perceived quality levels. Another solution which deals with this explosion of mobile broadband data is the coexistence of multiple radio access technologies.

In this context, users are accessing video content on the move and via heterogeneous networks. For example, Figure 4.1 presents a scenario inspired from the daily life of Jack, a student or business professional who while going from home to his office, wants to access multimedia services (e.g., watching the news, watching music video clips with his preferred band or watching movies, etc.) anytime and anywhere. On his path, Jack will have a number of available wireless networks (e.g., UMTS, WLAN A, WLAN B) to choose from. However, the major question is how an ordinary user, without any background knowledge in wireless networks and their characteristics, could know which is the best deal for him? In order to help Jack, this thesis proposes an overall solution with several inter-linked algorithms.

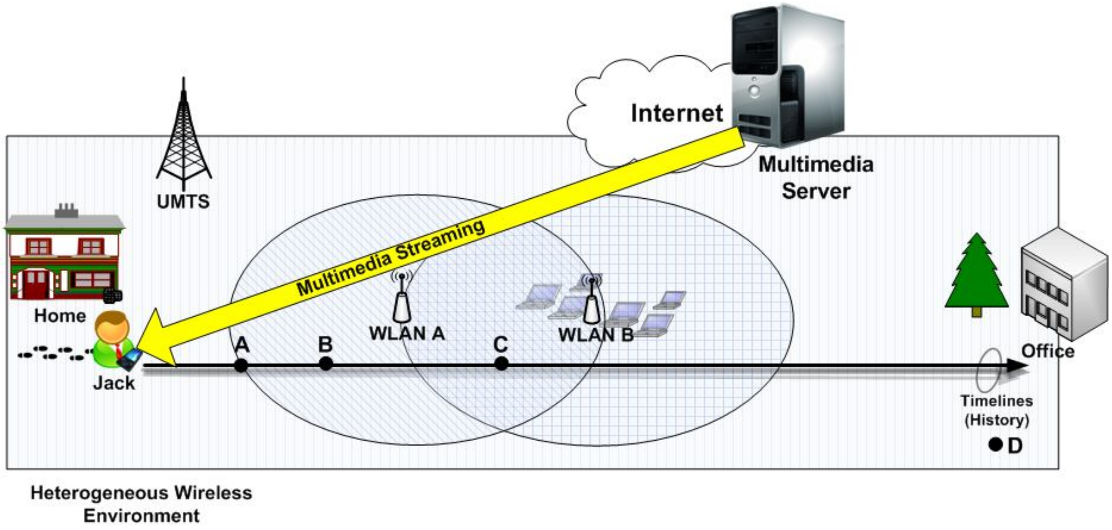


Figure 4.1. Heterogeneous Wireless Environment –Example Scenario of Jack's Daily Routine

The proposed solution comprises four main components. Each component has a role in helping Jack to be *'Always Best Connected'* on his path to his office. Figure 4.1 depicts this use-case with four reference location points (i.e., A, B, C, D), as follows:

- **Point A –** Jack has the option to choose from a number of available wireless networks (e.g., UMTS and WLAN A). A network selection mechanism **– PoFANS (Power-Friendly Access Network Selection Mechanism)** is proposed, integrated in Jack's mobile device, which will automatically perform the network selection for him, considering his preferences, application requirements, and network conditions. PoFANS indicates the best target network option and triggers the handover process. Note that the handover execution mechanism is not considered in this work.
- **Point B –** As Jack moves within a WLAN network, his device needs to cope with the errors from the wireless environment, the adaptive multimedia delivery

mechanism – **SAMMy (Signal Strength-based Adaptive Multimedia Delivery Mechanism)** can be employed. Point B is representative of a location at which SAMMy can be used. The mechanism will adapt the multimedia stream based on the network conditions in order to maintain an acceptable quality level for Jack.

- **Point C –** Point C is a representative of a point where an **Adapt-or-Handover solution** can be employed The solution will decide if it is better for Jack to handover to a new network (e.g., WLAN B) or it is better to adapt the multimedia stream, in order to conserve the energy of the mobile device.
- **Point D –** as Jack is taking the same path every day, he will be crossing the same networks and, building a history of his interactions on different network operators sites. A **reputation-based network selection mechanism** is proposed that makes use of game theory in order to model the user-network interaction as a repeated cooperative game.

Next, the architecture of each component will be presented and the coresponding algorithm will be described in detail.

4.2. Power-Friendly Access Network Selection Mechanism (PoFANS)

Imagine Jack with his multi-interface mobile device, which enables him to connect to one or more radio access network technology (e.g., WLAN, WiMAX, Cellular, etc.). In his way to his office, Jack wants to select the best network from the available wireless networks (see Figure 4.1 Point A). The proposed network selection mechanism is a novel power-friendly access network selection strategy, referred to as PoFANS, which could select the least power consuming network in order to avoid Jack's mobile device running out of battery in the middle of an important event (e.g., video conference, video streaming, voice call or any other real time application), while maintaining good user perceived quality levels at the same time.

4.2.1. PoFANS Architecture

Because multimedia applications are known to be high energy consumers and since the battery lifetime is an important factor for mobile users, PoFANS bases its selection decision on the user mobility, user preferences, application requirements, network conditions, and the energy consumption of the mobile device. PoFANS can be set to enable the battery lifetime of the mobile device to last longer while running multimedia services and maintaining good user perceived quality levels by selecting the least power consuming network choice.

Figure 4.2 illustrates the PoFANS architecture based on the TCP/IP protocol stack model. PoFANS resides at the application layer, providing a middleware framework for multimedia delivery. For example, a video application which uses the proposed PoFANS mechanism can employ a transport layer protocol such as UDP, a network layer protocol such as Mobile IP, and regular MAC and PHY layer protocols for delivery.

The aim of PoFANS is to select the best value network from the available networks. In order to do this, various information is required, including network conditions (e.g., available throughput), monetary cost of each network, energy consumption, and user preferences. All this information is gathered by the mobile device and this can be done by employing various mechanisms for monitoring the available networks, or obtaining information from various entities or agents which provide the required information. For example, the new standard IEEE 802.21 provides three main services, as illustrated in Figure 4.2: (1) *Media Independent Event Service* – triggered when changes occur at the physical layer (i.e., link parameters change, new networks available, interrupted/established session); *(2) Media Independent Command Service* – enables the higher layers to control the link layer by reconfiguring or select an appropriate link; *(3) Media Independent Information Service* – provides an interface for the handover policy in order to gather information about the available networks.

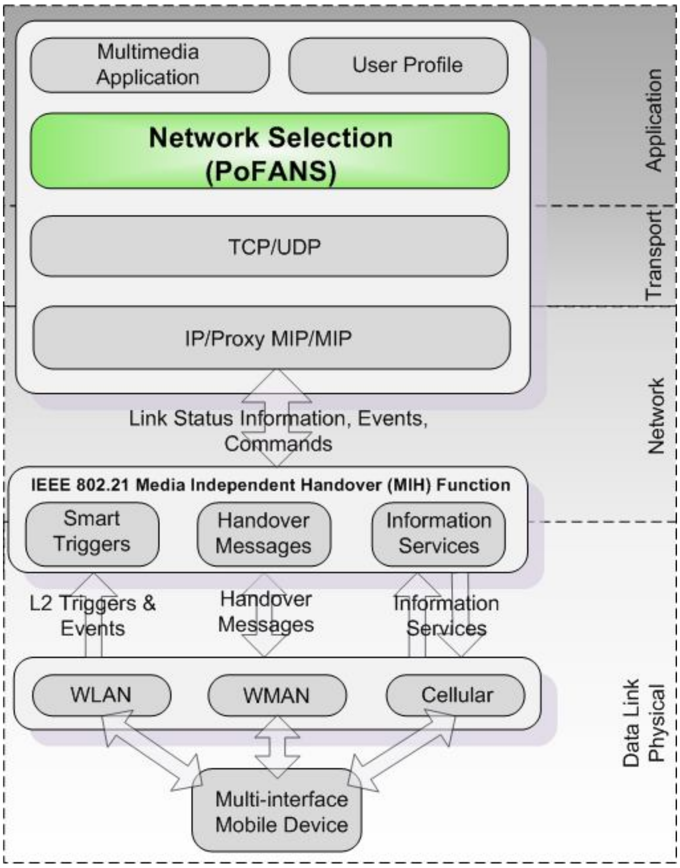


Figure 4.2. PoFANS Overview Architecture

PoFANS will make use of the IEEE 802.21 standard in order to gather all of the information about the available wireless networks (e.g., available throughput, monetary cost, etc.). By using this information plus the information about the multimedia application requirements and user preferences, PoFANS will select a target network.

A more detailed block architecture of PoFANS is presented in Figure 4.3. PoFANS is a Client-side module that selects the best value network for the user. The module comprises four main sub-modules: Data Collector, Network Filter, PoFANS Energy Prediction, and PoFANS Score Generator. Next these four modules are described in detail.

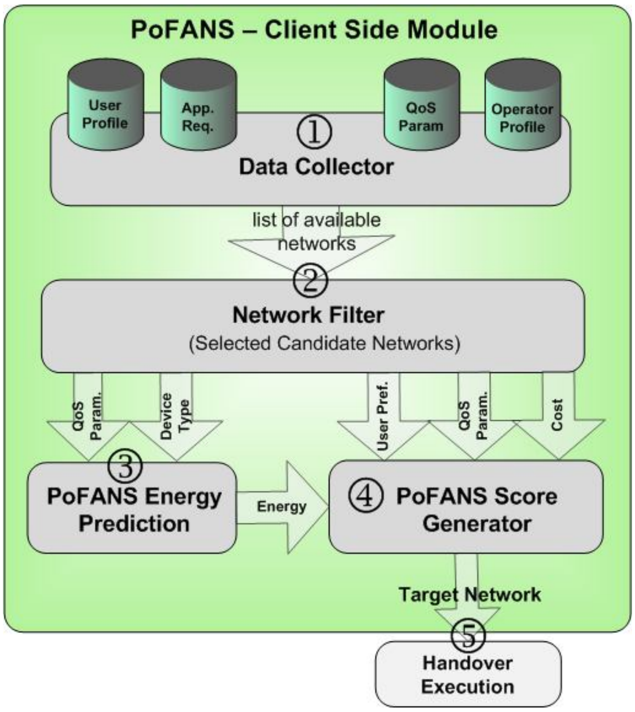


Figure 4.3. PoFANS Architecture

4.2.1.1. Data Collector Module

The role of the Data Collector module is to provide all the information required by PoFANS. As mentioned above, PoFANS bases its decision on five main parameters: user mobility, user preferences, available throughput, energy consumption, and monetary cost.

As illustrated in Figure 4.3 the Data Collector module contains four databases: **user profile**, **application requirements**, **QoS parameters**, and **operator profile**.

The main goal of using PoFANS is to satisfy the user preferences. Thus, it is important to let users participate in the process of selecting the best value network for themselves. In this context, the **user profile** provides information about the user preferences, the profile can also exploit location information available on the mobile device to store user mobility patterns. There are many ways of collecting data from the user. However, frequent user interaction is undesirable because it can become tedious and also interrupt the user. One solution would be to collect the data on a one-time basis (e.g., when the user sets up his/her mobile device for the first time). However, the user should be able to change his/her preferences whenever they wanted. This can be done by integrating a GUI (e.g., user profile) in the user's mobile device. In order to obtain information about the **user mobility**, three categories can be defined and linked to certain locations: *(1) high speed user* – for example, this category contains typical vehicular speed with values above 5.3km/h; *(2) low speed user* – for instance, this category contains walking speed with values below 5.3km/h; and *(3) stationary users* – for instance, the users that are using their internet connection in fix positions (e.g., hotspots).

The **user preferences** play an important role in the decision making. The decision making of PoFANS is based on three main criteria of importance to the user: *quality*, *energy*, and *cost*. An important feature of any decision making scheme across multiple criteria is the chance given for the user to specify their preferences concerning the importance of the criteria. The users may give varying importance to each criterion. For example, if the user is on a strict budget, then the cost might be weighted higher, always looking for an affordable solution. If the user prefers to conserve the energy of his/her mobile device, then the energy will be given higher importance, meaning it will be weighted higher. If the user is more quality-oriented (high quality multimedia application), then the weight for quality will be higher. However, the aim is to find a good trade-off between the three. As mentioned, this information could be provided in the user profile, and the user should be able to modify the weighting for each criterion, depending on his/her needs.

Different applications have different **application requirements.** For example a multimedia application has a minimum transmission bandwidth requirement that will ensure a minimum acceptable quality level to the user. These application requirements can be provided in the metadata of the application, and sent to the Data Collector module at runtime.

The IEEE 802.21 standard is used in order to gather all the information about the **QoS parameters** (e.g., available throughput) provided by the available wireless networks.

In this work it is assumed that dynamic pricing is not used by the networks and so the monetary cost of using a network is known in advance of the call. This monetary cost information may be stored on the mobile device in the **Operator Profile**. This information may be updated if there are any changes in pricing. For example, when you arrive in a new country currently you get a Short Message Service (SMS) alerting you to the call charges on the local networks, this information could be used to update the operator profile. Monetary cost could also be obtained by interrogating corresponding services located at the provider side (through the use of IEEE 802.21). The monetary cost represents the cost involved in using the services of a certain network and is expressed in Euro/Kbyte.

After collecting all the required information about the available wireless networks, the Data Collector module will provide the list of available wireless networks plus their information to the Network Filter module.

4.2.1.2. Network Filter Module

The role of the Network Filter module is to perform a first elimination of the available networks. After receiving the list of available networks, their characteristics (e.g., available throughput, monetary cost) and all the other information (e.g., application requirements, user profile) from the Data Collector module, the Network Filter module will eliminate all the networks which do not meet a minimum/maximum criterion. For example, if the user has a strict budget, defined in the User Profile, consequently all the networks which provide the required service for a monetary cost that goes above the user's budget will be eliminated from the decision. Or if the available bandwidth provided by some networks is below the minimum transmission bandwidth required by the application to work, those networks will be eliminated as well. Only the networks that pass the parameter thresholds will be considered as candidate access networks for the network selection algorithm, reducing the computation and decision time.

After this filtering, the Network Filter module will send the list of candidate networks to the PoFANS Energy Prediction module and PoFANS Score Generator module.

4.2.1.3. PoFANS Energy Prediction Module

The role of the PoFANS Energy Prediction module is to compute the estimated energy consumption of the running application for each of the candidate networks.

The estimated energy consumption for the real time application under consideration is computed using equation (4.1) as defined in [181].

$$E_i = t(r_t + Th_i r_d) \quad (4.1)$$

where: E_i - the estimated energy consumption (Joule) for RAN i; t represents the transaction time (seconds); r_t is the mobile device's energy consumption per unit of time (W); Th_i is the available throughput (kbps) provided by RAN i; r_d is the energy consumption rate for data/received stream (Joule/Kbyte). Note that in the original equation defined in [181], a constant c was used, but as the calculations in Chapter 6 have shown that this constant is 0, the constant will not be further considered here.

The transaction time (length) can be predicted from the duration of the multimedia application. The parameters r_d and r_t are device specific and can be stored on the device in the User Profile. r_d and r_t differ for each network interface and they can be provided by the device manufacturer in the device specifications. Otherwise, they can be determined by running different simulations for various amounts of data and defining a power consumption pattern for each interface. In this work, a Google Nexus One device was used. Real experimental tests were carried out, in order to build an energy consumption pattern, and they are introduced in Chapter

5. The energy consumption pattern for the Google Nexus One mobile device is modeled as shown in Section 6.5.

After the PoFANS Energy Prediction module has computed the estimated energy consumption for each of the candidate networks, the information is sent to the PoFANS Score Generator module for further processing.

4.2.1.4. PoFANS Score Generator Module

The role of the PoFANS Score Generator module is to compute a score for each candidate network. The network with the highest score will be selected as the target network. After the target network is selected, the handover execution is triggered. As can be seen in Figure 4.3, the handover execution is not part of PoFANS, consequently the handover process is not detailed in this work. The focus is instead on the network selection decision.

The proposed network selection score function makes use of the multiplicative exponential weighted (MEW) method. The PoFANS score function is defined in equation (4.2) and is based on four criteria: the energy consumption, the quality of the multimedia stream, the monetary cost, and the user mobility. The criteria can be divided into two classes: (1) the larger the better – higher values of the criteria are considered to be better than low values of the criteria (e.g., throughput); (2) the smaller the better – smaller values of the criteria are considered to be better than high values of the criteria (e.g., energy consumption, monetary cost). Because each criterion presents different ranges and units of measurement, they need to be scaled. The goal of the scaling process is to map all criteria onto non-dimensional values within the range [0,1] to make them comparable. In order to do this, each criterion is scaled with the help of utility functions.

$$U_i = u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \cdot u_{m_i}^{w_m} \qquad (4.2)$$

where: U_i – overall score function for RAN i; u_e, u_q, u_c, and u_m are the utility functions defined for energy, quality in terms of received bandwidth, monetary cost for RAN i, and user mobility respectively. Also $w_e + w_q + w_c + w_m = 1$, where w_e, w_q, w_c, and w_m are the weights for the considered criteria, representing the importance of a parameter in the decision algorithm. The weights are given by the Data Collector module, being collected from the user profile as previously explained in Section 4.2.1.1. If the user does not provide the weights, the default settings assume the preference towards always selecting the cheapest network. As noticed in equation (4.2) the score function is built based on the utility functions defined for each criterion: energy utility, quality utility, cost utility, and mobility utility. The overall score function has values in the [0,1] interval and no unit. Each utility function is further described below in detail.

a) Energy Utility - u_e

The energy follows the principle “the smaller the better” meaning that for small values of energy consumption the value of the energy utility, u_e, is high, whereas for high values of energy consumption the utility is low. The energy utility is based on the estimated energy provided by the PoFANS Energy Prediction module and is defined in equation (4.3). The energy utility has values in the [0,1] interval, and no unit.

$$u_e(E) = \begin{cases} 1 & , \quad E < E_{\min} \\ \dfrac{E_{\max} - E}{E_{\max} - E_{\min}} & , \quad E_{\min} <= E < E_{\max} \\ 0 & , \quad otherwise \end{cases} \qquad (4.3)$$

where: E_{min} - the minimum energy consumption (Joule), E_{max} - the maximum energy consumption (Joule), and E – the energy consumption for the current network (Joule). E_{min} and E_{max} are calculated for Th_{min} and Th_{max} respectively. The energy consumption is computed using equation (4.1).

b) Quality Utility – u_q

In order to map the received bandwidth to user satisfaction for multimedia streaming applications, a zone-based sigmoid quality utility function is defined, and illustrated in Figure 4.4. The utility is computed based on: the minimum throughput (Th_{min}) needed to maintain the multimedia service at a minimum acceptable quality (values below this threshold result in unacceptable quality levels i.e., zero utility), the required throughput (Th_{req}) in order to ensure high quality levels for the multimedia service; the maximum throughput (Th_{max}), values above this threshold result in quality levels which are higher than most human viewers can distinguish between and so anything above this maximum threshold is a waste. The mathematical formulation of this quality utility function is given in equation (4.4). The quality utility has values in the [0,1] interval and no unit.

$$u_q(Th) = \begin{cases} 0 & , \quad Th < Th_{\min} \\ 1 - e^{\frac{-\alpha * Th^2}{\beta + Th}} & , \quad Th_{\min} <= Th < Th_{\max} \\ 1 & , \quad otherwise \end{cases} \qquad (4.4)$$

where: α and β are two positive parameters which determine the shape of the utility function (no unit), *Th* is the predicted average throughput for each of the candidate networks (Mbps), Th_{min} is the minimum throughput (Mbps), and Th_{max} is the maximum throughput (Mbps).

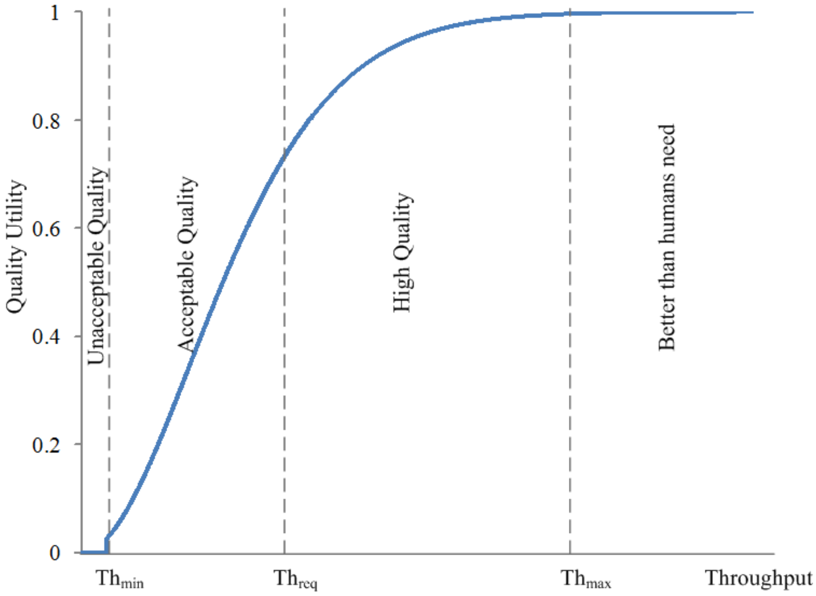


Figure 4.4. Zone-based quality sigmoid utility function

In order to determine the exact shape of the utility function the values of α and β need to be calculated. For this, two equations are needed. The first equation can be obtained from knowing that when the throughput reaches Th$_{max}$ the corresponding utility u will be equal to u_{max}. Thus, the first equation is defined as follows:

$$1-e^{\frac{-\alpha * Th_{\max}{}^{2}}{\beta+Th_{\max}}} = u_{\max} \quad (4.5)$$

From equation (4.5) a relationship between α and β can be obtained as follows:

$$\alpha = \frac{\ln(1-u_{\max})(\beta + Th_{\max})}{-Th_{\max}^{2}} \quad (4.6)$$

Now that the relationship between α and β is defined, a second equation is needed in order to calculate their values. The required throughput, Th$_{req}$, illustrated in Figure 4.4 can be defined mathematically as the throughput before which the utility function is convex and after which the utility becomes concave. This means that the second-order derivative of the utility function is zero at this point. After computing the second-order derivate and replacing α with equation (4.6), equation (4.7) is obtained:

$$\begin{aligned}&[1+2\ln(1-u_{\max})(\frac{Th_{req}}{Th_{\max}})^{2}]\beta^{3}+[Th_{req}+2\ln(1-u_{\max})\frac{Th_{req}^{2}}{Th_{\max}}\\&+2\ln(1-u_{\max})\frac{Th_{req}^{3}}{Th_{\max}^{2}}]\beta^{2}+[2\ln(1-u_{\max})\frac{Th_{req}^{3}}{Th_{\max}}+\ln(1-u_{\max})\frac{Th_{req}^{4}}{2Th_{\max}^{2}}]\beta \qquad (4.7)\\&+\ln(1-u_{\max})\frac{Th_{req}^{4}}{2Th_{\max}}=0\end{aligned}$$

The positive solution of equation (4.7) represents the value of β. The values used for Th_{min}, Th_{req}, Th_{max}, α, β, and the modeling of the quality utility function are further detailed in Section 6.4.

c) Cost Utility - u_c

Because there is a natural tendency to reduce the monetary cost, the cost parameter follows the principle "the smaller the better". This means that for small values of the monetary cost, the cost utility, u_c, has high values, whereas for high monetary cost the cost utility is small. Consequently the cost utility, u_c, is defined as in equation (4.8):

$$u_c(C) = \begin{cases} 1 & , \quad C < C_{\min} \\ \dfrac{C_{\max} - C}{C_{\max} - C_{\min}} & , \quad C_{\min} <= C < C_{\max} \\ 0 & , \quad otherwise \end{cases} \tag{4.8}$$

where: C - is the monetary cost for the current network (euro), C_{min} - minimum cost that the user is willing to pay (euro) and C_{max} – the maximum possible cost that the user can afford to pay (euro). The values for C, C_{min}, and C_{max} are provided by the Data Collector module as described in Section 4.2.1.1. The user can store his budget limit on his mobile device (e.g., User profile), which will be C_{max}, and of course the value of C_{min} is considered to be zero (e.g., free of charge services). In this work the monetary cost of each network, C, is considered to be flat rate cost expressed in Euro/Kbyte. It is assumed that the flat rate charged is known in advance by the mobile user and does not change frequently (i.e., on a daily or weekly basis) and definitely will not change during a user-network session. The cost utility has values in the [0,1] interval, and no unit.

d) Mobility Utility - u_m

Information about user mobility is obtained from the Data Collector module as described in Section 4.2.1.1. Based on the corresponding user mobility category, the mobility utility u_m, is defined as follows:

$$u_m = \begin{cases} 0 & if \quad high\ speed\ user\ \&\ WLAN \\ 0.5 & if \quad high\ speed\ user\ \&\ WMAN\ /\ Cellular \\ 1 & if \quad otherwise \end{cases} \tag{4.9}$$

The user mobility has an impact on the utility function only for the case of high speed users. Since a high speed user may be in the coverage area of a short range network for a few seconds/minutes only, there is no need for handover and therefore for network selection. The mobility utility has values in the [0,1] interval, and no unit.

4.2.2. PoFANS Algorithm

As mentioned, the aim of PoFANS is to select the best value candidate network that fulfils the user requirements, maintaining the user 'always best connected' for multimedia streaming. The network selection is based on the user preferences, application requirements, quality of the multimedia application, energy consumption of the mobile device, the monetary cost of the network, and the user mobility. PoFANS is a client-side module that computes a score for each of the candidate networks. The outcome of PoFANS is a ranked list of the candidate networks, and the network with the highest score will then be selected as the target network.

Changes in the networks available, current network conditions (including network congestion, interference, etc.), user preferences, and/or efficiency of the energy consumption may trigger the network selection process. Changes or variations in these parameters, may determine a change in the ranking list of the candidate networks provided by PoFANS. PoFANS may be used no matter what type of networks are available nor neither their number.

The pseudo-code of the decision making process of PoFANS is described in Algorithm 1. The **computational efficiency** is an important concern when dealing with network selection algorithms. In this particular case a number of different processes are executed. For example, let us consider the case of one mobile user with the PoFANS network selection algorithm enabled on his/her mobile device and located in the coverage area of a number of available wireless networks. First, the algorithm will start an **elimination process** and from the list of available wireless networks only the networks that pass the required thresholds will be further processed as candidate networks. The elimination process should reduce an amount of the computational load. For each remaining **candidate network** the **energy consumption**, the **energy utility**, the **quality utility**, **the cost utility**, **the mobility utility**, and the **overall score function** are computed. The network that has the maximum score is selected as **the target network**. The process is repeated every time the current network fails to fulfill the user requirements or another better network is available.

Algorithm 1 PoFANS Network Selection Algorithm

```
INPUT:

$w_e$; - energy weight      }
$w_q$; - quality weight     }
$w_c$; - cost weight        }  user preferences
$w_m$; - mobility weight    }
```

```
$Th_{min}$; - application requirements – the minimum acceptable throughput
$C_{max}$; - user's budget – the maximum cost the user is willing to pay for the services

$Throughput_i$; - the available throughput of RAN i
$Monetary\_Cost_i$; - the monetary cost of RAN i

PROCEDURE:
i = 0;

ELIMINATION PHASE
Input:
List of Available Networks;

Procedure:
for i = 0 to number of available networks  do
    if $Throughput_i \leq Th_{min}$ or $C_i > C_{max}$ then
        eliminate $Network_i$
    end if
end for

Output:
List of Candidate Networks;

ENERGY PREDICTION PHASE
Input:
t; - the transaction time (seconds) – the duration of the multimedia stream
$r_t$; - the mobile device's energy consumption per unit of time (W)
$r_d$ ; - the energy consumption rate for data/received stream (Joule/Kbyte)
c; - constant
List of Candidate Networks;

Procedure:
for i = 0 to number of candidate networks  do
    $Energy_i = t(r_t + Throughput_i\, r_d) + c$;
end for

Output
$Energy_i$;

SCORE GENERATION PHASE
Input
List of Candidate Networks;

Procedure:
for i = 0 to number of candidate networks  do
    compute utilities: $u_{e_i}$ , $u_{q_i}$ , $u_{c_i}$ , $u_{m_i}$ ;
    compute score $U_i = u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \cdot u_{m_i}^{w_m}$
end for

Output:
Ranked List of Candidate Networks;

OUTPUT:
Ranked List of Candidate Networks;
with
the Target first choice Network – the network with the highest score ($U_i$)
```

4.3. Signal Strength Adaptive Multimedia Delivery Mechanism (SAMMy)

Recall Jack's path from his home to his office (see Figure 4.1), after the PoFANS network selection mechanism, selects the best available network and the handover process has been executed (if necessary), Jack moves towards Point B as illustrated in Figure 4.5. Delivering streaming video with QoS provisioning over wireless networks is more challenging than in wired networks due to the constraints of wireless links, and the user mobility. It is essential to provide QoS mechanisms to cater for multimedia throughput, delay, and jitter constraints, especially within the wireless environment where connections are prone to interference, high data loss rates, and/or disconnection.

In this context, the Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy) is proposed. SAMMy adapts the multimedia stream level, depending on the network conditions. The aim of the mechanism is to maintain an acceptable user perceived quality and make efficient use of the wireless network resources.

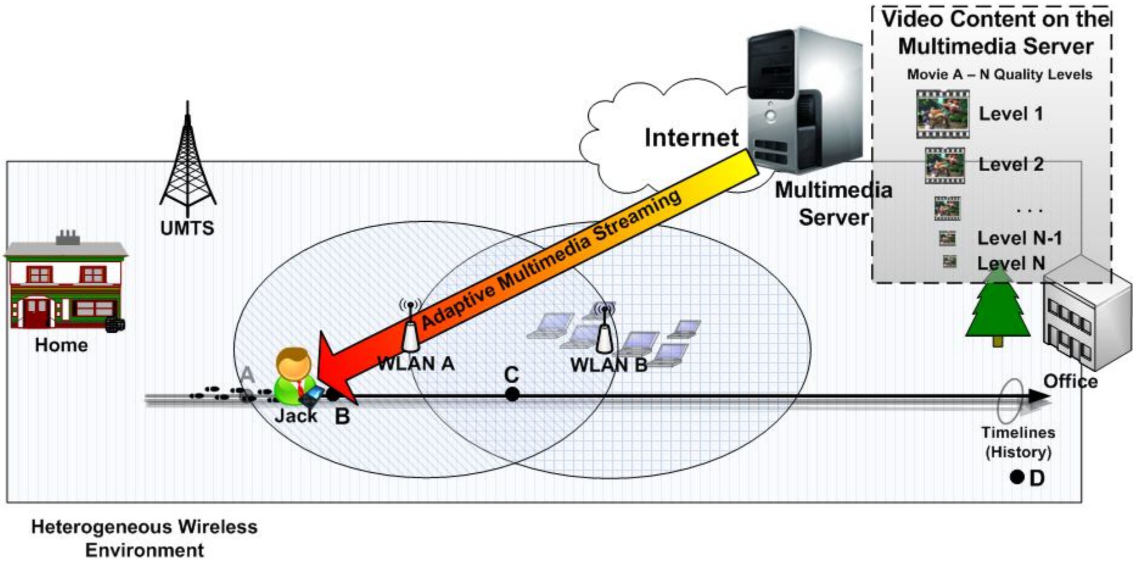


Figure 4.5. Wireless Video Delivery – Example Scenario

4.3.1. SAMMy Architecture

Figure 4.6 illustrates the proposed SAMMy architecture based on the TCP/IP protocol stack model. SAMMy resides at the application layer, providing a middleware framework for multimedia delivery. The transport protocol used by SAMMy is UDP because of its best suitability for multimedia applications. However the solution can be adapted to work with any transport protocol. SAMMy was implemented to work with WLAN but can be adapted to work for any other radio access network technology.

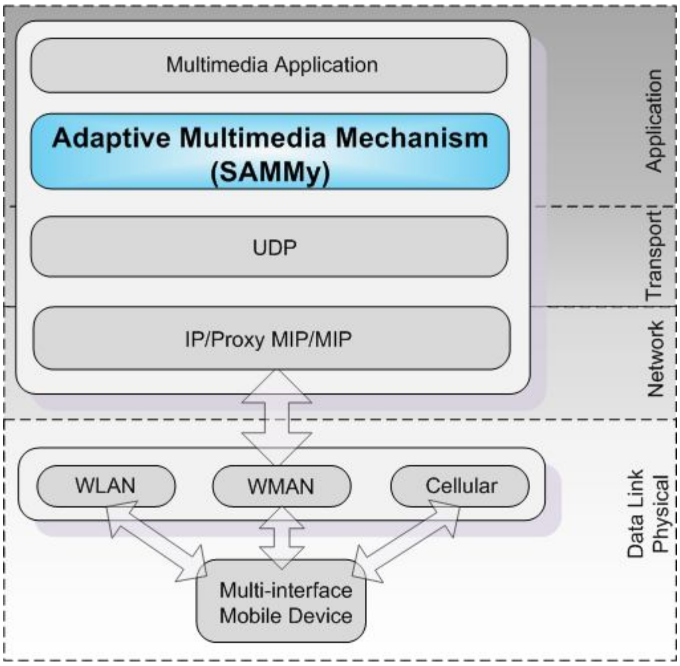


Figure 4.6. SAMMy Overview Architecture

The aim of SAMMy is to adapt the multimedia stream in order to cope with the wireless errors and maintain an acceptable user perceived quality level.

A more detailed block architecture of SAMMy is presented in Figure 4.7. SAMMy is a distributed solution and consists of a server-side module which uses SAMMy to stream real-time multimedia content over wireless networks, and a client-side module which attaches to the multimedia client application, receives and displays the multimedia stream content.

SAMMy Server-side module is composed of three sub-modules: the Video Content, SAMMy Quality Selector, and SAMMy Feedback Interpreter. **The Video Content** stored on the server is encoded at different quality levels (e.g., different frame rate, frame size, bit rate, etc.). Consequently for a Movie A, the multimedia server can store a number of N Quality Levels (with Level 1 – the highest quality level to Level N – the lowest quality level). These quality levels correspond to different amounts of data to be delivered.

SAMMy Feedback Interpreter receives feedback information, containing statistical data regarding the packet loss from the mobile device. Based on this received feedback information, SAMMy Feedback Interpreter will trigger the **SAMMy Quality Selector** which selects the most suitable quality level and consequently adjusts the multimedia delivery rate that is sent back to the mobile device. A more detailed description of the principles behind SAMMy is provided in the next section.

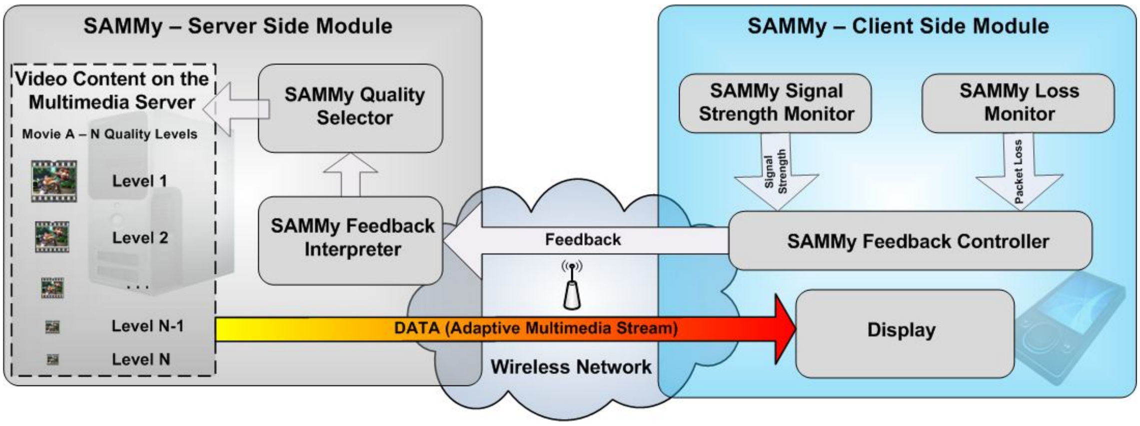


Figure 4.7. SAMMy Architecture

SAMMy Client-side module comprises of three sub-modules: SAMMy Signal Strength Monitor, SAMMy Loss Monitor, and SAMMy Feedback Controller.

SAMMy Signal Strength Monitor is responsible for monitoring the received signal strength (link quality) of the mobile device and it has two operation modes: (1) *instant reading mode* which triggers the module to measure the instantaneous received signal strength of the mobile device, and (2) *the prediction-based mode* which predicts the received signal strength for a future location of the mobile user. In order to predict the received signal strength, information about the user current location within the wireless network (relative to the AP) is needed.

This information about received signal strength and location can be obtained through the use of the IEEE 802.11k features for WLAN networks. The protocol's location report is used to gather information at the mobile device side on the current location and the beacon report will provide information about the link quality (signal strength). The IEEE 802.11k standard provides information about the current location but the acquisition mechanism for obtaining the position itself is not included in the standard. For the acquisition of the current position several location based mechanisms could be used. For example the Global Positioning System (GPS) [182], can be used in order to determine the radio station current location, the time, and the velocity. Also other schemes could be used such as measuring the round trip time in order to determine the distance between mobile nodes [183]. If the associated AP supports network-based foreign positioning, the radio station can send a local location request to the AP in order to obtain information about its current position [184]. The report includes a Location Configuration Information (LCI) element which indicates information on latitude, longitude and altitude [185]. Based on the information gathered from the mobile's recent report of location and velocity, the future location of the mobile can be predicted.

The IEEE 802.11k beacon report includes a Received Channel Power Indicator (RCPI) field which indicates the received channel power of the Beacon, Measurement Pilot or Probe Response frame expressed in dBm. It also includes a Received Signal to Noise Indicator (RSNI) field which indicates the received signal to noise indication for the Beacon, Measurement Pilot or Probe Response frame, also expressed in dBm [184]. Having this information, and assuming that the mobile station moves at a constant speed in a known direction, the received signal strength can be predicted for the future locations as the mobile station moves. Different propagation models can be used in order to predict the received signal strength, for example the Friis free space propagation model [190] as given in equation (4.10):

$$P_r(d) = P_tG_tG_r\lambda^2/(4\pi)^2d^2L \qquad (4.10)$$

where P_r and P_t are the received and transmit powers (in Watts), G_r and G_t are the received and transmit antenna gains (dimensionless numbers without units), λ is the carrier wavelength (in meters), L is the system loss factor (dimensionless number without units), and d is the distance between the user and the antenna (in meters).

The information about the signal strength is then reported to the SAMMy Feedback Controller.

SAMMy Loss Monitor is responsible for monitoring the packet loss rate on the current connection. SAMMy Loss Monitor intercepts the packets received on the current connection for a predefined time interval of length t ($[t_n, t_{n+1}]$). Based on the packet timestamp and sequence number, each packet is counted and the packet loss is calculated. The average value of the packet loss rate is periodically reported to the SAMMy Feedback Controller. After the report was delivered, all the counters and average values are reset, and the monitoring starts again.

SAMMy Feedback Controller gathers the information about the signal strength of the mobile device and the average packet loss rate. All the information is included in a feedback report which is sent back to the Server. At the server-side, the SAMMy Feedback Interpreter, receives the feedback from the client and decides whether to increase or decrease the quality level of the multimedia stream. The decision of increasing or decreasing the rate is done based on the information about signal strength and packet loss.

As it is known that multimedia applications are vulnerable to degradation caused by packet loss, SAMMy bases its adaptation mechanism on **Received Signal Strength** (RSS) and **packet loss**. Even though **delay** and **delay variation** (jitter) are considered to be among the parameters associated with the user perceived video quality levels, they are not used by SAMMy. The main reasons for considering only the packet loss in the decision mechanism are outlined below:

- it has been shown that a constant delay has little effect on the user perceived quality for non interactive real-time media streaming services [186]. In the case of interactive services (e.g., video conferencing) the delay may impact the quality of the service by adding periods of pause in the conversation. However it does not have a direct impact on the user visual perceived quality. As the delay might affect the ordering of the packets in the network, a large delay could indicate a congestion condition in the communication path. Thus, **the delay can be linked to the packet loss rate** [187].

- delay variation could be considered an indirect source of packet loss, as it can cause the packets, to arrive at the client, out of order and after their play-out time, in which case they are discarded. Thus, **the jitter can also be linked to the packet loss rate** [188].
- the packet size is another parameter that can impact the perceived quality indirectly, and which can be linked to the packet loss, in the sense that a lost packet has a greater impact if its size is larger.

The communication between entities is illustrated in Figure 4.8. SAMMy Feedback Controller gathers the information from the SAMMy Signal Strength Monitor and SAMMy Loss Monitor about the signal strength and the average packet loss rate, respectively. The information is processed and encapsulated in a Feedback Report message which is sent to the Server. At the Server-side, the SAMMy Feedback Interpreter analyzes the received feedback report, decides whether to increase or decrease the quality level, and sends the decision to the SAMMy Quality Selector module which selects the suitable quality level from the Video Content. The selected quality level is delivered and displayed on client's mobile device.

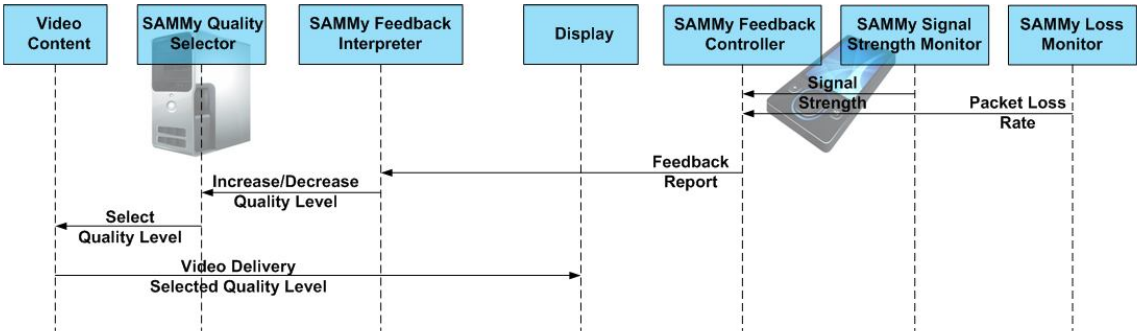


Figure 4.8. SAMMy Message Exchange

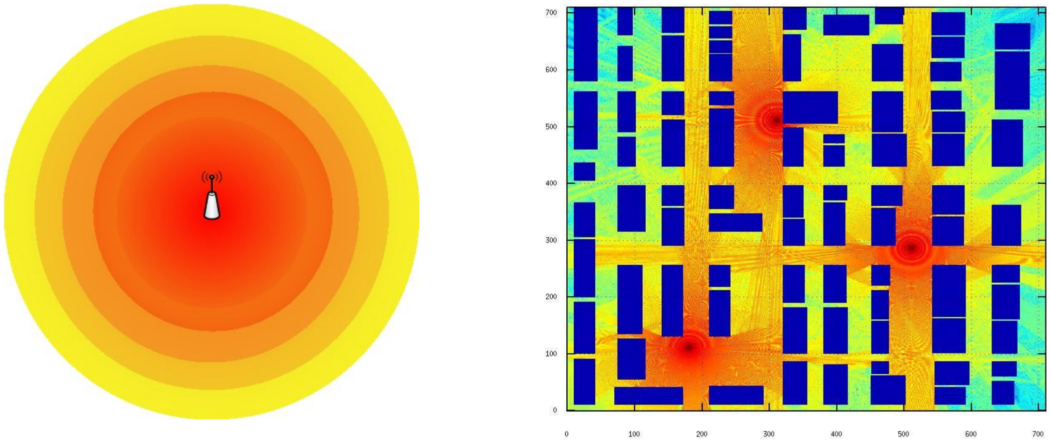
SAMMy makes use of the information about packet loss in order to change the data rate (increase/decrease) of the multimedia service, therefore reducing the loss rate at the expense of slightly lower video quality level. Users tend to accept a lower quality level (uncorrupted multimedia stream) rather than a lossy video (corrupted multimedia stream). A detailed description of the decision algorithm will be further presented in this chapter.

4.3.2. SAMMy Basic Principle

When evaluating the performance of an IEEE 802.11 WLAN, it is known that an important factor, that needs to be considered, is the propagation of Radio Frequency (RF) signals. Previous studies [189] have shown that it is not enough to consider the signal strength only, when analyzing the performance of different wireless applications because of the RF dynamics.

The RF environment changes dynamically as people move through the coverage area. Also the presence of different objects or object movement can cause reflections which can lead to the mobile device reading the same Receive Signal Strength Indication (RSSI) value twice or two different values. In this context, when obstacles are present in the environment, the coverage area of the AP will no longer be a perfect concentric disc shape. Figure 4.9a illustrates the propagation of the signal strength within the coverage area of an AP when there are no obstacles. It can be noticed that the signal has high intensity near the AP, represented by the dark red color, which degrades as the mobile moves away from the AP towards the coverage border and low intensity signal strength, represented by the light yellow color. Figure 4.9b illustrates the signal strength propagation of APs when there are obstacles present (e.g., buildings), represented by the dark blue rectangles. It can be notice that near the APs the signal has high intensity represented by dark red color, whereas the signal intensity is varying near the obstacles. Effects caused by the obstacles such as canyon-ing, and shadowing can be seen.

For simplicity reasons, an open environment (without/with few obstacles) will be further considered in this work. However, this will not have any impact on the correct functionality of the proposed mechanism in a realistic environment.



a) without obstacles – open environment

b) with obstacles

Figure 4.9. Access Point Coverage Area in two situations: a) without obstacles – open environment and b) with obstacles

The IEEE 802.11 family supports multiple data rates, modulation techniques, and the receivers have different sensitivities for these modulations. For example, the IEEE 802.11b standard supports four data rates, of 1Mbps, 2Mbps, 5.5Mbps, and 11Mbps. Each rate corresponds to a different modulation scheme. Previous studies have shown that the lower rate schemes have greater transmission ranges than the higher rate schemes [190]. As the mobile user moves away from the AP, the signal attenuates until it drops below the threshold required to maintain a tolerable bit error rate. Path loss is only one of the factors which contribute to the cause of variation in the received signal-to-noise ratio (SNR). Some other factors include fading and interference.

As shown by the concentric rings in Figure 4.9a, as a mobile node moves away from a WLAN AP its received signal strength and maximum theoretical throughput level will drop stepwise. As a result, the AP coverage area can be divided into a number of M different areas based on the received signal strength. SAMMy uses these M different areas to help in avoiding using unachievable quality levels in these different areas or zones. Each area, A_i, is associated with one quality level, QL_j for multimedia delivery. This means that QL_j is the maximum level that can be achieved by a user located in area A_i. In order to delimit each area, a number of M thresholds are defined. The value for each of these thresholds is computed based on the estimated maximum received power and the wireless card receiver sensitivity.

The maximum power is considered to be the power received by the user's terminal if his location will be within one meter of the AP. The maximum power is estimated using equation (4.10) where d = 1 meter. As the mobile users move away from the AP, they will pass from one area to another and their corresponding maximum quality level will drop by 1 every time they go over a boundary. The wireless card receiver sensitivity varies for different manufacturers' wireless cards and is provided in the manufacturer specifications for a specific wireless card.

In case of fast fading the current quality level will not present a severe drop, instead the maximum achievable quality level will be changed depending on the new received signal strength value. If the current quality level is above the new maximum achievable quality level, then the current quality level will decrease in a smooth manner until it reaches the new maximum quality level.

As stated before, the SAMMy Loss Monitor module monitors the network traffic, and SAMMy Signal Strength Monitor module monitors the received signal strength of the device. When packet loss is detected or there is a drop in signal strength, the SAMMy Feedback Controller is notified and a feedback report is built and sent back to the server. **Positive feedback** was used to indicate that **no loss** has been detected since the last received feedback, and **negative feedback** indicates that **loss** has been **detected** since the last received feedback. Because of the error-prone wireless environment, it might happen that the feedback reports are lost as well. In order to avoid these situations, along with the feedback reports SAMMy keeps track of a timing function as well. The lowest quality level is considered to be the default, increasing it in a smooth manner. When SAMMy Feedback Interpreter receives the first negative feedback, a timer is started but the data will be sent at the same rate. If the subsequent feedback is a positive feedback, nothing happens. However if the timer expiries and no feedback was received within that period (e.g., the feedback report was lost) or the subsequent feedback is a negative feedback, then the quality level to be transmitted is decreased by one. Another timer is set to track the received and the lost positive feedbacks. In this situation, when ten consecutive positive feedback reports are received or the timer expires (e.g., missed feedback) the server will attempt to increase the quality level by one. The maximum achieved quality level depends on the Area the mobile user is located in. The two values (two and ten) were set based on the Auto Rate Fallback (ARF) mechanism [191] for IEEE 802.11. ARF is a rate adaptation scheme which was first proposed for Lucent Technologies WaveLAN-II networking devices and designed to switch rates between 1Mbps and 2Mbps. If a number of consecutive acknowledgment (ACK) frames are not received (e.g. two), the transmitter decreases the rate and starts a timer. The rate is increased only if another number of consecutive ACK frames are received (e.g. ten) or the timer's timeout occurs.

4.3.3. SAMMy Algorithm

As mentioned, the aim of SAMMy is to provide seamless multimedia adaptation, decrease the loss rate and consequently increase the user perceived quality level for video streaming applications in a wireless environment. SAMMy is a distributed solution, and comprises a server-side and a client-side module. The pseudo-code of the decision process handled by SAMMy is described in Algorithm 2.

At the client side, the signal strength and packet loss are monitored. Based on the receiver sensitivity and the maximum transmission range, the SAMMy Feedback Controller will divide the coverage area of the AP into a number of different Areas. For each defined Area, it allocates a maximum quality level that the user will be able to achieve in that particular area. The information about the user's maximum achievable quality level and the average packet loss rate is then encapsulated in a feedback report which is sent back to the server. At the server-side, the SAMMy Feedback Interpreter decides whether to decrease or increase the quality level based on the feedback received from the client. As mentioned, at the receipt of a negative feedback, a timer is started. If the subsequent feedback is a negative one or the timer expired, the server decides to decrease the quality level, and consequently the data transmission rate. The quality level is increased again only if ten positive feedbacks are received or a second timer expires.

Algorithm 2 SAMMy Adaptive Multimedia Algorithm

```
INPUT:
Signal Strength;
Receiver Sensitivity;
Maximum Transmission Range;
Feedback Report$_i$;
N Quality Levels with QL$_1$ – the highest quality level to QL$_N$ – the lowest quality level;

PROCEDURE:

SAMMy Feedback Controller – Client Side

Input:
Packet loss;
Signal Strength;
Receiver Sensitivity;
Maximum Transmission Range;

Procedure:
Compute M Thresholds: $\theta_1, \theta_2, ..., \theta_M$; - the thresholds are computed based on the receiver sensitivity and the maximum transmission range;

Define M Areas: $Area_0, Area_1, ..., Area_{M-1}$; - each area is delimited by the corresponding threshold previously computed;

Define QL$_{max}$ for each Area:
if Signal Strength $\epsilon$ $Area_0$ then $QL_{max} = QL_{1+0}$
elseif Signal Strength $\epsilon$ $Area_1$ then $QL_{max} = QL_{1+1}$
...
elseif Signal Strength $\epsilon$ $Area_{M-1}$ then $QL_{max} = QL_{1+M-1}$
end if

Output:
Feedback Report$_i$;  - includes packet loss information and the $QL_{max}$ achievable in that particular Area

SAMMy Feedback Interpreter – Server Side

Input:
Feedback Report$_i$;

Procedure:
Decision Making
if Feedback Report$_i$ = Negative Feedback then Start Timer1
if Feedback Report$_{i+1}$ = Negative Feedback or Timer1 expired then decrease QL by one
elseif Feedback Report$_i$ = Positive Feedback then Start Timer2
if Feedback Report$_{i+1}$ & Feedback Report$_{i+2}$ & … & Feedback Report$_{i+10}$ = Positive Feedback or Timer2 expired then increase QL by one (the maximum QL depending on the area the user is located in)
end if

Output:
Quality Level;

OUTPUT
Suitable Quality Level
```

4.3.3. SAMMy– Illustrative Example

For example, considering the case of an IEEE 802.11b multi-rate cell with the modulation schemes and receiver sensitivities as illustrated in Table 4.1 for a Cisco Aironet350 802.11b wireless card[1]. The SAMMy Feedback Controller will divide the coverage area of the AP into 5 different areas as illustrated in Figure 4.10. The thresholds for each Area were computed as follows. The threshold for Area 4, Θ_4 is given by the maximum transmission range threshold (RXThresh_). The following thresholds are computed based on the difference between the receiver sensitivity values. For example, based on the data presented in Table 4.1, the differences between two successive receiver sensitivities are as follows: -3, -2 and -4. Having Θ_4 = -75dBm, the rest of the thresholds would be: $\Theta_3 = \Theta_4 - (-3)$ = -72dBm; $\Theta_2 = \Theta_3 - (-2)$ = -70dBm; and $\Theta_1 = \Theta_2 - (-4)$ = -66dBm.

TABLE 4.1. Cisco Aironet350 802.11b wireless Card Specifications

Modulation Scheme	BPSK	QPSK	CCK5.5	CCK11
Theoretical Datarate [Mbps]	1	2	5.5	11
Receiver Sensitivity [dBm]	-94	-91	-89	-85
Range-outdoor (m)	610	457	305	244
Range-indoor (m)	107	76	61	46
RXThresh_	3.1622777e-11			
Transmit Power (mW)	100			

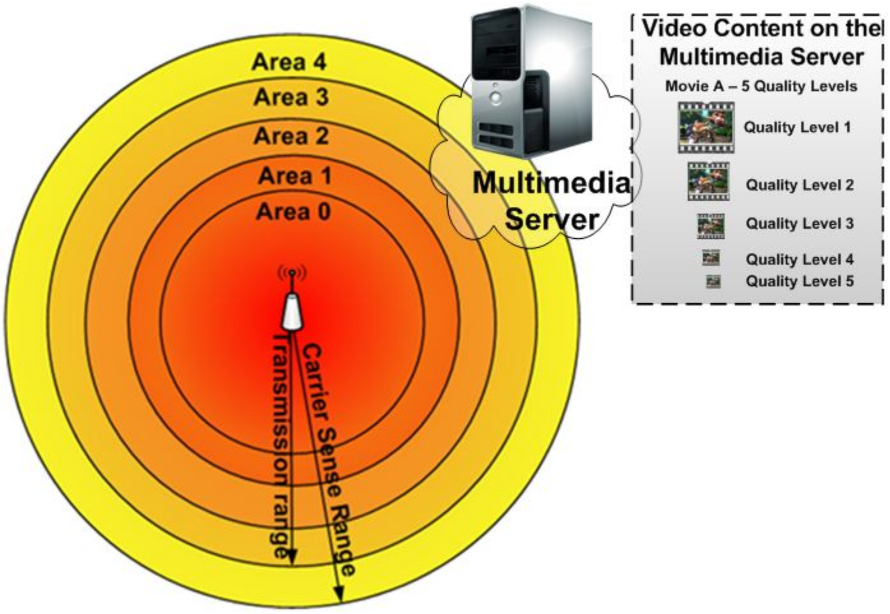


Figure 4.10. Divided AP Coverage Area-Illustrative Example

Assuming that the multimedia server stores a movie (e.g., Movie A) encoded at five different quality levels as illustrated in Figure 4.10 with Quality Level 1 (QL1) being the highest quality level and Quality Level 5 (QL5) the lowest quality level. For each defined Area there is a maximum QL, such that: Area 0 has QL_{max} = QL1, Area 1 has QL_{max} = QL2, Area 2 has QL_{max} = QL3, Area 3 has QL_{max} = QL4, and Area 4 has QL_{max} = QL5. This means that, for

---

[1] Cisco Aironet350 802.11b Wireless Card: http://www.cisco.com/en/US/prod/collateral/wireless/ps6442/ps4555/ps448/product_data_sheet09186a0080088828.html

example if the user is located in Area 1, then the maximum QL that can be achieved by the user in this area is QL2, and of course the minimum QL would be QL5. In this situation, SAMMy will perform the adaptation between QL5, QL4, QL3, and QL2, only.

An example of the Client-Server communication is illustrated in Figure 4.11. The mobile client will first detect the area the user is located in, and define QL_{max} which will be sent to the Server along with the Request for Movie A. The Multimedia Server will start the streaming service at the default quality level (QL5), presenting a quick start and increasing the quality level until it will reach QL_{max}. If the network conditions are good, the streaming will be maintained at the maximum possible quality level, according to the area the user is located in. If loss happens, congestion, or drop in signal strength, a negative feedback will be send to the server. At the reception of two negative feedback reports, the server will start decreasing the quality of the multimedia stream. If the network conditions are improving, the client will start sending positive feedback reports to the server. After receiving ten positive feedback reports the server will start improving the quality of the multimedia stream.

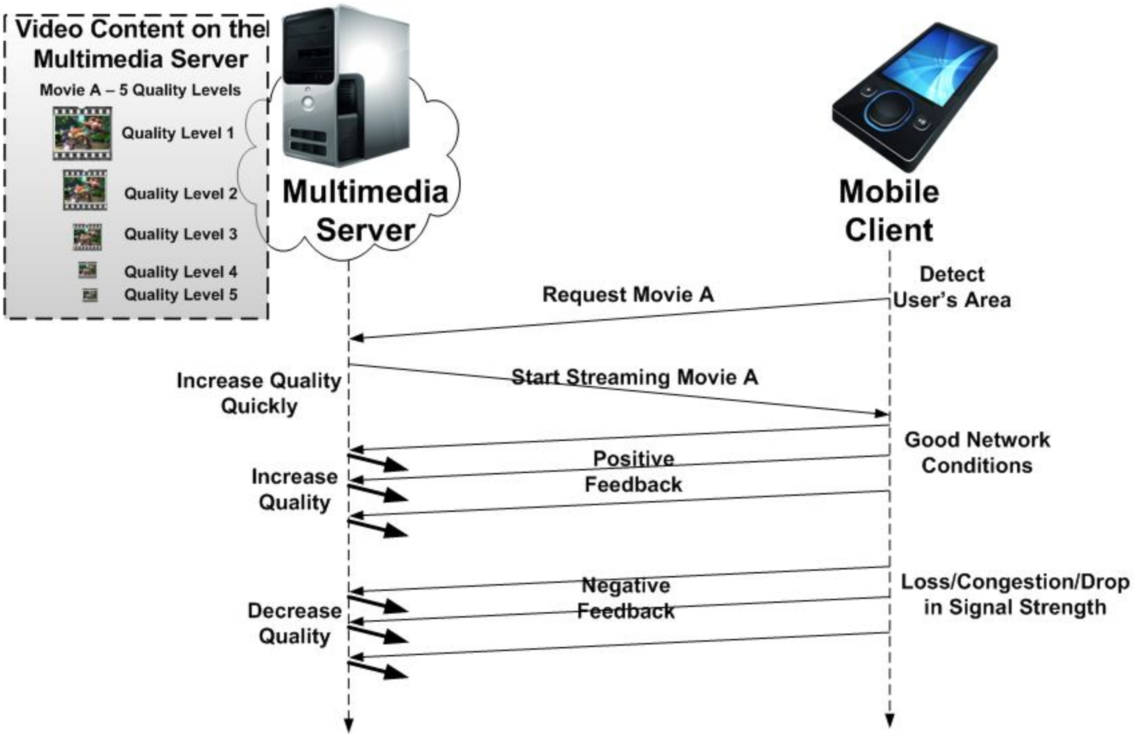


Figure 4.11. Client-Server Communication Example

4.4. Adapt or Handover Solution

Going back to Jack's path from his home to his office (see Figure 4.1), Jack is moving now towards Point C. As illustrated in Figure 4.12, he will be facing the decision **Adapt or Handover**. Having a number of available wireless networks (e.g., UMTS, WLAN A, and WLAN B) each of them supporting the multimedia delivery of different quality levels, the question that Jack is facing, in terms of energy efficiency, is: is it better to adapt the multimedia stream, or is it better to handover to a new network?

The proposed **Adapt-or-Handover** solution is designed to help Jack in this situation, and can take the decision on Jack's behalf. The Adapt-or-Handover solution represents a hybrid multimedia delivery mechanism that makes use of both the adaptive multimedia delivery mechanism (SAMMy) and the network selection mechanism (PoFANS). The aim is to achieve maximum power savings in a heterogeneous wireless environment while maintaining a certain level of user perceived quality.

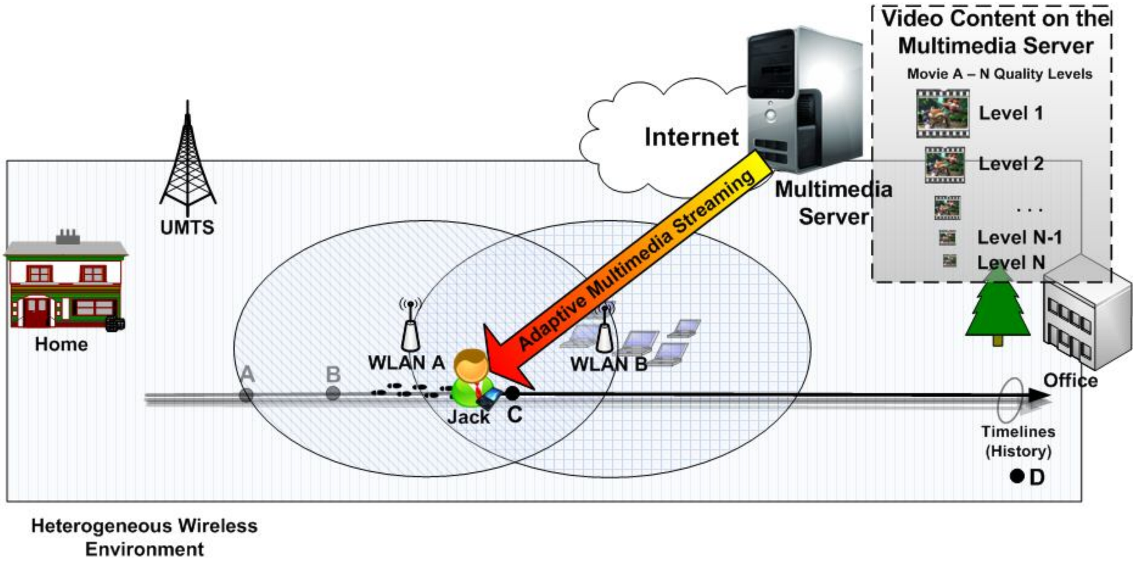


Figure 4.12. Adapt-or-Handover Illustrative Example

4.4.1. Adapt-or-Handover Architecture

The need for battery efficient devices and integrated power management tools represent a strong motivation to propose a hybrid multimedia delivery Adapt-or-Handover solution. The Adapt-or-Handover solution balances adaptive multimedia delivery and network selection in order to improve energy conservation on the end-user mobile device, while maintaining good user perceived quality levels.

Figure 4.13 illustrates the Adapt-or-Handover architecture based on the TCP/IP protocol stack model. As noticed in the figure, the Adapt-or-Handover solution resides at the application layer, combining the two previously proposed mechanisms (PoFANS and SAMMy) and providing a middleware framework for multimedia delivery. The block architecture and functionality of PoFANS and SAMMy are the same as previously described in this Chapter.

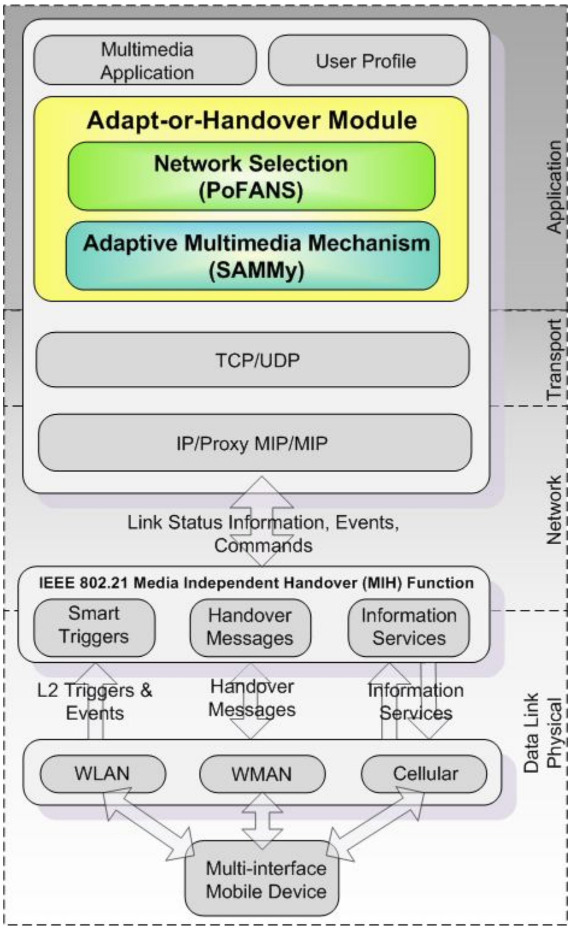


Figure 4.13. Adapt-or-Handover Overview Architecture

The Adapt-or-Handover solution, illustrated in Figure 4.13, is proposed to combine the benefits of the network selection mechanism (PoFANS) and the adaptive multimedia mechanism (SAMMy) in order to increase power savings. The basic principle behind the Adapt-or-Handover solution and a detailed description of the algorithm is further addressed in the next sections.

4.4.2. Adapt-or-Handover – Basic Principle

Figure 4.14 illustrates the Adapt-or-Handover basic principle. In the first step the network selection mechanism (PoFANS) and the adaptive multimedia mechanism (SAMMy) are enabled on the mobile user device. Imagine again the case of Jack being located in an area with a number of available wireless networks as illustrated in Figure 4.12. Each of the available networks can deliver a certain number or any of the quality levels located on the multimedia server depending on their network conditions. This list of available networks, together with the quality levels that they are able to provide are used as an input for PoFANS. This time, PoFANS will score each network and each quality level provided by a certain network. For example, if there are M available networks and each network can deliver any of the N Quality Levels located on the Multimedia Server, then the PoFANS mechanism will have a number of MxN options to choose from. The output of PoFANS will be a ranked list of these MxN options. The option that has the highest score is selected as the target network and target quality level. After Jack connect to the best value network chosen by PoFANS, the adaptive mechanism SAMMy will set the maximum quality level as the target quality level provided by PoFANS. SAMMy is enabled at all times and works as previously introduced in Section 4.3.

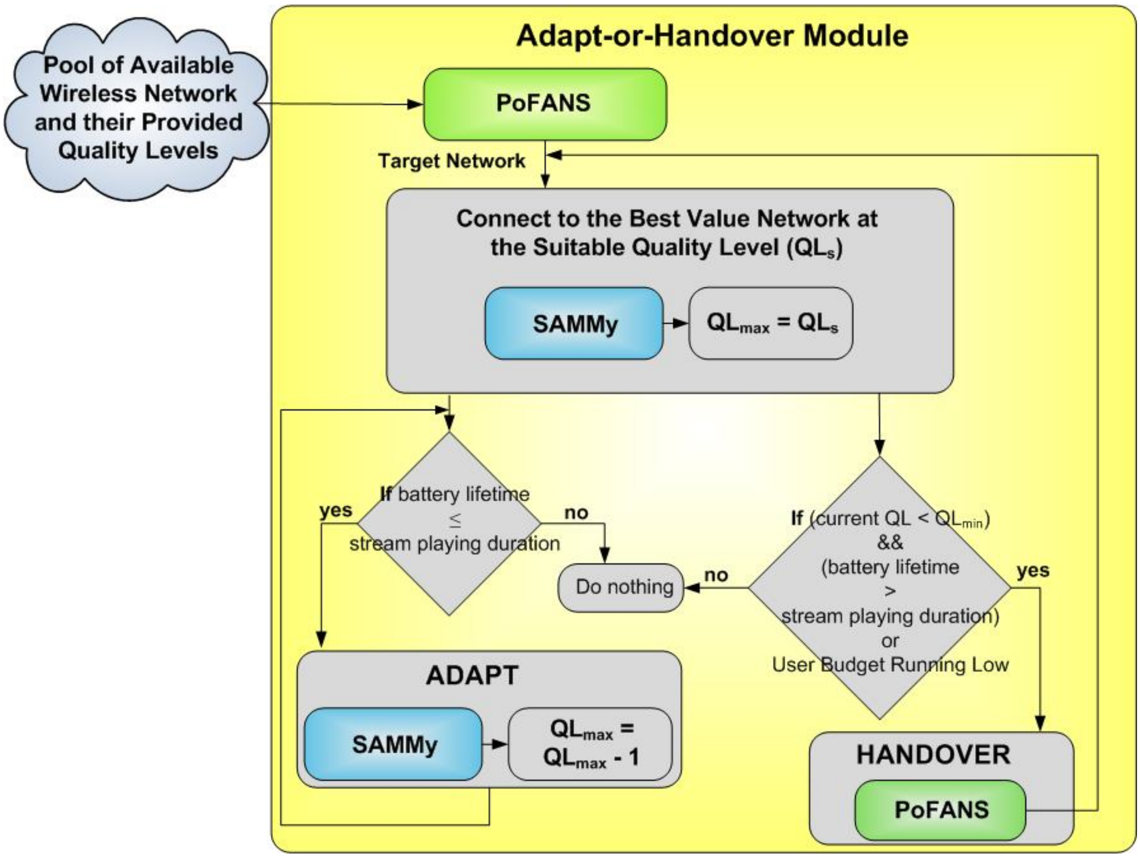


Figure 4.14. Adapt-or-Handover Basic Principle

The Adapt-or-Handover solution will decide to adapt the multimedia stream only if the battery lifetime of the mobile device is less than the stream playing duration. In this case the maximum quality level provided by SAMMy will be decreased by one.

On the other hand, the Adapt-or-Handover solution will trigger the handover process, only if the current quality level is lower than the minimum acceptable quality level of the user and the mobile device has enough battery lifetime to play the multimedia stream, or the user budget is running low so he has to handover to a cheapest network. The minimum acceptable quality and the user budget level of the user are taken from the User Profile as explained in Section 4.2.

If the device does not have enough battery lifetime to handover to a new network, then the handover is canceled and the energy conservation will get higher priority. In this case SAMMy will adapt the quality level so that the stream will have enough battery to play till the end.

4.4.3. Adapt-or-Handover Algorithm

As mentioned, the Adapt-or-Handover solution balances adaptive multimedia delivery (SAMMy) and network selection (PoFANS) in order to improve energy conservation at the end-user mobile device. The pseudo-code of the decision process handled by the Adapt-or-Handover solution is described in Algorithm 3. The Algorithm follows the basic principle of the Adapt-or-Handover solution previously described.

Algorithm 3 Adapt-or-Handover Decision Algorithm

```
START:

  PoFANS Decision
    Input:
      M Available Wireless Networks;
      N Quality Levels;
    Procedure:
      MxN Options;
      Rank Options;
    Output:
      Connect to Target network;
      Target QL;

  SAMMy Decision
      $QL_{max}$ = Target QL;

ADAPT DECISION
  if (battery lifetime ≤ stream playing duration) then
          ADAPT - SAMMy Decision
          $QL_{max} = QL_{max} - 1$;
  end if;

HANDOVER DECISION
  if (current QL < $QL_{min}$) && (battery lifetime > stream playing duration) || (User Budget running low)
     then
          HANDOVER - PoFANS Decision
          Go to START;
  end if;
```

4.5. Reputation-based network selection mechanism

Recall Jack's path as illustrated in Figure 4.1. Jack is a business professional, who likes to access multimedia applications while going from home to his office. In order to help Jack on his path, several mechanisms were proposed, such that: at point A, a novel network selection mechanism (PoFANS) helps Jack on selecting the best value network; when reaching point B, an adaptive multimedia mechanism (SAMMy) helps Jack to cope with the wireless errors, and maintains an acceptable perceived quality level of the multimedia application, whereas at Point C, an Adapt-or-Handover solution helps Jack on deciding, in terms of energy efficiency, whether to adapt the multimedia stream or to handover to a new network.

As Jack takes the same path every day, he will be crossing the same networks, as illustrated in Figure 4.15 at point D. This enables the possibility of building a history with the network operators. In this context, a reputation-based network selection mechanism is proposed. The mechanism makes use of game theory in order to model the user-network interaction.

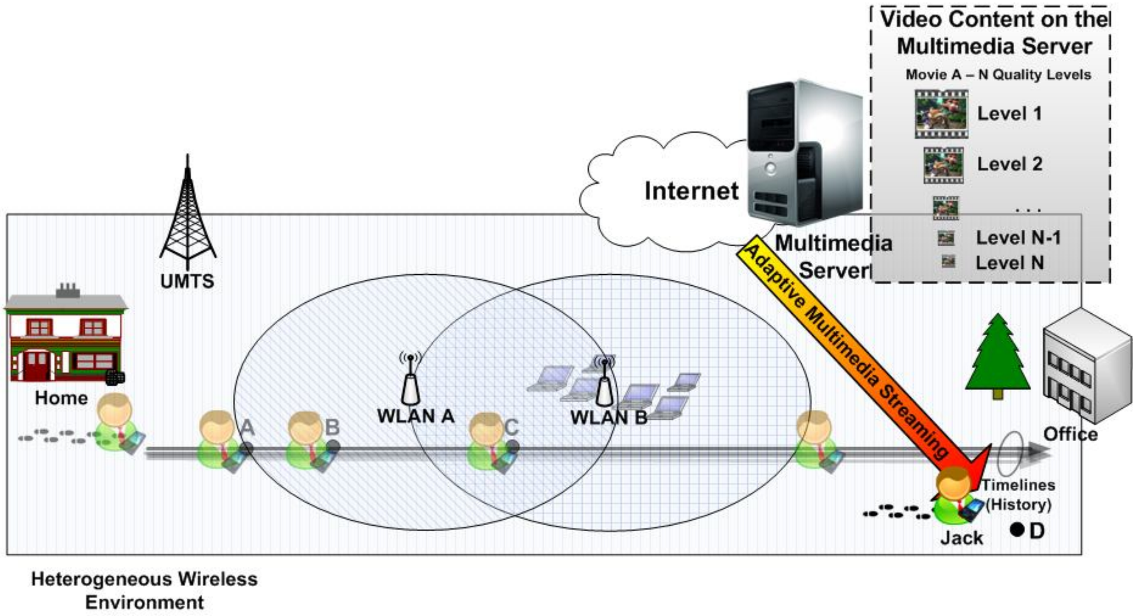


Figure 4.15. Jack's Daily Routine – Full Scenario

4.5.1. Reputation-based Network Selection Architecture

The reputation-based network selection solution is based on the network selection mechanism (PoFANS) previously described in Section 4.2. Figure 4.16 illustrates the general overview of the proposed reputation-based network selection architecture based on the TCP/IP protocol stack model. As PoFANS, the reputation-based network selection resides at the application layer. The idea behind this proposed solution is that each user can have different interactions with different network operators, depending on the user preferences and service requirements. As a result of this interaction a reputation factor can be computed for that particular network operator. For example, if the user was satisfied with the offered services, the network will receive a higher reputation value reflecting the user satisfaction. The detailed functionality and basic principle of the algorithm is further described.

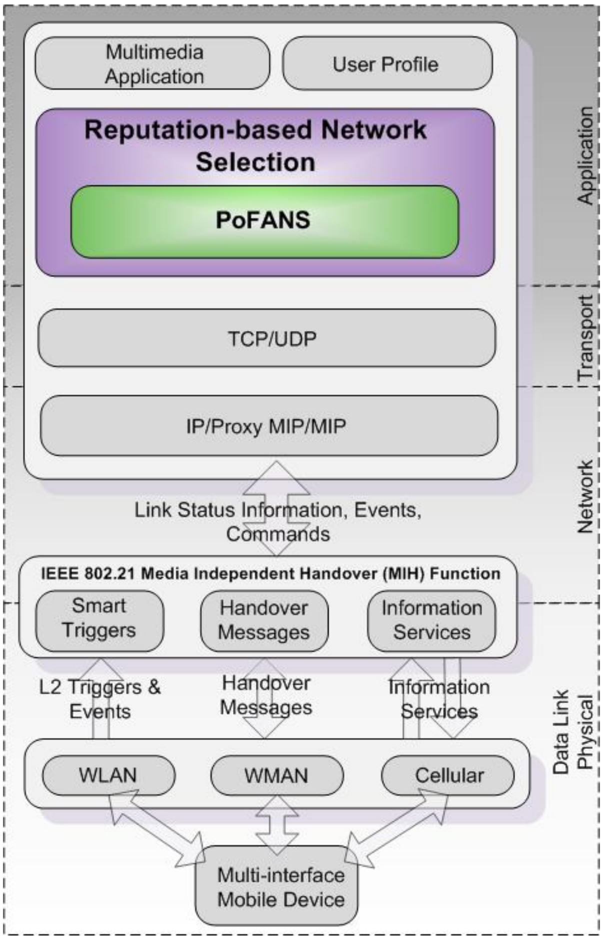


Figure 4.16. Reputation-based Network Selection Overview Architecture

4.5.2. Reputation-based Network Selection – Basic Principle

The proposed reputation-based network selection mechanism aims at building a reputation-based system between the users and the networks they are visiting. This is done by making use of the **repeated cooperative game** from **Game Theory** in order to model the user-network interaction and to compute the reputation of the network as illustrated in Figure 4.17. The proposed solution represents in fact an extension of the previously proposed PoFANS solution described in Section 4.2. Having a pool of available wireless networks and their provided quality levels, the Adapt-or-Handover solution is enabled on the mobile device. First the PoFANS mechanism will select the best value network, and the target quality level. After the user connects to the target network, the repeated cooperative game starts. The user-network interaction is modeled as a repeated game using game theory. The outcome of the game is a network reputation factor which will be stored in the Operator Profile (Section 4.2), on the user's mobile device and will be used by the PoFANS Score Generator. At the end of every user-network interaction, a network reputation factor is computed which will impact the score of each network next time the network selection takes place.

The same principle as PoFANS is used, the only difference is in the definition of the score function, as given in equation (4.11).

$$U_i = \varphi_i[u_{e_i}^{w_e} \cdot u_{q_i}^{w_q} \cdot u_{c_i}^{w_c} \cdot u_{m_i}^{w_m}] \qquad (4.11)$$

where: U – overall score function for RAN i; φ_i is the reputation factor of RAN i; u_e, u_q, u_c, and u_m are the utility functions defined for energy, quality, monetary cost for RAN i, and user mobility respectively; and w_e, w_q, w_c, and w_m are the weights for the considered criteria, representing the importance of a parameter in the decision algorithm. The definition and acquisition of the variables, except the reputation factor were introduced previously in Section 4.2. For this reason, these aspects will be skipped in this section, introducing only the novelty issues as compared to PoFANS.

The network reputation factor φ_i, represents the degradation observed by the user in his/her past interactions with the network i, the higher the value of the network reputation factor the smaller the observed degradation. φ has values within the [0,1] interval, and no unit of measurement. A more detailed description of the network reputation factor is given later in the next section.

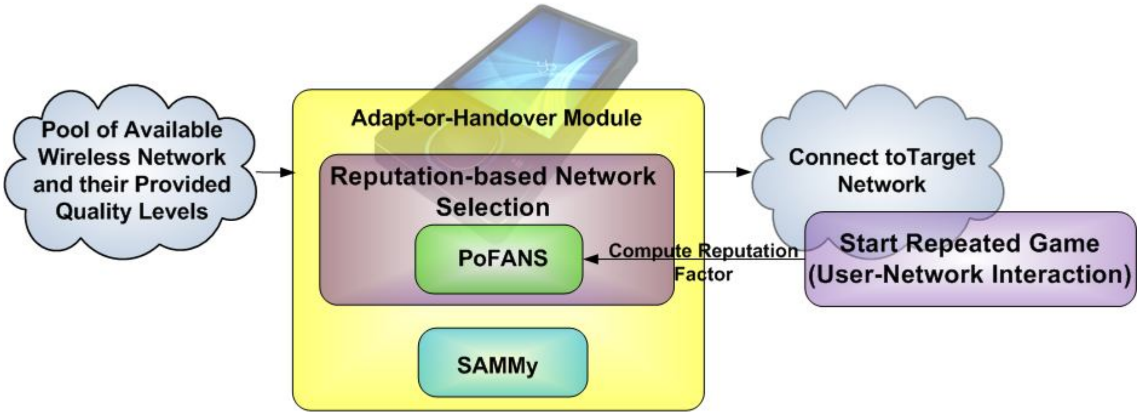


Figure 4.17. Reputation-based Network Selection Basic Principle

The repeated game between the user and the network is modeled as a **Two Player Repeated Cooperative Game** from Game Theory. The game formulation and the game components are further described in the next section.

4.5.3. Two - Player Repeated Cooperative Game Formulation and Components

In order to study the interaction between the user and the network, game theory is used and the problem is formulated as a cooperative **repeated Prisoner's Dilemma game** (see Figure 4.18). The user and the network cooperate in order to achieve **Nash Equilibrium**. The aim is to reach both the user and the network satisfaction. The outcome of the game is a network reputation factor that will be further used in the network selection process.

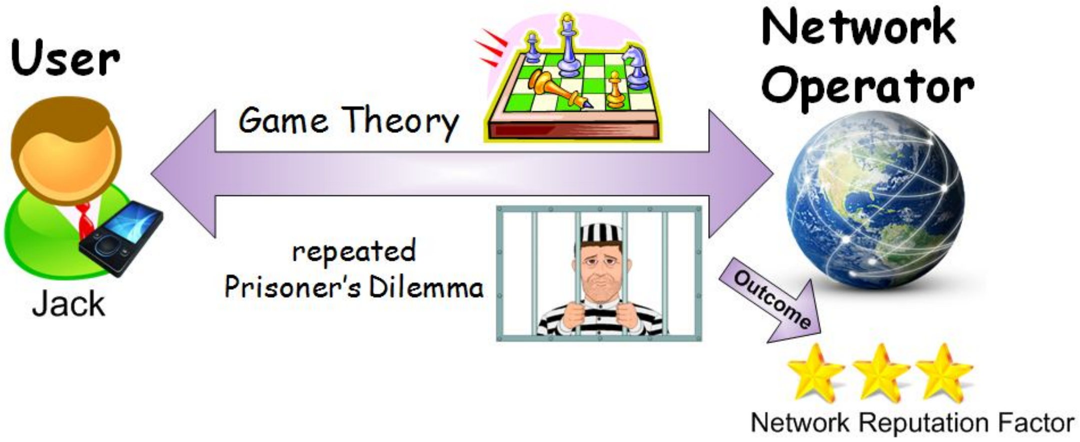


Figure 4.18. User-Network Interaction

The game can be defined as follows:

- **Players:** The players in this game are the user and the network.
- **Strategies:** Following the model of the repeated Prisoner's Dilemma game, a set of three strategies for each player are defined.

The **user strategies** are:

- *Cooperat*e: the user accepts the network's offer and stays;
- *GRIM:* always cooperate as long as the network cooperates;
- *Defect:* the user decides to leave the network if the network does not offer the minimum requested QoS, or a better offer is available;

The **network strategies** are:

- *Cooperate:* the network accepts to maintain the QoS at the required level for the user;
- *GRIM:* always cooperate as long as the user cooperates;
- *Defect:* the network decides not to fulfill the QoS requirements of the user anymore, acting selfishly by trying to increase its own revenue and admitting new users to a crowded cell, attempting to accommodate more users at the cost of a reduced level of quality for some/all existing users;

The *GRIM* strategy is the one in which the players *Cooperate* as long as the opponent does the same. If one of the players fails to reciprocate, the opponent will switch to *Defect* permanently or temporarily. If the network *Defects* then the value of the network reputation factor α is decreased. This will impact the network's score next time the Network Selection Decision takes place.

- **Payoffs:** the payoff functions for the user and the network are defined as follows:

- *User payoff function*

Each player's gain when playing the repeated cooperation game is defined through payoff functions. The user satisfaction and the perceived quality of the service are two directly proportional factors. As seen in Figure 4.4, the quality of the service is an increasing function of the average received throughput. In order to have a non zero utility for the user satisfaction a minimum amount of throughput is needed. At the other extreme, if the received throughput is more than the maximum needed for the service, the improvement in the quality is unnoticeable for the human viewers. When the received throughput is in between the two thresholds, Th_{min} and Th_{max}, the utility presents significant changes. In order to avoid brutal changes in the quality by jumping from a high quality level to a low quality level, which can be disturbing for the user, an adaptive multimedia mechanism is integrated (e.g., SAMMy). SAMMy can smoothly change from one quality level to another with reduced impact on the user satisfaction. The overall user satisfaction is represented by the score function (equation (4.11)) which finds a trade-off between the quality of the service, the energy consumption of the mobile device, and the monetary cost that the user has to pay for the required service.

In this context, the user payoff (π_M) is defined as in equation (4.12). π_M for the user can be expressed as the difference between the benefit obtained in terms of service quality (score function) and the cost incurred, as the price paid by the user for the specific service.

$$\pi_M = U_i * B - C_i + P_{new} - C_{HO} \qquad (4.12)$$

where: π_M - user's payoff (euro), U_i - the score function of the current network i (values within [0,1]), B – the user's budget (euro), C_i – the cost of the current network i (euro), P – the user's payoff if he/she would handover to a new network (is 0 when the user Cooperates) (euro), C_{HO} – the cost of handover to a new network (is 0 when the user Cooperates) (euro).

- *Network payoff function*

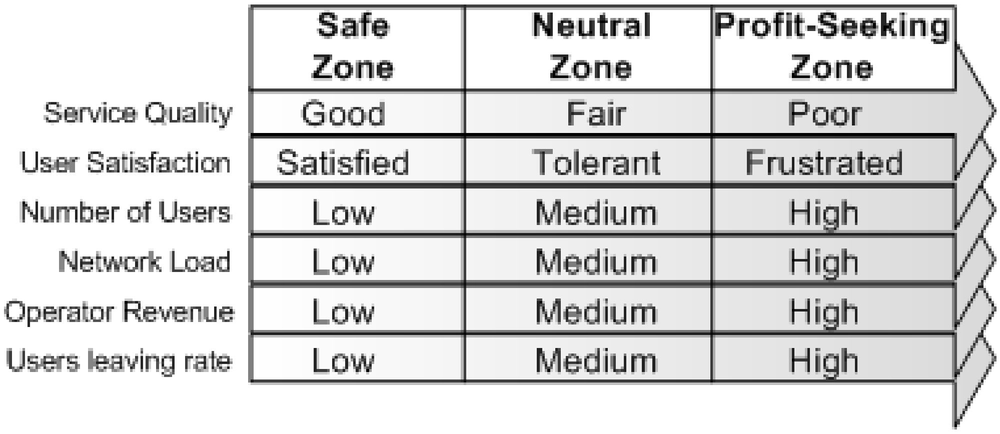
On the network operators' side the operator's attitude towards long-term and short-term gains in profit can be identified. If the network acts selfishly by trying to maximize its own revenue, then the immediate maximization of its payoff would be the increase in the number of customers. However, admitting a large number of users into one network is not always the best option when trying to maximize the profit for the service. Admitting more and more users into one cell or AP generates the risk of degrading the service quality of experience (QoE) for the already connected users. As the number of admitted users increases, the quality of the service decreases which leads to users leaving the network and a corresponding decrease in revenue for the operator.

The network payoff, π_N is defined as in equation (4.13):

$$\pi_N = G - C_{QoS} - L_{rev} \quad (4.13)$$

where: π_N – network's payoff (euro), G – the network gain (money gained from user payments for the services used in the network) (euro), C_{Qos} – the cost paid by the network for the current QoS provisioning (euro), L_{rev} – the loss of revenue in case the user decides to defect/leave the network (is 0 if the user Cooperates) (euro).

For example, the operator's attitude towards profit gains can be divided into three zones: **safe zone, neutral zone**, and **profit-seeking zone**. In the **safe zone**, the network operator works on the principle: *'accept less rather than lose everything'*. It is assumed that there is a minimum number M_{min} of users which can be accepted into the network without interfering with each other, ensuring high quality levels of the multimedia services for all the users in the network. The aim of the operator in this zone is to keep the number of users within a minimum threshold. In the **profit-seeking zone** the network operator is looking to increase his revenue on a short-term basis. He is taking the chance of admitting a large number of users (more users, more revenue) into the network with a high increase in the probability of users leaving the network, being unsatisfied with the services (more users, more load, low service quality). The **neutral zone** is somewhere between the safe zone, and profit-seeking zone. In this zone the network operator has an indifferent attitude. He is willing to accept more users as long as the number does not exceed M_{max}. M_{max} represents the maximum number of users which can be accommodated in the network maintaining the average quality utility of the system below the profit-seeking zone. Figure 4.19 illustrates the variation of different parameters over the three zones. As approaching the profit-seeking zone, the service quality provided to the user is decreasing leading to a frustrated user. In the profit-seeking zone the operator's revenue will reach a short-term maximum, by serving a high number of users with the risk of increasing the users leaving rate.



	Safe Zone	Neutral Zone	Profit-Seeking Zone
Service Quality	Good	Fair	Poor
User Satisfaction	Satisfied	Tolerant	Frustrated
Number of Users	Low	Medium	High
Network Load	Low	Medium	High
Operator Revenue	Low	Medium	High
Users leaving rate	Low	Medium	High

Figure 4.19. Operator's Attitude Zones – Example

The basic principle of the Repeated Game is illustrated in Figure 4.20. Imagine again Jack, located in an area where he has a number of available wireless networks. In these settings he enables the Reputation-based Network Selection mechanism so that the best value network is selected. The proposed mechanism is based on PoFANS and adds the use of a reputation factor when generating the score for each available network, as previously explained. At the first interaction between Jack and the new network, the reputation factor will be 1, as Jack does not have any history with that particular network. After the best value network is selected, the **repeated game starts**. The **Network Moves Monitor** module will monitor the network's move, and when the network plays *Defect* meaning that the network does not fulfill Jack's QoS requirements, or when Jack plays *Defect*, meaning that Jack decides to leave the network even though the QoS requirements are fulfilled, the computation of the network reputation factor is triggered. That means that the user-network interaction has ended, and the **Compute Network Reputation Factor** module will compute the reputation factor for the current network. This network reputation factor will be sent to the Reputation-based Network Selection module, and stored in the Operator's Profile data base of the Data Collector module of PoFANS, on Jack's mobile device (see Section 4.2.1.1). The network reputation factor will be then used when the next network selection process takes place.

The computation of the network reputation factor is further detailed in the next section.

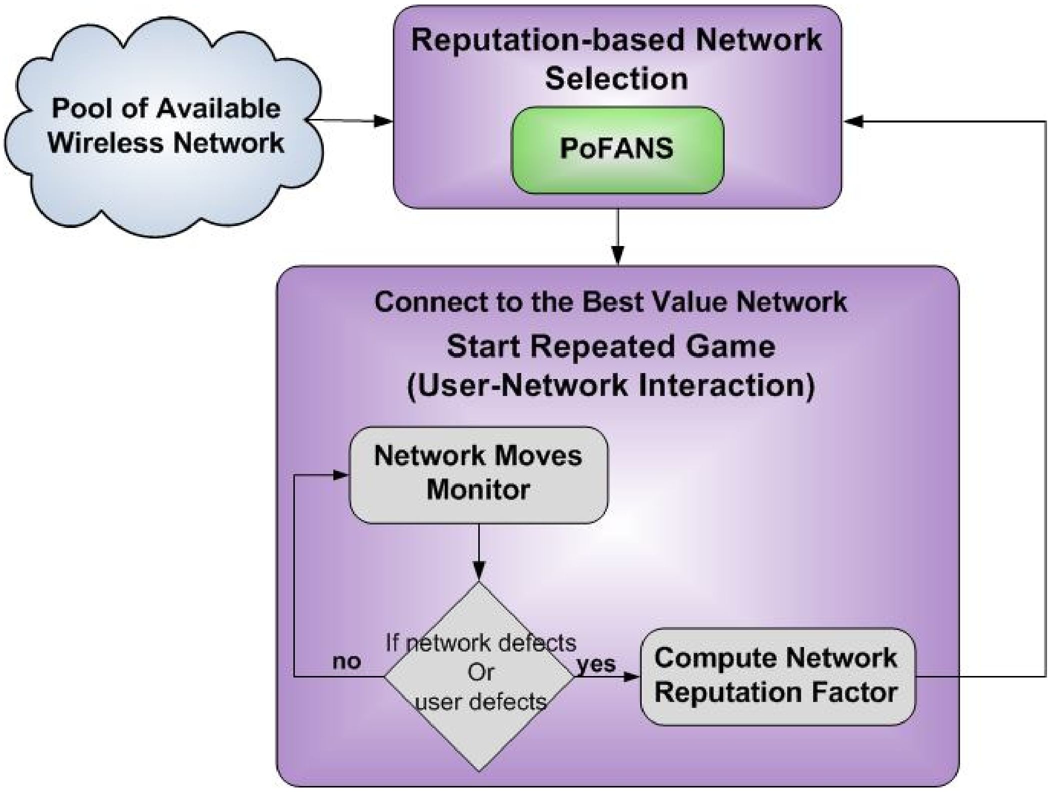


Figure 4.20. Repeated Game - Basic Principle

4.5.4 Network Reputation Factor

In order to strengthen the cooperation between users and networks by keeping track of past behavior, a network reputation factor is defined. This reputation factor is then considered in the network selection decision. φ is computed based on the user's past interactions with the network. It is assumed that at the first contact between user and network, $\varphi = 1$, meaning that the network reputation factor will not have any impact on the selection as there is no history between the user and the network.

Assuming a mobile user which had a number of *n* past interactions with a network *i*, a simple computation of φ_i can be given by equation (4.14):

$$\varphi_i = \sum_{j=1}^{n} u_{\pi_{ji}} \Big/ n \qquad (4.14)$$

where, $u_{\pi_{ji}}$ represents the normalized value of the user's average payoff at the end of interaction *j* with network *i*. The normalized value is computed using equation (4.15). The normalization function of the payoff follows the principle 'the larger the better'.

$$u_\pi(\pi_M) = \begin{cases} 0 & , \quad \pi_M < \pi_{M_{\min}} \\ \dfrac{\pi_M - \pi_{M_{\min}}}{\pi_{M_{\max}} - \pi_{M_{\min}}} & , \quad \pi_{M_{\min}} <= \pi_M < \pi_{M_{\max}} \\ 1 & , \quad otherwise \end{cases} \qquad (4.15)$$

where u_π represents the payoff normalization function; π_M - user payoff; $\pi_{M_{\min}}$ - the minimum possible payoff that the user can get; $\pi_{M_{\max}}$ - the maximum possible payoff the user can get from the user-network interaction.

In equation (4.14), both the most recent interaction as well as the oldest are given the same importance. Considering the fact that people tend to remember recent experience more than the past ones [192], a weight for each interaction is defined. In this way the reputation computation becomes more dynamic preventing the case in which an operator, after getting high reputation in the past, can change his/her attitude by acting selfish, in the recent times. For this reason the present interactions will have a higher weight which will reduce smoothly as the interaction becomes older.

The network reputation factor, φ for a network *i*, is defined based on the age of the interaction as given in equation (4.16):

$$\varphi_i = \sum_{j=1}^{n} w_{ji} u_{\pi_{ji}} \Big/ n \qquad (4.16)$$

where w_{ji} represents the weight assigned to interaction j with network i.

The weight of the interaction is computed using equation (4.17):

$$w_{ji} = (e^{(j-n)/\rho} - 1) \big/ (e^{-n/\rho} - 1) \qquad (4.17)$$

where j is the interaction with network i, n is the total number of interactions, ρ (Rho) is the importance tolerance of the weights.

The values of w_{ij} are within [0,1] interval, with 1 representing high importance and 0 representing low importance. This is based on the idea that recent interactions are given higher importance which is reduced with time passing. For example, imagine the scenario of Jack, having a choice of two available networks. Jack has a past history of six interactions with each of the two networks. The weights for each interaction are computed using equation (4.17) with n=6 and using different values for ρ (e.g., 1, 2.5, 5, and 10). By varying the values of ρ the importance tolerance of the weights in the final decision is analyzed. Figure 4.21 illustrates the assigned weights for each of the six interactions and for varying values of ρ.

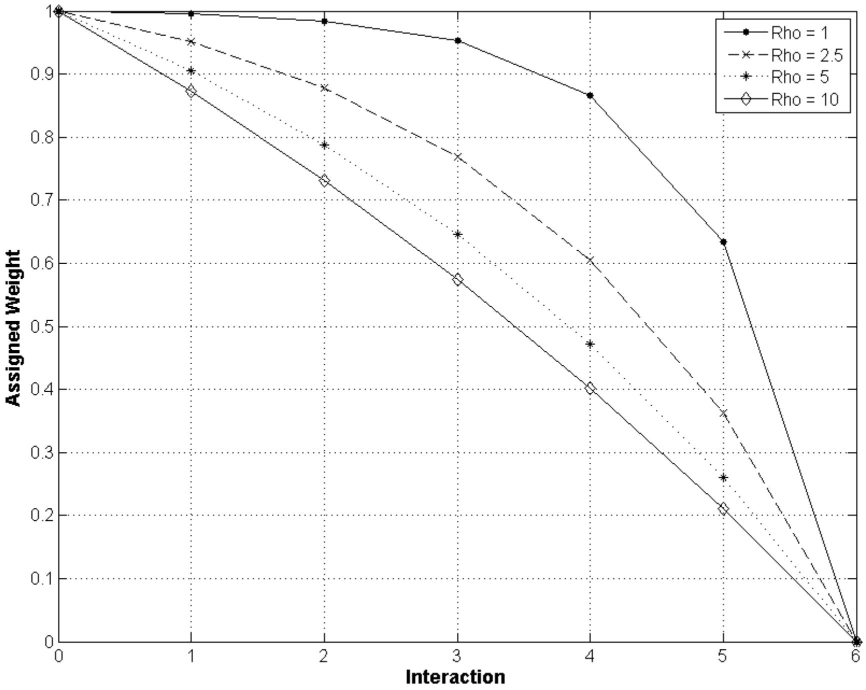


Figure 4.21. Interaction weights for different values of ρ

On the X axis the number of interactions is represented, with 0 being the most recent interaction and 6 being the oldest interaction. As only the last 6 user-network interactions are considered, the 7th interaction's (represented by 6 on the X axis) weight is zero. On the Y axis the assigned weight is illustrated, the most recent interaction is the most important, its weight being 1. As it can be noticed, for small values of ρ (e.g., 1 or 2.5) the assigned weights' utility is gradually becoming less important as the interactions become older. For higher values of ρ (e.g., 5 or 10) the assigned weights' utility is decreasing faster, almost linearly, as the interactions become older. In this work, the value of ρ is considered to be 2.5, as it presents a more gradual decrease in the importance tolerance of the user-network interactions.

Note that the reputation factor for each of the networks considers the last *n* interactions with any of the networks. These *n* interactions can be more frequent with some of the networks more than with others. Meaning that the interactions with a certain network can happen over the last few days whereas the interactions recorded for another network could have taken place over the last year. This aspect is not considered by the reputation factor presented here but it could be considered as part of future work.

4.6. Technical Considerations and Assumptions

Recall Jack's decisions on his way from home to his office, illustrated in Figure 4.22. Jack can represent the case of a business professional, student, etc. who wants to be always best connected to the Internet in order to access multimedia content while on his regular commute to work. As seen in this chapter, several solutions were proposed in order to help Jack along his path, and maintain an acceptable user perceived quality of the multimedia application while considering the energy conservation of the mobile device.

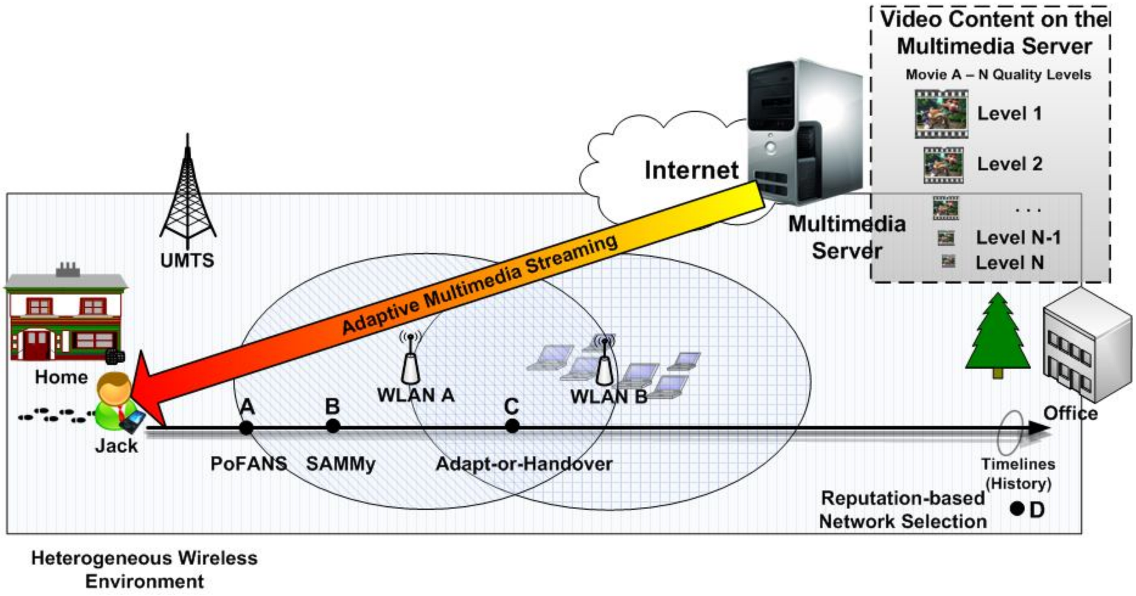


Figure 4.22. Heterogeneous Wireless Environment – Jack's Daily Routine

In this thesis the network selection decision (PoFANS) is designed for a single multi-interface user device, running only one application (video delivery) at a time, while using a single link connection with one of the available RANs. The discovery process of the available RANs is not part of PoFANS, so it is not addressed in this thesis. The link setup and handover execution are not addressed either.

As seen, PoFANS takes into consideration several parameters, such as: user preferences, received throughput, energy consumption of the mobile device, the monetary cost, and user mobility. The user preferences are used to weight the other parameters involved (e.g., quality, energy, cost, etc.) and they are taken from the User Profile, as described in Section 4.2. There are many ways of gathering the data from the user. For example, in [60][61] the authors propose probing the user while the authors in [193] obtain the weights through questionnaires on user and service requirements. Another solution makes use of a GUI in the user's mobile terminal in order to collect the user preferences. One solution could be taking the user preferences at start-up time of the mobile terminal, and trying to minimize the user interaction by integrating an intelligent learning mechanism that could predict the user preferences over time. Of course the user will still have the possibility to manually set his/her preferences. In order to collect information about the available networks (e.g., available throughput, monetary cost, etc.) the use of IEEE 802.21 standard is proposed.

In this context, the present thesis does not provide/implement any mechanism for gathering the information. However different existing ways/protocols that can be used in order to gather the required information were outlined in this chapter. It is assumed that the information is available at the client-side. All these gathered parameters are then used in evaluating the network selection strategy. The proposed network selection score function is the core of the network selection process, and the main focus of this thesis. PoFANS is designed to select the best value network for the user. After the target network is selected, the handover process is triggered. The handover process itself is not part of PoFANS, so it is not part of this thesis.

As mentioned, PoFANS was designed for single user scenario having a single link connection with a certain network at a time. This means that the group user scenarios, group handover, or single user multiple connections scenario are also not addressed in this thesis. Group user scenarios are the scenarios in which multiple users, travelling in group (e.g., bus), are using the same network selection mechanism with similar preferences, leading to group handover. Single user multiple connections scenario, represents the scenario in which one user will access the application though multiple connections/interfaces simultaneously, so the traffic will be split among the connections and resulting available bandwidth to the device is increased.

The adaptive multimedia mechanism (SAMMy) was designed and tested only for WLAN networks. The mechanism can be adapted to work with cellular networks as well. However this is not in the scope of this thesis as the Adapt-or-Handover solution, was designed to cover the cellular networks. The functionality of each proposed mechanism was previously described in this chapter. Similar with PoFANS, the information acquisition for SAMMy is not the purpose of this thesis, however ways and protocols for information acquisition were outlined (e.g., the use of the IEEE 802.11k standard). All this information is considered to be available at the client-side.

4.7. Chapter Summary

This chapter presents the proposed system architecture, highlighting the main functionalities, basic principle, and algorithm of each proposed solution. The four main contributions of the thesis are as follows:

- **PoFANS - Po**wer-**F**riendly **A**ccess **N**etwork **S**election Strategy which is modeled as a multiplicative exponential weighted (MEW) function taking into consideration the energy consumption of the mobile device when running real-time applications, the monetary cost of the network, user mobility, application requirements, and estimated network conditions in terms of average throughput. The benefit of the proposed algorithm is that it bases its decision on the estimated energy consumption which enables the battery lifetime of the mobile device to last longer while running multimedia services and maintaining an acceptable user perceived quality by selecting the least power consuming network. The novelty of the proposed mechanism is that it finds a good trade-off between energy consumption and user perceived quality levels.
- **SAMMy** – **S**ignal Strength-based **A**daptive **M**ulti**M**edia Deliver**y** Mechanism for wireless networks which makes use of 802.11k radio measurements in order to collect information on the radio interface, and the location of the mobile node relative to the access point (AP). The novelty of the proposed mechanism is that it takes into consideration the **dynamics of the RF environment** by considering the **RSSI** together with **packet loss** in the adaptive decision. Mobile radio stations predict their receive power based on location and estimated current path, and based on that receive power and packet loss, the station requests the multimedia streaming source to adjust the transmission rate in advance. The benefit of the proposed mechanism is that it makes use of the information about user location, receive signal strength, and packet loss, seamlessly adapting the multimedia stream, decreasing the loss rate and increasing the user perceived quality level for video streaming applications in wireless networks while providing a fair share of bandwidth.
- **Adapt-or-Handover** represents a hybrid multimedia delivery solution which combines the adaptive multimedia delivery mechanism (SAMMy) with the network selection solution (PoFANS). The proposed solution makes use of user preferences, location-based and network related information in order to decide **when to adapt the multimedia stream** or **when**

to handover to a new network, acting in the user's best interest and achieving maximum power savings.

- **Reputation-based Network Selection Mechanism** represents an extension of PoFANS by making use of **Game Theory** and defining a network reputation factor, in the network selection decision. The main focus is on the user-network interaction. A **two-player repeated cooperative game** is formulated using the model of **repeated Prisoner's Dilemma** and the main components of the game are described. Using the cooperative approach, it is assumed that players will cooperate in order to **maximize their payoffs**. In a realistic scenario, players may choose to cheat or to behave selfishly by seeking to optimize their own payoffs. The equilibrium of the game is analyzed is Chapter 7 where it is shown that by defining **incentives for cooperation** and **disincentives against cheating** or selfish behavior, **repeated interaction leads to cooperation**.

Consider the heterogeneous scenario where users have a pool of choices with different RANs belonging to different operators and users are able to freely choose between them without any contractual agreement. In this situation there is a need for an **assurance of service guarantees from both parties**. The repeated user-network interaction can be seen as an **ongoing relationship** in which by using cooperative game theory it is shown that **cooperation can be sustained without a contract**.

Chapter 5

Experimental Testing: Environment, Scenarios, Results and Analysis

As there is little analysis in the literature on the relationship between the wireless environment and the mobile device energy consumption, this section investigates the impact of network-related factors (e.g., network technology, network load, signal quality level, location, etc.) on the power consumption of the mobile device in the context of video delivery.

This chapter presents the real test-bed environment setup in which the measurements were conducted. It investigates the energy consumption of an Android mobile device and the efficiency of the system in several scenarios while performing video delivery over an IEEE 802.11g and two cellular networks (e.g., UMTS and HSDPA). The results are presented and analyzed.

5.1. Introduction

Energy conservation has become a critical issue around the world. Despite multimedia streaming to battery powered mobile devices gaining popularity, battery power capabilities are not keeping up with the advances in other technologies (e.g., processing and memory) and it is rapidly becoming a concern. The deficiency in battery power and the need for reduced energy consumption provides motivation for researchers to develop energy efficient techniques in order to manage the power consumption in next-generation wireless networks.

This chapter investigates the relationship between the wireless environment and the energy consumption of the mobile device in the context of video delivery. It represents an in-depth study on how the wireless link quality and the network load impact the energy consumption of an Android device while performing on-demand streaming over an IEEE 802.11g network. The study offers a better understanding of the device's energy consumption and demonstrates the necessity of considering network-related parameters (e.g., link quality, network load) when designing energy-efficient wireless video transmission schemes. It also highlights energy saving benefits brought by the use of an adaptive multimedia mechanism. The results of the real experimental testing will be further used in the simulation-based testing environment.

5.2. WLAN Test-Bed Setup

The WLAN test-bed is illustrated in Figure 5.1, and consists of: an IEEE 802.11g Wireless Router, a Multimedia Server, a Traffic Generator, a Network Monitor, an Android Mobile Device used as the client device, and a Power Consumption Monitor.

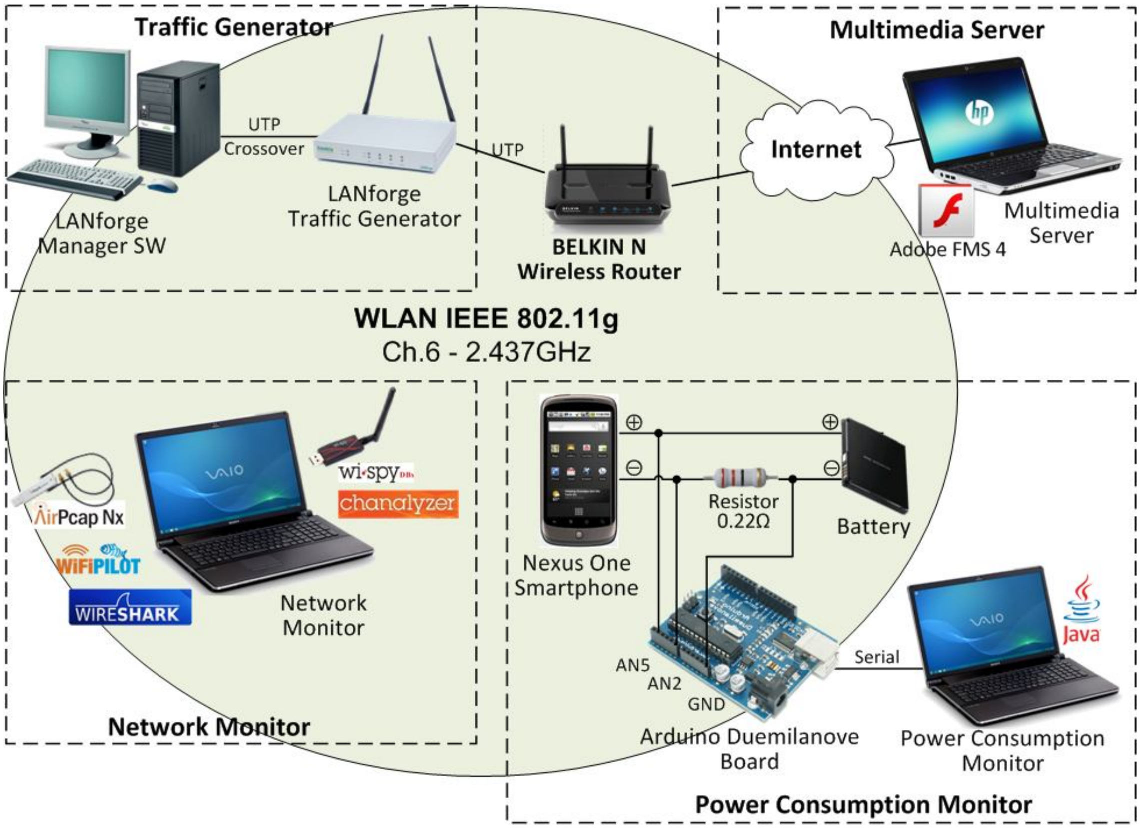


Figure 5.1. WLAN Test-Bed Environment

5.2.1. Equipment Specifications

The equipment involved in the measurements test-bed environment and the software used are listed below:

- **Belkin N Wireless Router**[1]

The router was configured to run on channel 6 (frequency 2.437GHz) with no other networks running on the same channel, in order to avoid the interferences. In order to set-up an IEEE 802.11g network, the router was configured for IEEE 802.11g mode.

- **Multimedia Server**

The Multimedia Server was running on a HP Pavillion dv3-2230ea Laptop with MS Windows 7 Home Edition x64, Intel Core 2 Duo T6600 at 2.20GHz and 4GB RAM. The software used on this laptop is the Adobe Flash Media Server 4[2] which enables the support for RTMP (TCP) and RTMFP (UDP) streaming and is compatible with Android platforms. The server was installed with the included Apache HTTP server for storing the HTML files containing the embedded flash video player. The video player used is a custom flash player component created in Adobe Flash CS5.5. Jperf 2.0.2[3] Server mode was also installed and is an open source tool, used between two endpoints (Server and Client) in order to measure the network performance (e.g., available bandwidth).

- **Traffic Generator**

The traffic generator used was a CT520 LANforge-WiFIRE 802.11a/b/g from Candela Technologies[4], which enables creating up to 32 wireless virtual stations. It has support for various real-world protocols (e.g., TCP/IP, UDP/IP, FTP, HTTP, etc.) and is capable to generate 45 Mbps or more traffic depending on the protocol mix, the wireless mode and environment, and the data rate speed of the network under test. The LANforge Manager Software used for controlling the traffic generator was installed on a desktop PC running MS Windows XP, connected via crossover cable. The traffic generator was connected to the wireless router via UTP cable.

- **Network Monitor**

A Sony Vaio VGN-CS11S laptop running MS Windows 7 Enterprise x86, Intel Core 2 Duo P8400 at 2.26GHz, and 4GB RAM was used to monitor the wireless network. Two pieces of external hardware equipment were connected to the laptop through the USB interface: Wi-Spy DBx[5] and AirPcap Nx[6]. Both were used to monitor the levels of interference, as well as capture and analyze the traffic in the wireless network. The Wi-Spy DBx comes with Chanalyzer 4[7] software and AirPcap Nx includes the WiFi Pilot 2.4[8] and Wireshark[9] software.

- **Mobile Device**

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[1] Belkin N Wireless Router - www.belkin.com

[2] Adobe Flash Media Server - http://www.adobe.com/products/flashmediaserver/

[3] Jperf - http://code.google.com/p/xjperf/

[4] CT520 LANforge-WiFIRE 802.11a/b/g - Candela Technologies http://www.candelatech.com/lanforge_v3/ct520_product.html

[5] Wi-Spy DBx - http://www.metageek.net/products/wi-spy/

[6] AirPcap Nx - http://www.metageek.net/products/airpcap/

[7] Chanalyzer 4 - http://www.metageek.net/products/chanalyzer-4/

[8] WiFi Pilot - http://www.metageek.net/products/wifipilot/

[9] Wireshark - http://www.wireshark.org/

The mobile device used as a client was an HTC Google Nexus One Smartphone running Android version 2.3.4. The mobile device was rooted in order to gain administrative access (full control) on the Android operation system. The applications used on the Android device are listed below:

- Adobe Flash 10.2 which is built in the Android native web-browser was used for playing the multimedia streams received over RTMP and RTMFP;
- Advanced Task Killer[10] and Advanced Task Manager[11] were used to terminate all the unnecessary running applications;
- WiFi Analyzer[12] and Network Signal Info[13] were used for tracking the received signal strength of the mobile device and the surrounding wireless networks;
- Smart Battery Monitor[14] was used in order to read the battery details (e.g., battery level, temperature, status, voltage, etc.);
- CurrentWidget[15] was used (running in background) for logging the information about the battery (e.g., battery level, voltage, temperature, current drained, etc.);
- iPerf [16]was used in Client mode and they work in conjunction with Jperf installed on the server side for measuring the available bandwidth in the network.

- **Power Consumption Monitor**

In order to store the power consumption measurements of the mobile device, a Sony Vaio VGN-CS11S laptop running MS Windows 7 Enterprise x86, Intel Core 2 Duo P8400 at 2.26GHz and 4GB RAM, was used. The Power Consumption Monitor is illustrated in Figure 5.2. The Android mobile device is connected to an Arduino Duemilanove[17] board that is connected to the Sony laptop through USB. The Android mobile device has a lithium-ion battery with four pins. The two pins located on the outer sides are labeled as positive (+) and negative (-). The other two inner pins are used to report diagnostic information to the phone. The power consumption of the Android mobile device is measured by inserting a high-precision 0.22Ω measurement resistor in series between the negative battery terminal and its connector on the phone. This was done by removing the battery of the mobile device and connecting it from outside. An Arduino Duemilanove board was used for measuring the battery voltage as well as the voltage drop on the resistor, in order to determine the current. A Java application running on the Sony laptop calculates (by using Ohm’s Law) the device power consumption based on the voltage values sent by the Arduino board and saves the values with a frequency of 1Hz. An image of the real setup of the Android mobile device is illustrated in Figure 5.3.

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[10] Advanced Task Killer - http://www.appbrain.com/app/advanced-task-killer/com.rechild.advancedtaskkiller
[11] Advanced Task Manager - https://market.android.com/details?id=com.rechild.advancedtaskkiller
[12] WiFi Analyzer - https://market.android.com/details?id=com.farproc.wifi.analyzer
[13] Network Signal Info - http://www.appbrain.com/app/network-signal-info/de.android.telnet
[14] Smart Battery Monitor - http://www.appbrain.com/app/smart-battery-monitor/at.aauer1.battery
[15] CurrentWidget - http://www.appbrain.com/app/currentwidget/com.manor.currentwidget
[16] iPerf for Android - http://www.appbrain.com/app/iperf-for-android/com.magicandroidapps.iperf
[17] Arduino Duemilanove - http://www.arduino.cc/en/Main/ArduinoBoardDuemilanove

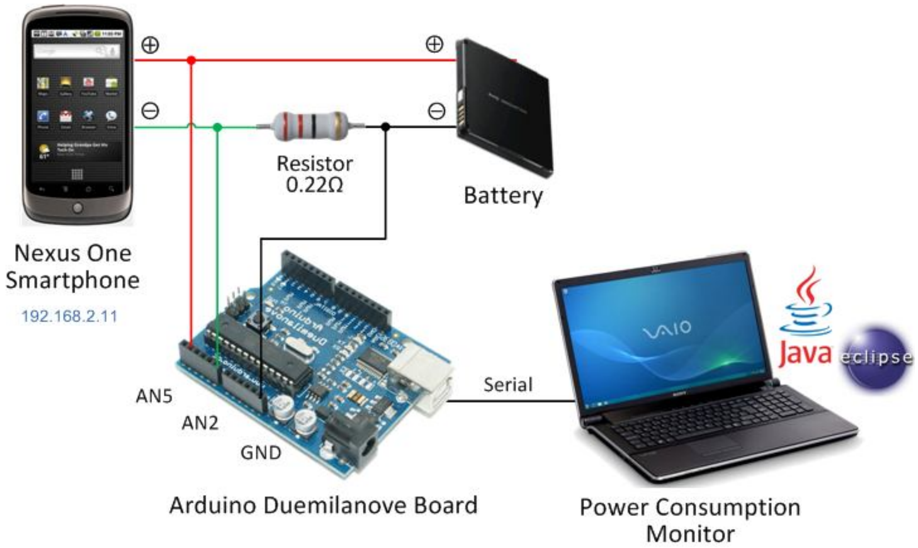


Figure 5.2. Power Consumption Monitor Setup

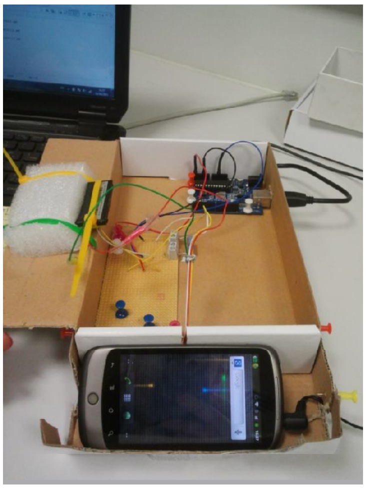
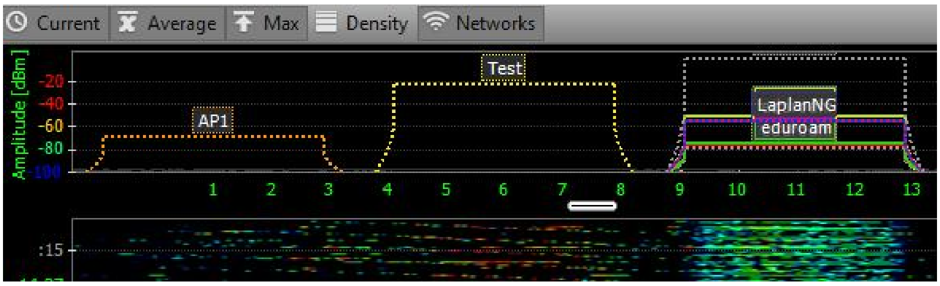


Figure 5.3. Android Mobile Device - Real Setup

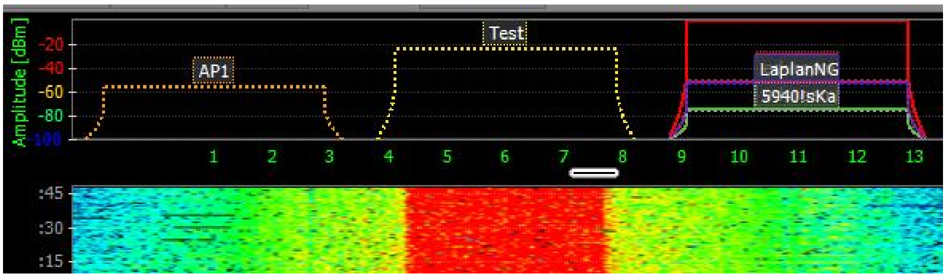
5.2.2. Wireless Environment

The Belkin N Wireless Router was used to set up the IEEE 802.11g Test Network. The router was connected to the internet through the university campus network (Dublin City University). The wireless network was deployed in the basement of the Engineering Building in order to reduce potential interferences, as there is a significantly lower number of wireless networks in range. The SSID of the network was ‘Test’ running on Channel 6 (frequency 2.437GHz) with no other networks running on the same or adjacent channels.

Wi-Spy DBx USB spectrum analyzer from MetaGeek together with the accompanying Chanalyzer 4 software, were used for monitoring the surrounding wireless networks and the interference levels. Chanalyzer 4 was running on the Network Monitor station. Figure 5.4 illustrates the 2.4 GHz band in two situations: when no traffic is generated in the Test network, and when the network is loaded with background traffic using the traffic generator. The wireless channels are represented on the x axis, whereas the y axis represents an indication of the signal amplitude (signal strength) in dBm. The area below the x axis indicates the activity in each network. For example, when there is background traffic present in the Test network, this is represented by the intense red color, indicating high network load. As it can be seen, the other wireless networks in range are running on different (and non-adjacent) channels, keeping interferences at a minimum.



(a) no traffic generated in the test network



(b) the test network is loaded with traffic

Figure 5.4. Chanalyzer 4 screenshots illustrating the wireless environment: (a) no traffic generated in the test network; (b) the test network is loaded with traffic.

In order to better understand what exactly is happening in the network, the traffic was captured with the help of AirPcap Nx that includes WireShark 1.4.8 and Wifi Pilot 2.4 software, both running on the Network Monitor station. The goal of the network traffic analysis is to:

- monitor the on-demand video streaming (e.g. received throughput, retransmissions vs. normal traffic, etc.),
- double-check that the background traffic is generated properly by the virtual stations created using the Traffic Generator.

5.2.3. Background Traffic Specifications

Background traffic was generated in order to assess the impact of network load on mobile device energy consumption. The background traffic was selected based on the traffic estimations provided by Cisco in [1] and by Plum Consulting[18] in a report for Ericsson and Qualcomm. According to them, over the next five years the ratio of downlink (DL) to uplink (UL) traffic could rise to 10:1 while the video traffic is expected to reach 66% of the total mobile traffic. Thus, the choice on the background traffic is based on the traffic forecast for 2015 and is listed in Table 5.1. In this way a more realistic environment is created and the expectations in terms of network conditions over the next five years can be analyzed.

In order to load the IEEE 802.11g network, first the available bandwidth was measured using Jperf in Server mode at the Server side, and Iperf for Android in Client mode on the mobile device. Iperf measures the available bandwidth between two end points by generating probe traffic into the network. In order to obtain accurate results, 10 Iperf readings were taken at 30-50s intervals between readings and computed the average available bandwidth which was in the range of 21-23Mbps. Based on these measurements the traffic load of the network was selected in the range of 20-21Mbps. The load level was selected so that a high load of the network is maintained but it is not overloaded, or used at its maximum capacity. The traffic type was selected according to Table 5.1. The number of wireless clients generating background traffic is in the range of 25-28 clients, located near the AP with the signal strength values between -25dBm and -35dBm. Video here represents traditional video traffic over UDP with data rates between 0.25Mbps and 2Mbps and packet size of 1514bytes. The other traffic represents web-browsing/e-mail, and file sharing, etc. This is TCP traffic with data rates between 0.250Mbps and 1Mbps and packet size in the range of 300-1514bytes.

TABLE 5.1. BACKGROUND TRAFFIC

Type	**% Traffic Cisco 2015**	**% downlink**	**% uplink**
Video	66%	98%	2%
Other	34%	76%	24%

The traffic generated by the Android mobile device falls into the downlink video traffic category. As the corresponding traffic data rate changes according to the video quality level, the background traffic is changed as well in order to maintain the same percentage (66%) in all scenarios.

5.2.4. Multimedia Encoding and Streaming

The Blender Foundation's ***10 minute long Big Buck Bunny***[19] animated clip was used for testing. A high quality version of the clip was transcoded at five different quality levels, following recommendations for encoding clips for multi-bitrate adaptive streaming[20]. The

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[18] Plum Consulting - www.plumconsulting.co.uk

[19] Big Buck Bunny Clip - http://www.bigbuckbunny.org/.

[20] Smooth Streaming Multi-Bitrate Calculator - http://alexzambelli.com/WMV/MBRCalc.html

encoding characteristics of the five test sequences are presented in Table 5.2. H.264/MPEG-4 AVC video compression and AAC audio compression were used together with MP4 container[21].

TABLE 5.2. ENCODING SETTINGS FOR THE MULTIMEDIA TEST SEQUENCES

	Encoding Parameters				
Quality Level	**Video Codec**	**Overall Bitrate [Kbps]**	**Resolution [pixels]**	**Frame Rate [fps]**	**Audio Codec**
QL1	H.264/ MPEG-4 AVC Baseline Profile	1920	800x448	30	AAC 25 Kbps 8 KHz
QL2		960	512x288	25	
QL3		480	320x176	20	
QL4		240	320x176	15	
QL5		120	320x176	10	

The encoded resolution was varied together with the bitrate in order to maintain a consistent level of compression quality. Figure 5.5 illustrates an example of variable resolution encoding. For example, Figure 5.5 a) presents a high quality level encoded at 800x448 and 1920kbps. If the same resolution is kept and the bit rate only is lowered as in Figure 5.5 b), some compression side effects can be noticed, such as: blockiness, color smearing, twirling details, etc. On the other side, by lowering the resolution together with the bitrate as shown in Figure 5.5 c) the blockiness effect is not visible, the picture presents some blurry aspects but the quality is relatively good.

Considering these aspects, the highest resolution was selected as 800x448 pixels to fit the screen resolution of the Android Nexus One device (800x480 pixels), while maintaining the original aspect ratio of the multimedia clip (16:9). The smallest resolution was selected as 320x176 and was kept the same for the last three quality levels. Going below this value, the risk of providing bad quality to the user appears, as very small video can result in bad full-screen experience. The video frame rate was also step-wise decreased from 30fps for QL1 to 10fps for QL5. The overall bitrate was decreased by half between consecutive quality levels from 1920Kbps (QL1) to 120Kbps (QL5). Out of these overall bitrate values, 25 Kbps corresponded to the audio stream while the rest corresponds to video stream. The audio component was not varied for the different quality levels.

The test sequences were streamed to the Android device over both TCP and UDP protocols in order to analyze the impact of the transport protocol on the energy consumption of the Android device. Adobe Flash Media Server 4 was used for streaming the videos using the proprietary application level streaming protocols RTMP (TCP) and RTMFP (UDP). The streams were embedded in web pages and were played back on the device using Adobe 10.2 Flash Player inside the Android native web browser. The video playout display area was scaled to the device screen resolution.

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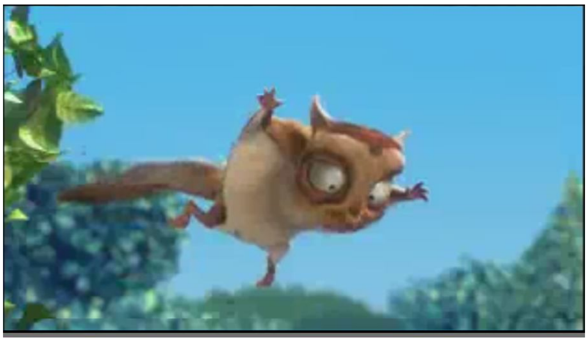
[21] MP4 multimedia container format - http://en.wikipedia.org/wiki/MPEG-4_Part_14

a) encoding at 800x448/1920kbps

b) encoding at 800x448/120kbps



c) encoding at 320x176/120kbps

Figure 5.5. Variable Resolution Encoding - Example

5.2.5. Objective Quality Assessment

Since video quality is an important aspect of multimedia delivery, Peak Signal-to-Noise Ratio (PSNR), a full-reference objective metric, was measured in order to estimate the human perceived visual quality offered by the five encoding settings used. MSU Video Quality Measurement Tool[22] software was used for computing the objective PSNR quality values. PSNR is measured by comparing the quality of the degraded versions (QL2 to QL5) with regard to that of the highest quality sequence (QL1). Since this is done on a pixel-by-pixel basis, all the clips were scaled to the same video resolution and video frame rate. Although employing the scaling process is not ideal, by computing PSNR, one gets a good idea of the human perceived quality levels for these video sequences.

5.2.6. Subjective Quality Assessment

Since objective metrics do not always correlate with the subjective scores, a subjective study was also conducted in order to assess how human subjects perceive the quality of the multimedia clip encoded at the five quality levels previously selected (see Table 5.2). For the purpose of subjective testing, four 20 seconds long sequences with different spatial and temporal characteristics were extracted from the original 10 minute long clip (*Big Buck Bunny*). Representative frames of the four sequences are presented in Figure 5.6.

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[22] MSU Video Quality Measurement Tool - http://compression.ru/video/quality_measure/video_measurement_tool_en.html

a) Sequence A b) Sequence B

c) Sequence C d) Sequence D

Figure 5.6. Test sequences used for the subjective study

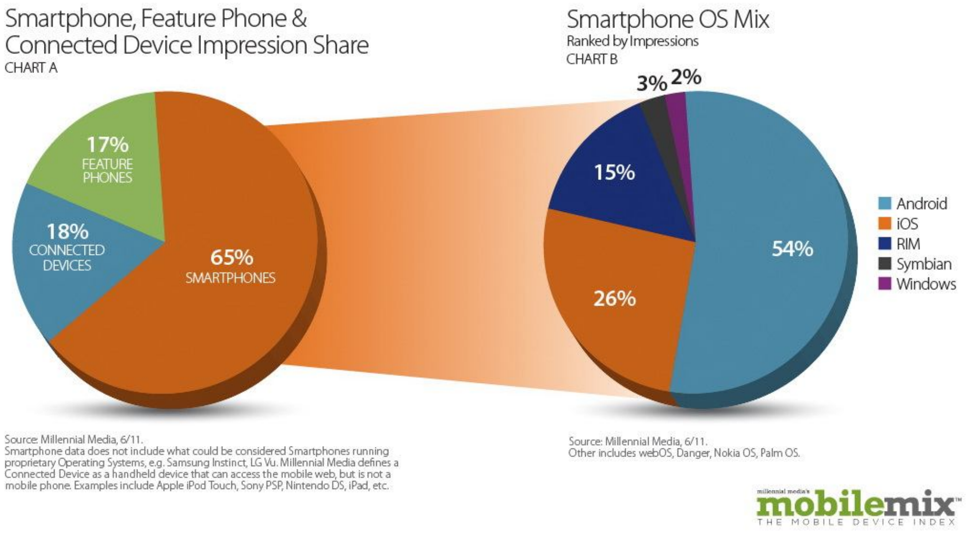
In case of sequence A (Figure 5.6a) the camera pans slowly over a natural landscape scene, thus the sequence presents a medium level of spatial information and a low level of temporal information. Sequence B (Figure 5.6b) is the most complex to encode. It presents fast changing scenes with dynamic elements as well as characters, thus having the highest levels of spatial and temporal complexity. Sequence C (Figure 5.6c) is especially difficult to encode at good quality low resolutions due to the small moving details represented by the closing credits. This sequence has high spatial information but low temporal complexity. Sequence D (Figure 5.6d) presents two characters, from which only one is slowly moving across the scene, on a static background. Therefore the scene has the lowest level of spatial information. Each of the four sequences was encoded at the five quality levels, resulting in a total number of 20 test sequences for the subjective study.

The test sequences were played locally in full screen on the Android Nexus One device and displayed in a random order (to minimize the order effect), maintaining similar testing conditions for all the participants. Standard recommendations for assessing the visual quality of multimedia applications were followed as in *ITU-T P.910* [194]. The Absolute Category Rating (ACR) [194] method was used, in which case the subjects have rated individually the quality of each sequence on a 5-point scale (e.g., 1 - Bad, 2 - Poor, 3 - Fair, 4 - Good, 5 - Excellent). A number of 16 (Males = 10, Females = 6) non-expert subjects with ages between 22 and 45 years old (Average Age (AVG) = 28, standard deviation (STDEV) = 6) have participated in the study.

All the subjects have reported that they had normal vision or have corrected to normal vision (they were wearing glasses).

5.2.7. The Choice of Client Mobile Device

A HTC Google Nexus One smartphone running Android 2.3.4 was selected as the client Mobile Device. Figure 5.7 illustrates the state of the global smartphone landscape as reported by Millennial Media in [195]. According to their report the Android mobile devices have grown rapidly in popularity over the recent years, reaching 54% of the global smartphone market.



Source: Millennial Media, 6/11.
Smartphone data does not include what could be considered Smartphones running proprietary Operating Systems, e.g. Samsung Instinct, LG Vu. Millennial Media defines a Connected Device as a handheld device that can access the mobile web, but is not a mobile phone. Examples include Apple iPod Touch, Sony PSP, Nintendo DS, iPad, etc.

Source: Millennial Media, 6/11.
Other includes webOS, Danger, Nokia OS, Palm OS.

Figure 5.7. Global Smartphone landscape [195]

This confirms that the Android Mobile Device is one of the state-of-the-art mobile devices suitable for our tests. Moreover, as opposed to other smartphones, in particular to iPhone, the Android mobile device presents the advantage that has a user replaceable battery. Having access to the battery contacts, the device power consumption can be measured using hardware equipment, thus having more accurate results than using locally installed software.

5.3. Cellular Test-Bed Setup

The test-bed used for running the power measurements on the cellular network is illustrated in Figure 5.8. The tests were run in the DCU campus inside the Electronic Engineering building through the cellular networks provided by two mobile internet service providers in Ireland: O2[23] and eMobile[24]. The O2 Communications Ireland is a subsidiary of Telefonica that offers HSDPA services nationwide since 2007. O2 is one of the leading mobile service providers in Ireland. On the other side, eMobile is new in the market, launching its services in September

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[23] O2 Ireland - http://www.o2online.ie/o2/

[24] eMobile Ireland - http://www.emobile.ie/

2010 and is part of the Eircom Group[25], which is the largest telecommunications service provider in Ireland. eMobile is the second mobile brand of Eircom and offers UMTS services over the network infrastructure of an existing mobile subsidiary, Meteor[26]. Because of the security reasons and the lack of required specialized equipment, obtaining network related information (e.g., available bandwidth, received throughput, network load, etc.) is not possible. In this case, the only information that can be gathered is the power consumption of the mobile device and network generic information (e.g., network type, maximum downlink rate, cell id (CID), location area code (LAC), mobile country code (MCC), mobile network code (MNC), signal strength (SS)) provided by the Network Signal Info Android application and listed in Table 5.3.

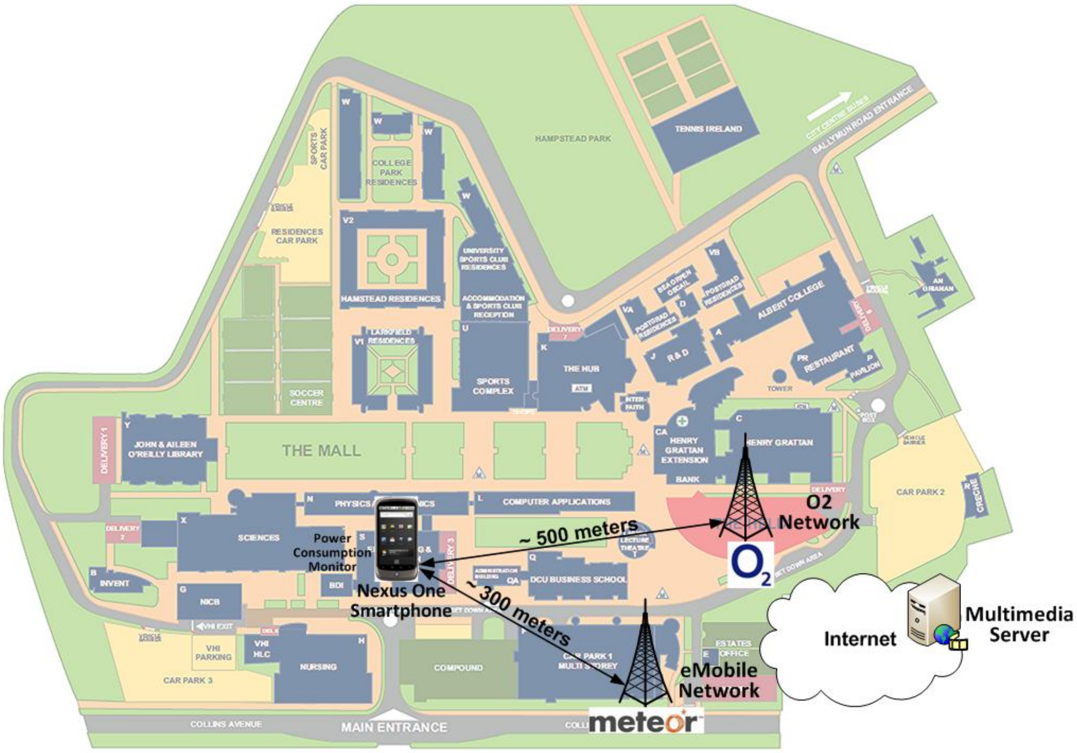

Figure 5.8. Cellular Test-bed Environment

TABLE 5.3. CELLULAR NETWORKS CHARACTERISTICS

Operator	Network Type	Downlink Rate	CID	LAC	MCC+MNC	SS
O2	HSDPA	7.2Mbps	2044410	36006	27202	-95dBm
eMobile	UMTS	384kbps	60902	3006	27203	-73dBm

The Multimedia Server described in Section 5.2 stores the multimedia streams. Because cellular networks have lower transmission rates than WLAN (e.g., UMTS has 384kbps whereas IEEE 802.11g has 54Mbps), three quality levels were considered for streaming. The quality levels represent a subset of the five quality levels encoded for the WLAN test-bed as described

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[25] Eircom Ireland - www.eircom.net
[26] Meteor Ireland - www.meteor.ie

in Section 5.2.4. This helps at analyzing the impact of the network technology on the energy consumption. The three quality levels were streamed to the mobile device through the cellular networks. Unfortunately the O2 network blocked streaming over UDP, and therefore the tests were conducted only for streaming over TCP. This was not the case for eMobile, where both protocols were enabled and full tests have taken place.

5.4. Experimental Test Scenarios

In order to study how the network related parameters (e.g., link quality, location, technology, network load, etc.) impact the power consumption of an Android Mobile Device, a measurement analysis was conducted, with the main goals listed below:

- Understanding the energy-quality tradeoff;
- Understanding the impact of transport protocol (e.g., TCP or UDP) on the energy consumption while performing VoD over WLAN;
- Understanding the impact of link quality on the energy consumption while performing VoD over WLAN;
- Understanding the impact of the network load on the energy consumption while performing VoD over WLAN;
- Understanding the impact of both link quality and network load on the energy consumption while performing VoD over WLAN;
- Understanding the impact of network technology (e.g., WLAN, UMTS, HSDPA) on the energy consumption while performing VoD.

Consequently six scenarios were considered as illustrated in Figure 5.9 and described below. In all considered scenarios the Multimedia Server stores the ***five ten-minute clips*** *(Big Buck Bunny)*, each clip corresponding to a different quality level as explained in Section 5.2.4. The clips are streamed sequentially to the Android mobile device over either of two transport protocols (UDP and TCP).

1) Scenario 1 – No Load, Near AP

The first scenario considers the case of a mobile user, located near the AP (approximately 1m away), without any background traffic in the network, and the signal strength of the mobile device varies between -48dBm and -52dBm.

2) Scenario 2 – No Load, Far AP

In the second scenario the mobile user is located in an area with poor signal strength, varying between -78dBm and -82dBm. The tests were run without any background traffic in the network in order to study the impact of the link quality on the energy consumption of the Android mobile device.

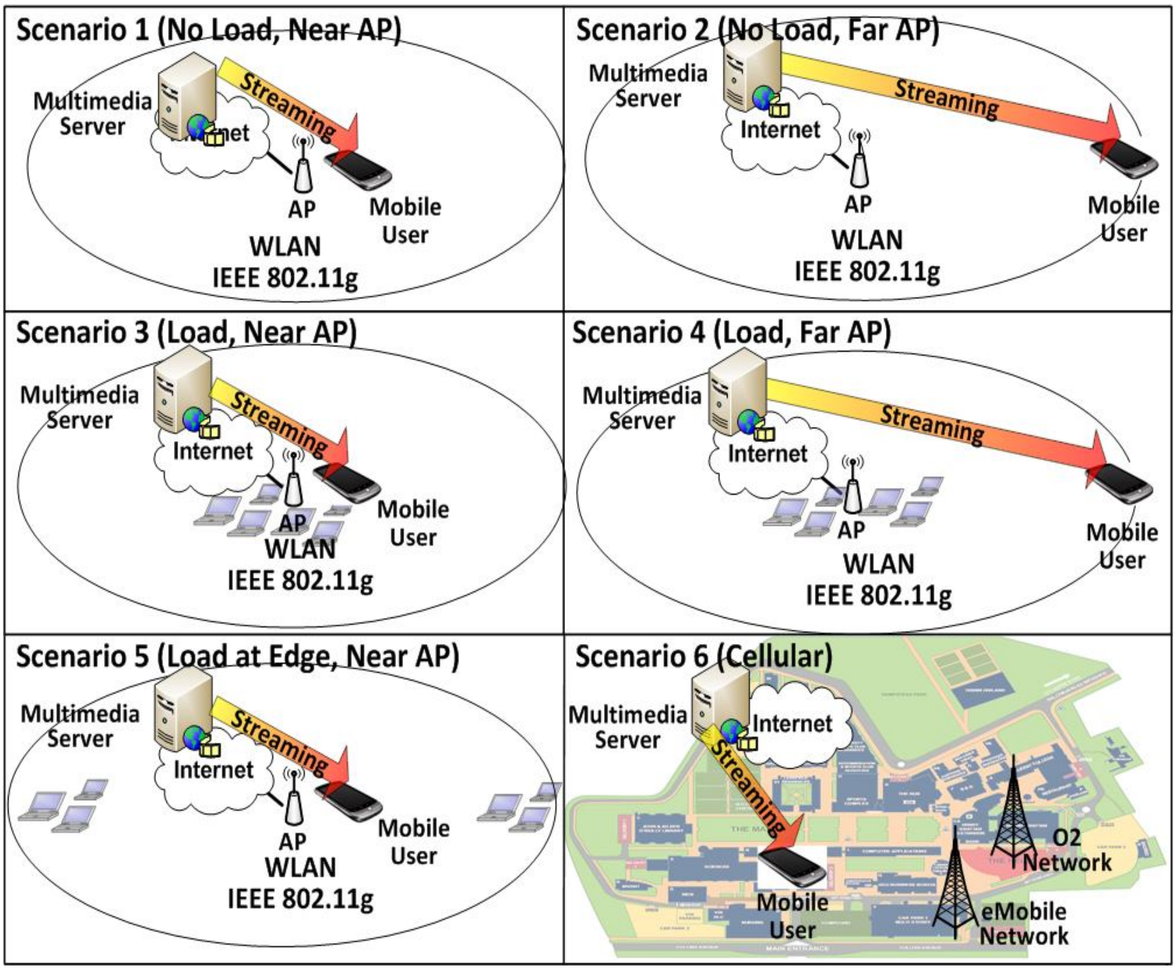


Figure 5.9. Considered Scenarios

3) Scenario 3 – Load, Near AP

The third scenario is similar to the first one, except that background traffic was added in order to load the network, and study the impact of the network load on the energy consumption of the Android mobile device. LANforge traffic generator was used to create a number of 25 to 28 virtual wireless stations, each of them generating traffic as previously explained. The background traffic is located near the AP with the signal strength varying between -28dBm and -32dBm.

4) Scenario 4 – Load, Far AP

Scenario 4 is similar to Scenario 2 except that background traffic was added as in Scenario 3 (Load, Near AP). In this way the impact of both poor link quality (-78dBm - -82dBm) and network load, on the energy consumption of the Android mobile device can be studied.

5) Scenario 5 – Load at Edge, Near AP

In scenario 5 the mobile user is located near the AP and the background traffic was moved in an area with poor signal strength varying between -78dBm and -82dBm. While for Scenario 3 and 4 (when the background traffic was near the AP) the traffic load of 20-21Mbps with 25 to

28 virtual wireless stations was considered, for Scenario 5, the traffic load is considered to be between 4Mbps and 4.3Mbps with 11 to 12 virtual wireless stations, and the traffic type as listed in Table 5.1. This is based on the assumption that when the users are located near the AP their maximum theoretical transmission rate is up to 54Mbps while when located in an area with poor signal strength, their maximum theoretical transmission rate might be up to 11Mbps. Consequently the same ratio of traffic load was kept, when located in areas with poor signal strength. This helps to study the impact of network load distribution on the energy consumption of the Android mobile device.

6) Scenario 6 – Cellular

Scenario 6 considers the case of the mobile user performing VoD over cellular networks. Two cellular network operators were considered O2 (HSDPA network) and eMobile (UMTS) network as previously discussed. In this case the impact of the network technology on the energy consumption of the Android mobile device is studied.

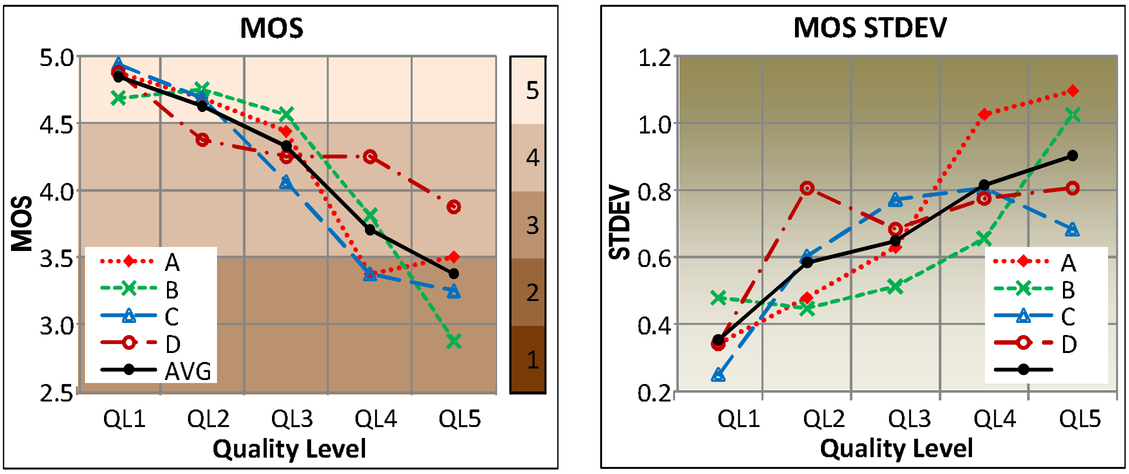
5.5. Experimental Results and Analysis

For each considered scenario and for each of the quality levels the tests were repeated three times (a total of 252 tests were carried out), the results were collected and the average values computed. These values will be further used throughout the paper for analysis of the results and discussions.

5.5.1. Impact of the Video Quality Levels on Human Perceived Visual Quality during Local Video Playback

In order to assess the user perceived quality of the five quality levels, subjective tests were performed. As described in Section 5.2.6, the subjects were asked to view 20 test sequences and rate their overall quality on 1-5 scale (bad to excellent). For each sequence, the mean value represented by the Mean Opinion Score (MOS), and the standard deviation (STDEV) of the statistical distribution of the assessment grades were computed. The results of the subjective study are presented in Figure 5.10.

All the sequences corresponding to QL1-QL3 scored above 4 (Good), with eight of them scoring above 4.5 (Excellent). Out of the eight test sequences corresponding to QL4 and QL5, four scored above 3.5 (Good) on average, while the other two below 3.5 but above 2.5 (Fair) on average. On average across the four test sequences, two quality levels scored Excellent (MOS_QL1 = 4.84 and MOS_QL2 = 4.63), two scored Good (MOS_QL3 = 4.33 and MOS_QL4 = 3.70) and one Fair (MOS_QL5 = 3.38). The average standard deviation values, shown in Figure 5.10b increase as the video quality decreases (STDEV_QL1 = 0.35 to STDEV_QL5 = 0.90). The Pearson correlation further indicates that there is decreasing relationship between the MOS and STDEV values (r = -0.846), thus the ratings across participants tend to have a higher variation, for the clips with lower perceived quality.



Sequence	QL1	QL2	QL3	QL4	QL5
A	4.88	4.69	4.44	3.38	3.50
B	4.69	4.75	4.56	3.81	2.88
C	4.94	4.69	4.06	3.38	3.25
D	4.88	4.38	4.25	4.25	3.88
AVG	4.84	4.63	4.33	3.70	3.38

Sequence	QL1	QL2	QL3	QL4	QL5
A	0.34	0.48	0.63	1.02	1.10
B	0.48	0.45	0.51	0.66	1.02
C	0.25	0.60	0.77	0.81	0.68
D	0.34	0.81	0.68	0.77	0.81
AVG	0.35	0.58	0.65	0.82	0.90

a) MOS b) MOS STDEV

Figure 5.10. Results of the Subjective Quality Assessment

5.5.2. Impact of the Video Quality Levels on Energy Consumption during Local Video Playback

In order to study how much energy can be conserved by potentially adjusting the quality level of the video, local video playback of each quality level was performed. All the tests were performed with the same and minimal background activities in the mobile device, with all the wireless connectivity disabled (Airplane Mode) and the power save mode turned off. The results are illustrated in Table 5.4. The Discharge and Battery Life values were estimated using equation (5.1) and equation (5.2) presented below:

$$Discharge\ [mAh] = Avg.\ Energy[J] * 1000/(3.7V*3600sec.) \qquad (5.1)$$

$$Battery\ Life\ [hrs] = 1330mAh*3.7V/Avg.\ Power[mW] \qquad (5.2)$$

where 3.7V and 1330mAh represent the nominal voltage and capacity, respectively of the mobile device’s battery. The Discharge parameter represents the total charge drawn from the battery during the corresponding clip playback/streaming. The Battery Life represents the amount of time the fully charged device will take to discharge while playing a certain quality level. For example, if only QL1 videos are played the device has an estimated battery life of 4 hours, while by choosing to play only QL5 videos, the battery life is doubled. The results show that by decreasing the video quality level, energy savings are achieved. Switching from QL4 to QL5 provides a low saving of 4.5% for a corresponding MOS decrease from Good to Fair. However switching from QL1 to QL3 provides a 44.8% energy saving for a MOS decrease from Excellent to Good, while a switch from QL1 to QL2 offers 34% energy savings at no significant change in MOS.

TABLE 5.4. RESULTS FOR LOCAL PLAYBACK

Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	PSNR [dB]	Subjective MOS
QL1	712	1196	53	4.11	-	4.84
QL2	470	788	35	6.24	47	4.63
QL3	393	658	29	7.48	41	4.33
QL4	374	627	28	7.85	36	3.70
QL5	357	598	27	8.23	31	3.38

5.5.3. Impact of the Video Quality Levels on Energy Consumption while Performing VoD Streaming over WLAN

Considering Scenario 1, with the mobile device located near the AP and without background traffic, the energy consumption while performing VoD Streaming over UDP was measured. The difference between these results and the local playback gives an overview of the energy consumption over the wireless network. The impact of the wireless interface on the energy consumption is illustrated in Figure 5.11 and Table 5.5. The results show that by decreasing the video quality level with VoD Streaming, a 6.7% (for a QL1 to QL2 drop) up to 62.7% (for a QL1 to QL5 decrease) decrease in energy consumption can be achieved on the wireless interface only. Because the link has good quality and enough available bandwidth is provided for VoD, the playback is smooth and un-interrupted, maintaining the same user perceived quality, thus the same subjective MOS values as for local playback.

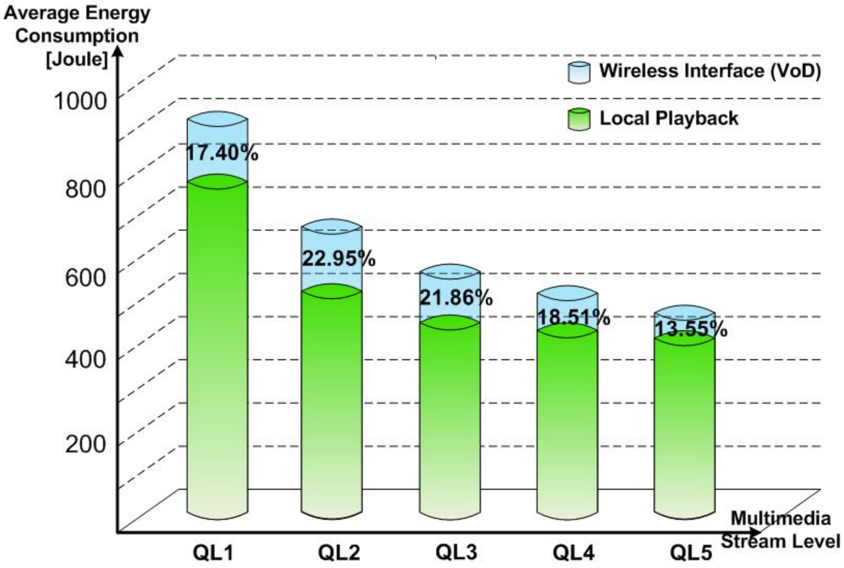


Figure 5.11. Avg. Energy Consumption for VoD Streaming

5.5.4. Impact of the Transport Protocol on Energy Consumption while Performing VoD Streaming over WLAN

TCP was built for reliable data transport offering fairness to users by dividing the available resources (e.g., bandwidth) in an almost equal manner. As TCP congestion control mechanisms can affect video streaming, the traditional method of transporting video was over UDP. However, nowadays with the increase in bandwidth, the use of TCP has become ubiquitous for streaming video, and more and more Service Providers are adopting it in combination with multimedia adaptive solutions (e.g., Apple HTTP live streaming, Move Networks, etc.). Considering Scenario 1, the same five quality levels were run, keeping the same conditions and changing only the transport protocol UDP and TCP, respectively. The results presented in Table 5.5 show that TCP is more energy efficient than UDP.

TABLE 5.5. SCENARIO 1 - UDP VS. TCP VOD STREAMING

	Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Avg. Th. [Mbps]
UDP	**QL1**	862	1445	65	3.41	2.07
	QL2	610	1022	46	4.82	1.05
	QL3	503	841	38	5.85	0.52
	QL4	459	764	34	6.44	0.26
	QL5	413	699	31	7.04	0.14
TCP	**QL1**	842	1410	63	3.49	2.02
	QL2	567	953	43	5.16	1.00
	QL3	475	799	36	6.16	0.51
	QL4	434	726	33	6.78	0.26
	QL5	398	666	30	7.39	0.14

Figure 5.12 illustrates the difference between them in terms of energy consumption over the wireless interface. For example, looking at QL1, 13% energy savings can be achieved on the wireless interface by transmitting over TCP rather than UDP. An observation (noticed when analyzing the Wireshark trace files) that could be considered one of the reasons for which TCP performs better, is that its packet size distribution is 1280-2559 bytes, meaning larger, but fewer packets to be transmitted. On the other hand the UDP packet size distribution is lower, 640-1279 bytes, meaning more packets to be transmitted over the wireless interface. This affects the energy consumption of the mobile device, as the device will have to use its wireless interface more often to receive the data packets. Note that there was no possibility to control the size of the UDP and TCP packet size.

The actual average throughput (Avg. Th.) received by the Android mobile device on the wireless network, was captured with Wireshark and listed in Table 5.5. As seen, the required throughput for each quality level (Table 5.2) is provided.

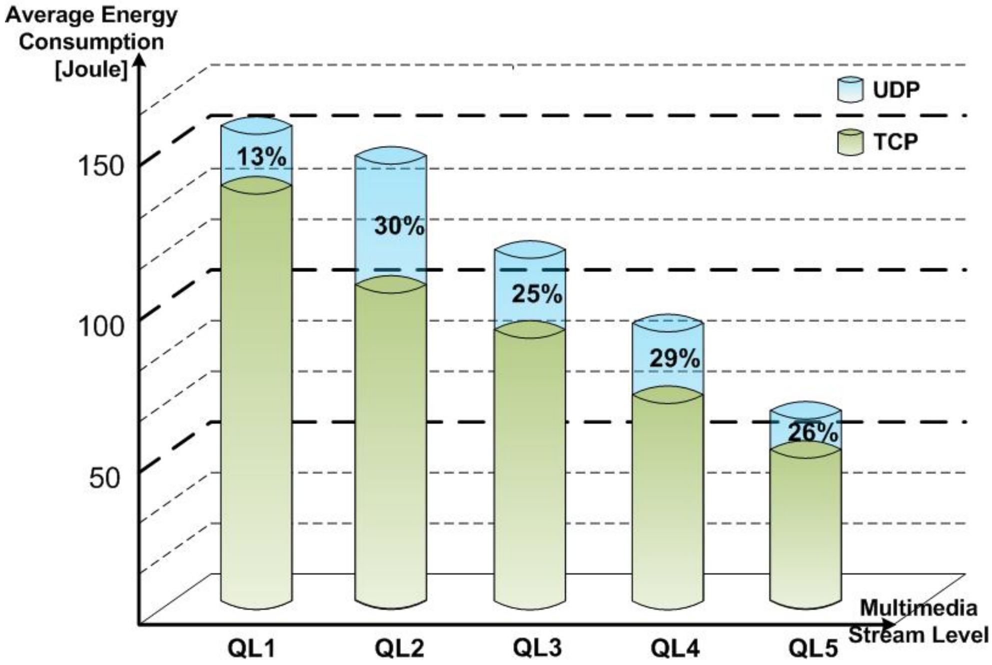


Figure 5.12. Scenario 1 - Avg. Energy Consumption UDP vs. TCP over the wireless interface

5.5.5. Impact of the Link Quality on Energy Consumption while Performing VoD Streaming over WLAN

In order to study the impact of the link quality on the energy consumption of the mobile device, Scenario 1, where the user is located near the AP with good signal strength (-48dBm to -53dBm), and Scenario 2, where the user is located in a poor signal strength area (-78dBm to -82dBm) are considered. In both scenarios no background traffic is considered, so the only factor varying is the signal strength (link quality). The results are listed in Table 5.5 and Table 5.6. Figure 5.13 illustrates the impact of the link quality on energy consumption for both transport protocols (UDP and TCP) by comparing the wireless interface energy consumption, for Scenario 1 vs. Scenario 2.

TABLE 5.6. SCENARIO 2 - UDP AND TCP VOD STREAMING

	Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Avg. Th. [Mbps]
UDP	**QL1**	875	1461	66	3.37	3.32
	QL2	628	1052	47	4.68	1.57
	QL3	512	857	38	5.74	0.59
	QL4	463	777	35	6.34	0.26
	QL5	420	704	32	6.99	0.13
TCP	**QL1**	865	1448	65	3.40	2.15
	QL2	586	982	44	5.01	0.98
	QL3	492	823	37	5.98	0.53
	QL4	446	746	33	6.60	0.32
	QL5	414	692	31	7.11	0.15

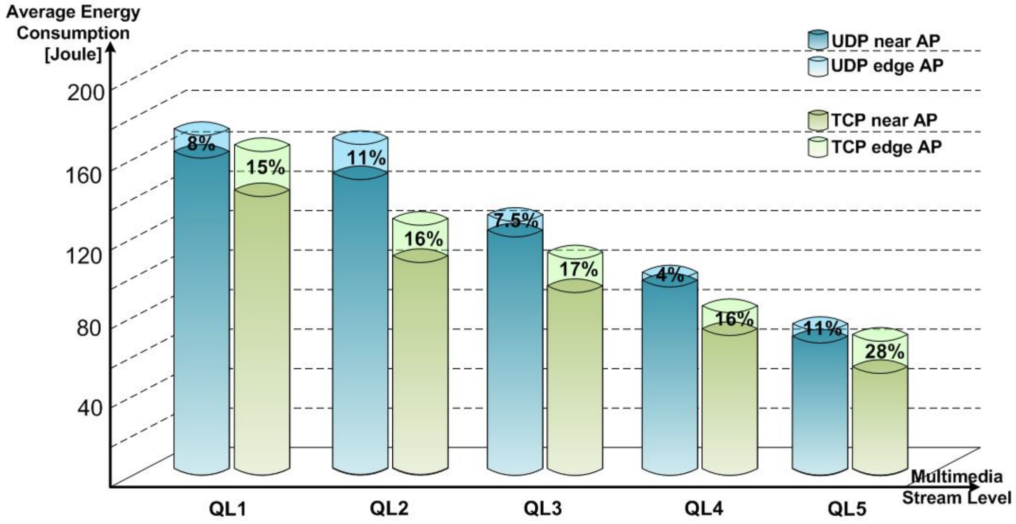


Figure 5.13. Scenario 1 vs. Scenario 2 Avg. Energy Consumption (UDP&TCP) over the wireless interface

As shown, poor signal strength has higher impact on the TCP wireless interface energy consumption over UDP, with as high as 28% increase in energy usage for QL5 at the edge. The decrease in signal strength has a lesser impact on UDP, with as low as 4% increase in energy for QL4 at the edge, up to an 11% increase (QL2 and QL5). However, even in these conditions, TCP remains more energy efficient than UDP. The actual received throughput results meet the required throughput for each quality level (Table 5.2) meaning smooth uninterrupted playback and maintained user perceived quality as for local playback.

5.5.6. Impact of the Network Load on Energy Consumption while Performing VoD Streaming over WLAN

By comparing Scenario 1 (no load in the network and the mobile user is located near the AP) with Scenario 3 (loaded network and the mobile user is located near the AP) the impact of the network load on the energy consumption of the mobile device is determined. Table 5.7 presents the energy information and network related measurements as they were captured by Wireshark.

TABLE 5.7. SCENARIO 3 - UDP AND TCP VOD STREAMING

	Quality Level	**Avg. Energy [J]**	**Avg. Power [mW]**	**Discharge [mAh]**	**Battery Life [hrs]**	**Avg. Th. [Mbps]**	**Avg. Ch. Traffic [Mbps]**	**Retr. [%]**
UDP	**QL1**	897	1489	67	3.30	2.27	24.32	3.82
	QL2	657	1102	49	4.47	1.18	25.12	7.98
	QL3	536	895	40	5.50	0.65	24.97	8.37
	QL4	466	779	35	6.32	0.36	24.90	5.61
	QL5	438	733	33	6.71	0.18	24.89	5.98
TCP	**QL1**	885	1483	66	3.32	2.09	24.46	4.07
	QL2	615	1030	46	4.78	1.06	24.66	4.79
	QL3	495	829	37	5.93	0.67	24.84	5.28
	QL4	462	774	35	6.36	0.35	24.18	9.1
	QL5	415	695	31	7.08	0.30	24.69	5.57

The average received throughput (Avg. Th.) more than meets the requested throughput for each quality level. This means that although in high network load conditions, every user receives their requested network resources. This is also shown by the average value of the overall channel traffic (Avg. Ch. Traffic). The payload of the overall network traffic was set as 20-21Mbps, but with network overhead it reaches 24-25Mbps (according to Wireshark).

Another important factor is the number of retransmissions (Retr.) that occur in the network. This value shows the relative number of the overall packets that were retransmitted vs. normal traffic, and it is expressed as a percentage. Due to the high number of clients (26 in this case) that share the network, the competition for the network resources is high and this is reflected by the retransmissions value. This affects the energy consumption as well, as illustrated in Figure 5.14. Looking at QL2 transmission over UDP, it can be seen that when the network is loaded it consumes more or less the same energy, on the wireless interface, as QL1. This is due to network contention, as the overall retransmissions doubled when compared with QL1. Also the average channel traffic presents an increase of 3.2% reflecting the increase in the resource competition. Even though the network load affects energy consumption for TCP video streaming (compared to Scenario 1), TCP is still more energy efficient than UDP. It is important to note that during this scenario the observed user perceived quality was not affected by the network load, the playback being smooth without interruptions.

In terms of energy consumption, the results show that the energy can increase as low as 8% for QL4 up to 30% for QL5, when streaming over UDP in a loaded network. Whereas when streaming over TCP, over the same loaded network, the results show that the energy consumption can increase as low as 20% for QL3 up to 33% for QL2.

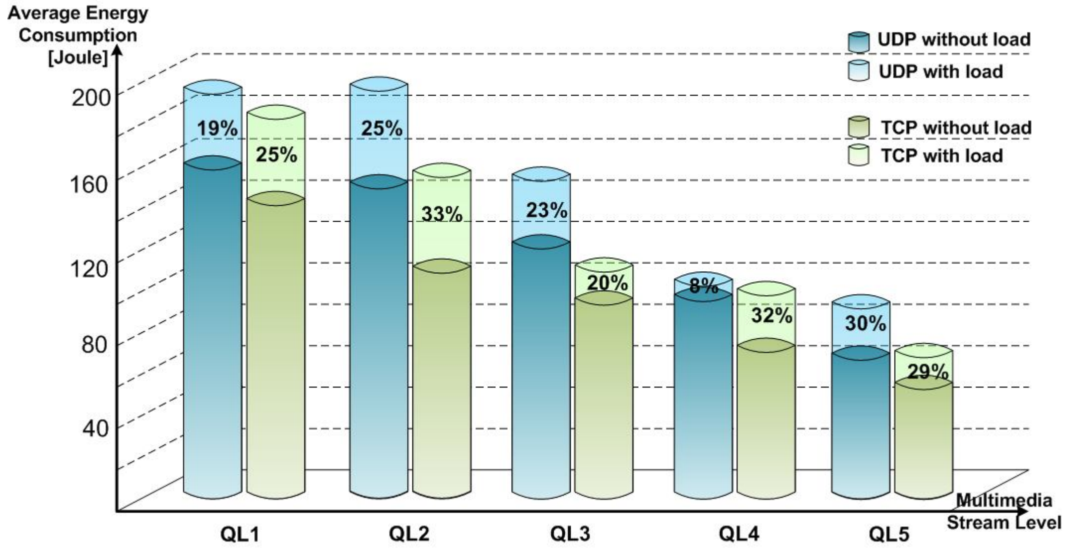


Figure 5.14. Scenario 1 vs. Scenario 3 Avg. Energy Consumption (UDP&TCP) over the wireless interface

5.5.7. Impact of Link Quality and Network Load on Energy Consumption while Performing VoD Streaming over WLAN

The impact of both link quality and network load is studied by comparing Scenario 1 (where the mobile device is located near the AP without any background traffic) and Scenario 4 (where the mobile device is located further away from AP with background traffic). In this case both the link quality and the competition with the background traffic will impact the energy consumption. The Scenario 4 results are listed in Table 5.8.

Although there is a decrease in the overall channel traffic, there still is an increased number of total WLAN retransmissions. An important parameter that needs to be mentioned is the Playout duration of the clip. Because of the competitive background traffic and the poor link quality, the mobile user will experience interruptions such as video freezing, leading to longer playback duration. This phenomenon has more impact on the QL1 multimedia stream, resulting in long periods of buffer starvation and frequent 4-10s periods of video motion loss (the re-buffering periods represent almost 60% of the playout duration) QL4 and QL5 are not affected. This is because a higher quality level means higher bitrate, therefore more data to be sent over an already loaded network.

The impact of the re-buffering periods on the user perceived quality was assessed by the estimated MOS, which decreases with the increase in buffering percentage level, as explained in [196]. Consequently, 15% re-buffering determines a quality decrease of 1MOS unit and 60% re-buffering severely affects the quality with a corresponding drop of more than 1.5MOS units. In this case the MOS of QL1 will drop below the MOS of QL4 and QL5, which maintain the same MOS as they do not introduce any buffering periods.

TABLE 5.8. Scenario 4 - UDP and TCP VoD Streaming

	Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Avg. Th. [Mbps]	Avg. Ch. Traffic [Mbps]	Retr. [%]	Playout [sec.]	Estimated MOS
UDP	**QL1**	1300	1362	98	3.62	1.32	20.13	11.83	958	< 3
	QL2	826	1193	62	4.13	1.02	20.71	10.35	695	3.58
	QL3	667	1015	50	4.86	0.45	20.15	9.12	659	3.43
	QL4	512	850	38	5.80	0.30	19.44	8.08	600	3.70
	QL5	468	783	35	6.29	0.14	18.88	11.75	600	3.38
TCP	**QL1**	1283	1365	96	3.62	1.42	21.65	8.51	948	< 3
	QL2	784	1169	59	4.21	1.09	21.07	10.29	671	3.63
	QL3	596	966	45	5.09	0.69	21.31	10.45	617	4.03
	QL4	518	867	39	5.68	0.26	19.48	10.12	600	3.70
	QL5	456	763	34	6.45	0.16	19.92	9.75	600	3.38

5.5.8. Impact of an Overloaded Network on Energy Consumption while Performing VoD Streaming over WLAN

In order to study what is happening when the network is overloaded, the overall traffic was increased so that the network is used at its maximum capacity. First the maximum capacity of the network was measured by generating a 50Mbps UDP stream (the theoretical data rate of an IEEE 802.11g network is 54Mbps). The average throughput of the stream reached 29-30Mbps. Based on this value the background traffic was created, using the mix from Table 5.1. Scenario 3 (Load, Near AP) and Scenario 4 (Load, Far AP) were considered again, this time with 29-30Mbps background traffic. The results for the two scenarios are presented in Table 5.9.

TABLE 5.9. OVERLOADED NETWORK - UDP AND TCP VOD STREAMING

		Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Avg. Th. [Mbps]	Avg. Ch. Traffic [Mbps]	Retr. [%]	Playout [sec.]
Near AP	**UDP**	**QL1**	1308	1332	98	3.71	1.41	25.98	5.85	993
		QL2	906	1113	68	4.43	0.84	24.94	5.17	820
		QL3	689	989	52	5.00	0.49	26.43	3.48	704
		QL4	518	866	39	5.68	0.34	26.50	3.43	600
		QL5	461	774	35	6.36	0.16	24.76	5.86	600
	TCP	**QL1**	1228	1358	92	3.63	1.37	26.65	4.33	909
		QL2	833	1111	63	4.45	0.9	25.84	4.57	765
		QL3	666	993	50	4.96	0.49	24.69	7.97	671
		QL4	490	823	37	5.98	0.35	26.52	4.64	600
		QL5	434	727	33	6.77	0.24	27.26	4.5	600
Edge AP	**UDP**	**QL1**	4251	823	319	5.98	0.17	21.46	10.48	5165
		QL2	1631	910	122	5.41	0.34	24.56	10.45	1793
		QL3	789	1022	59	4.82	0.44	23.89	9.55	773
		QL4	679	962	51	5.11	0.32	23.84	9.61	705
		QL5	562	874	42	5.63	0.19	23.34	8.67	643
	TCP	**QL1**	4034	809	303	6.08	0.21	20.39	9.48	4987
		QL2	1471	901	110	5.46	0.4	22.78	8.4	1633
		QL3	751	974	56	5.06	0.4	24.14	9.32	773
		QL4	518	867	39	5.78	0.31	24.79	9.86	619
		QL5	456	763	34	6.46	0.16	24.24	8.89	611

It can be seen that although the user is located near the AP he/she will experience interruptions with long periods of re-buffering, which was not the case when the network was loaded at 20-21Mbps. Moreover, when the user is located far from the AP, the QL1 streaming experience will be even worse, as the playout duration will reach almost nine times the normal playout length. In both cases QL4 and QL5 are the most efficient in terms of playout duration and energy efficiency. In conclusion, in the case of an overloaded network, adapting the video quality to a lower level proves to be more efficient in terms of both, energy and user perceived quality.

5.5.9. Impact of Traffic Distribution on Energy Consumption while Performing VoD Streaming over WLAN

When analyzing the impact of the network load on the energy consumption, one important characteristic is the traffic distribution. In order to study the impact of the traffic distribution, Scenario 3 (where the background traffic (20-21Mbps) is located near the AP) and Scenario 5 (where the background traffic (4-4.3Mbps) is located in an area with poor signal strength) were compared. The results of Scenario 3 are presented in Table 5.7, whereas the results of Scenario 5 are listed in Table 5.10. The impact of traffic distribution is more obvious when looking at QL1 and QL2. While in case of Scenario 3 the playout is smooth without interruptions, for Scenario 5 the playout for QL1 and QL2 presents frequent periods of video motion loss, with re-buffering periods representing: 19% and 11% for QL1 and QL2, respectively over UDP; 10% and 5% for QL1 and QL2, respectively over TCP. These re-buffering periods lead to increases, in playout duration and therefore, to increases in energy consumption. For the last three quality levels the playout is smooth without interruptions. It can be seen from Table 5.10 that the overall number of retransmissions is very high. This is because most of the traffic in the network is located in an area with poor signal strength.

TABLE 5.10. SCENARIO 5 – UDP AND TCP VOD STREAMING

	Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Avg. Th. [Mbps]	Avg. Ch. Traffic [Mbps]	Retr. [%]	Playout [sec.]
UDP	**QL1**	991	1389	74	3.5	1.88	5.54	18	714
	QL2	709	1058	53	4.65	1.03	5.44	35	670
	QL3	525	879	39	5.59	0.52	11.82	53	600
	QL4	477	800	36	6.15	0.28	3.97	9	600
	QL5	435	730	33	6.74	0.15	7.46	35	600
TCP	**QL1**	974	1467	73	3.35	2.07	5.96	14	664
	QL2	637	1016	48	4.84	1.14	6.01	17	627
	QL3	504	845	38	5.82	0.54	7.53	31	600
	QL4	451	756	34	6.5	0.27	6.53	25	600
	QL5	420	705	32	6.9	0.15	8.67	43	600

Considering the fact that the Android mobile device is located near AP, where there is good signal strength, one would have assumed that there will be no impact from the virtual stations located in poor signal areas. However the results show that because of the bad location of other mobile users (e.g., near the cell border) the users located near the AP will also be penalized in terms of user perceived quality, which is unfair.

5.5.10. Impact of the Network Technology on the Energy Consumption while Performing VoD Streaming

In order to study the impact of the network technology on the energy consumption, a set of measurements were conducted over two cellular networks: HSDPA from O2 and UMTS from eMobile. All the tests were performed with minimal background activities as for WLAN, and with the wireless interface disabled. The results are presented in Table 5.11. It can be noticed that although O2 offers HSDPA which is an enhanced version of UMTS with a theoretical data rate of 7.2Mbps, some video motion loss is experienced, with re-buffering periods representing 6% for QL3, 4% for QL4, and 1% for QL5, respectively. On the other hand, when streaming over UMTS, which has a theoretical data rate of 384kbps, the playout is smooth without interruptions and is more energy efficient as well. O2 is known as one of the top mobile service providers in Ireland, ranking on the second position right after Vodafone and owing 32.6% of the total market[27] while eMobile is new in the market (Sept. 2010) ranking on the last position. Based on this, as the network load cannot be actually measured, a realistic assumption, that the O2 network has more customers sharing the bandwidth, can be made. Thus it is more loaded than eMobile. This is reflected on the playout duration of the multimedia streams.

TABLE 5.11. SCENARIO 6 – UDP AND TCP VOD STREAMING

		Quality Level	Avg. Energy [J]	Avg. Power [mW]	Discharge [mAh]	Battery Life [hrs]	Playout [sec.]
O2 (HSDPA)	**TCP**	**QL3**	850	1330	64	3.70	640
		QL4	728	1173	55	4.19	621
		QL5	680	1119	51	4.39	607
eMobile (UMTS)	**UDP**	**QL3**	747	1254	56	3.92	600
		QL4	693	1160	52	4.24	600
		QL5	663	1110	50	4.43	600
	TCP	**QL3**	737	1230	55	4.00	600
		QL4	647	1078	49	4.56	600
		QL5	602	1004	45	4.90	600

Figure 5.15 illustrates a comparison overview in terms of energy consumption between local playback, the wireless interface (Scenario 1) and the UMTS interface while performing VoD over UDP.

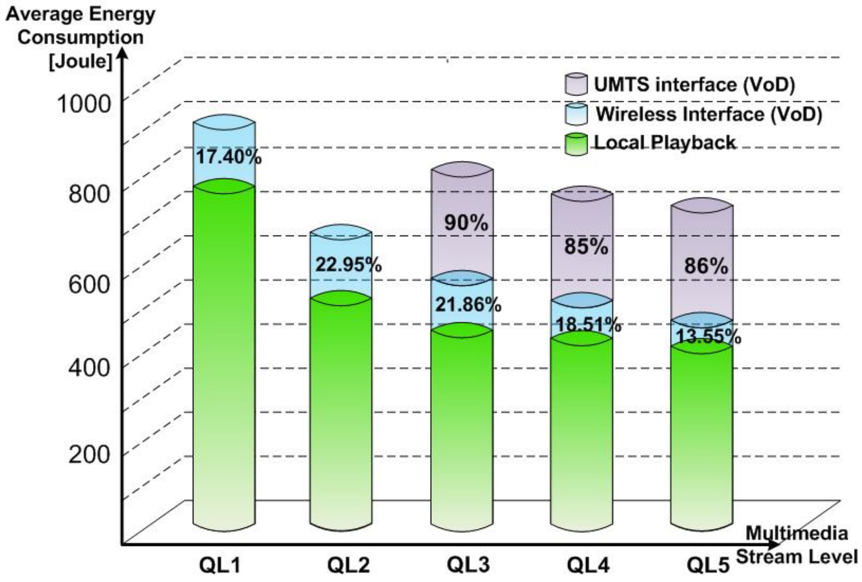


Figure 5.15. Avg. Energy Consumption for VoD Streaming: Local Playback vs. WLAN vs. UMTS

It can be noticed that while comparing with the local playback the UMTS interface accounts for 47% of the total energy consumption, presenting an increase of 85% to 90% in energy consumption. Comparing with the wireless interface by using the UMTS interface the energy consumption presents an increase of 50% (QL3) up to 61% (QL5). Comparing the

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[27] Europe mobile network operators - http://en.wikipedia.org/wiki/List_of_mobile_network_operators_of_Europe#Ireland

results obtained for on-demand streaming over UMTS as listed in Table 5.11, TCP is again more energy efficient than UDP.

5.5.11. User Perceived Impact of Video Buffering on Multimedia Quality

On-demand video streaming with QoS provisioning over wireless networks is challenging due to the constraints of the wireless links and user mobility. When assessing the quality of an on-demand streaming session, a number of factors need to be considered, such as: the quality of the encoded video source, network conditions, and device-related factors (e.g., decoding and displaying). In case of bad network conditions (e.g., high network load, high packet loss ratio, poor signal strength, etc.), the mobile terminal can suffer from buffer starvation, and the mobile user will experience periodic interruptions, periods of video motion loss, freezing of the video, etc. An in-depth study on the effect of interruptions on user-perceived streaming quality is presented by Tan et al. in [196].

The subjective study did not aim to assess the impact of video buffering on users perceived quality. However, in order to have an idea of the users' perception of buffering, the test subjects were asked to rate (on a 1-5 scale) what they consider to be the MOS given different freeze periods (<30s, 1min, 2min, 4min, and >6min) for a 10 minute high-quality mobile video clip. The results illustrated in Figure 5.16 show that, in order for the clip to maintain a 'Good' quality level, the buffering time should not exceed 1 minute.

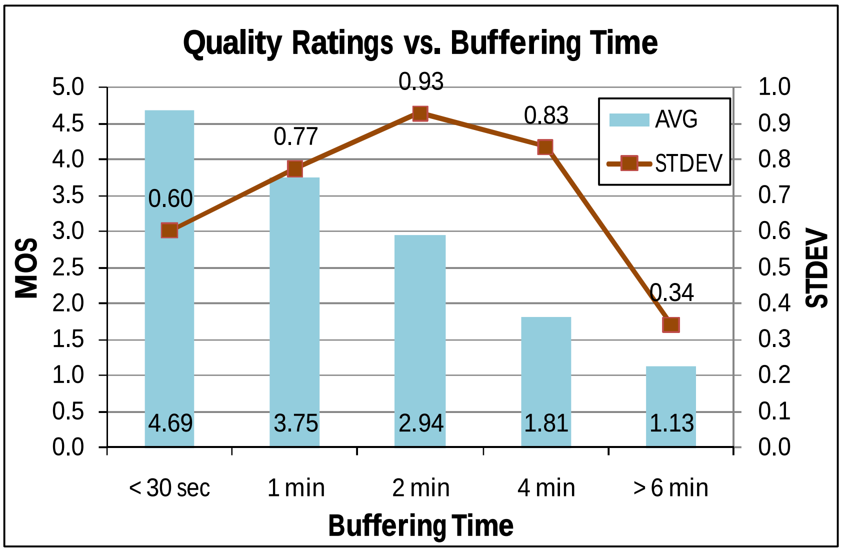

Figure 5.16. Subjective ratings reflecting users perception of how the video buffering impacts the multimedia quality

Looking at the answers and making abstraction of other factors that may occur in a real streaming scenario, an excellent video quality (e.g., QL1) will have a similar quality, as perceived by the user, with QL5 ('Fair'), if the buffering time is equal or higher than two minutes. Switching to a lower quality level reduces the probability of re-buffering periods, thus avoids the increase in playout duration, leading to energy conservation.

5.6. Chapter Summary

This chapter presents an in-depth study on how the wireless environment (e.g., link quality, network load, network technology, etc.) impacts on the energy consumption of a mobile device while performing VoD Streaming.

The tests were conducted on an Android Mobile Device (cellular interface disabled) in a controlled wireless (IEEE 802.11g) environment so to better understand the impact of each parameter on the energy consumption. Five different quality levels of the multimedia stream were considered and their impact on the energy consumption was analyzed. Subjective tests were carried out in order to validate the choice of the five quality levels.

The energy measurement results show that by changing the quality level of the multimedia stream the energy can be greatly conserved while the user perceived quality level is still acceptable. This is because different quality levels of the multimedia stream correspond to different amounts of data to be transmitted over the wireless network. Thus, a high quality level means a larger amount of data to be transmitted whereas by dropping the quality level, the amount of data to be transmitted is reduced. When receiving high quality levels the mobile device and its wireless interface have to process a large amount of data, meaning higher energy consumption of the mobile device. By lowering the quality level, the data to be received by the wireless interface and processed by the mobile device is less thus the energy consumption by the mobile device is reduced. This highlights the benefits that can be obtained by using an adaptive multimedia mechanism (e.g., Apple HTTP live streaming, Microsoft IIS server, Adobe Dynamic Streaming, and Akamai HD Video Streaming) in terms of energy consumption. These mechanisms can be further improved in order to integrate among other parameters, the energy consumption, making them more energy efficient. Another important observation is the impact of the transport protocol (e.g., UDP, TCP) on the energy consumption. The results show that TCP is more energy efficient than UDP in all situations. After analyzing the Wireshark trace files, it has been noticed that TCP has a larger packet size distribution than UDP. This means less data to be transmitted in case of TCP, leading to decrease in energy consumption of the mobile device.

In order to study the impact of network technology used on the energy consumption of the Android mobile device (WLAN disabled), a set of measurements were conducted over two cellular networks: HSDPA (O2 provider) and UMTS (eMobile provider). The results show that by using the cellular interface much more energy is consumed than by using the wireless interface.

Nowadays, the user mobility can be highly predicted and together with the users' patterns of usage it can be possible to identify where and when some wireless resources may be in high demand. Knowing the contextual information (e.g., link quality, network load, network technology, transport protocol, adaptive mechanism) and its impact on the energy consumption, it helps making more energy-efficient use of the wireless resources. Thus, these findings demonstrate the necessity of considering network-related parameters when designing energy-efficient wireless video transmission schemes.

The real test-bed experimental results presented in this chapter will be further used as an input for the simulation-based testing environment and numerical analysis. Next chapter details the deployment of the simulation-based testing environment and its validation. The results of the subjective tests presented here, are further used to model the quality utility previously introduced in Section 4.2.1.4. Whereas the energy measurement results are used to model a mathematical energy consumption pattern of the Google Nexus One Android device. Both are described in details in the next chapter.

Chapter 6

Simulation Testing Environment

This chapter presents the simulation-based testing environment and describes its validation by creating, running, and analyzing a simple wireless scenario. The quality utility introduced in Section 4.3.3.b is modeled and validated by using the results of the subjective tests for video quality assessment, previously presented in Section 5.5.1.The energy consumption equation introduced in Section 4.2.1.3 is modeled and based on the experimental results presented in the previous chapter, a mathematical energy consumption pattern for the Google Nexus One Android Device is proposed and validated. The choice of the Score Function introduced in Section 4.2.1.4 is evaluated through mathematical analysis performed in Matlab. Its performance is analyzed and compared against the main MADM ranking methods (GRA, SAW, and TOPSIS). The analysis is based on the experimental results from Chapter 5.

6.1. Building the Simulation-based Testing Environment

6.1.1. Enhanced Network Simulator

The simulation environment is based on the NS-2 Network Simulator (v2.33) [197]. In order to test the proposed solutions, there was a need to build a complex simulator-based testing environment. The standard version of the simulator provides support for the simulation of different protocols (e.g., UDP, TCP) over wired and wireless networks (e.g., IEEE 802.11b). The basic NS-2 allinone v2.33 simulator was enhanced in order to create the necessary heterogeneous environment and to be able to simulate as realistic environment as possible.

For the WLAN environment, the No Ad Hoc (NOAH) wireless routing agent [198] was integrated in order to allow direct communication between mobile users and the AP only. The NOAH package was updated to work with the NS-2 version 2.33.

The standard version of NS-2 supports the simulation of 802.11b wireless channels only, no support for 802.11g being included. The standard channel propagation model provided by the simulator does not consider the impact of interference, different thermal noises, or employed channel coding when determining the correct reception of frames. This means that the transmission range of a mobile node is modeled to be the same regardless of the data transmission rate. This is not realistic for 802.11 WLANs. The wireless update patch provided by Marco Fiore in [199] was used in order to improve the support for wireless communications scenarios by adding realistic channel propagation, multi-rate transmission support and Adaptive Auto Rate Fallback (AARF) [200]. The patch, computes the Signal to Interference plus Noise Ratio (SINR) in order to add the effect of interference and different thermal noises. The Bit Error Rate (BER) is also considered when deciding whether the frame was transmitted correctly or not and whether it has to be discarded. BER is taken from the empirical BER vs. SNR (Signal to Noise Ratio) curves measured for IEEE 802.11b PHY modes and provided by Intersil HFA3681B chipset as illustrated in Figure 6.1 [201]. The wireless update patch was initially built for NS-2.29 and had to be updated in order to work with NS-2.33.

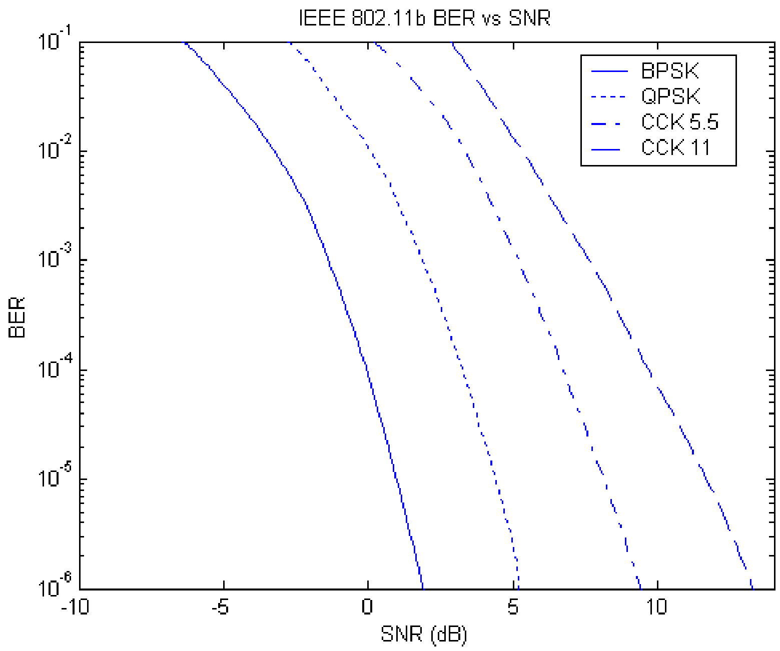

Figure 6.1. IEEE 802.11b BER vs. SNR [201]

Because IEEE 802.11g networks were used in the experimental test-bed as described in Chapter 5, the NS-2 source code was modified in order to add support for IEEE 802.11g. To obtain a more realistic behavior of the IEEE 802.11g channel, the wireless update patch provided by Marco Fiore was extended, and the multi-rate transmission support was updated for IEEE 802.11g.

IEEE 802.11g supports 12 data transmission rates (IEEE 802.11b + IEEE 802.11a) with the corresponding modulation scheme. As IEEE 802.11g uses the transmission rates and modulation schemes from both IEEE 802.11b and IEEE 802.11a, the values for BER were taken from the empirical BER vs. SNR curves provided for IEEE 802.11b [201] as in Figure 6.1 and IEEE 802.11a illustrated in Figure 6.2 [202]. The characteristics of the IEEE 802.11g physical layer integrated in the simulator are taken from Cisco Aironet 802.11a/b/g Wireless Card [203] and they are illustrated in Table 6.1.

TABLE 6.1. CHARACTERISTICS OF THE IEEE 802.11G PHY LAYER

Rate [Mbps]	**Modulation**	**Receive Sensitivity [dBm]**
1	*DSSS/BPSK*	-94
2	*DSSS/QPSK*	-93
5.5	*DSSS/CCK*	-92
6	*OFDM/BPSK*	-86
9	*OFDM/BPSK*	-86
11	*DSSS/CCK*	-90
12	*OFDM/QPSK*	-86
18	*OFDM/QPSK*	-86
24	*OFDM/16QAM*	-84
36	*OFDM/16QAM*	-80
48	*OFDM/64QAM*	-75
54	*OFDM/64QAM*	-71

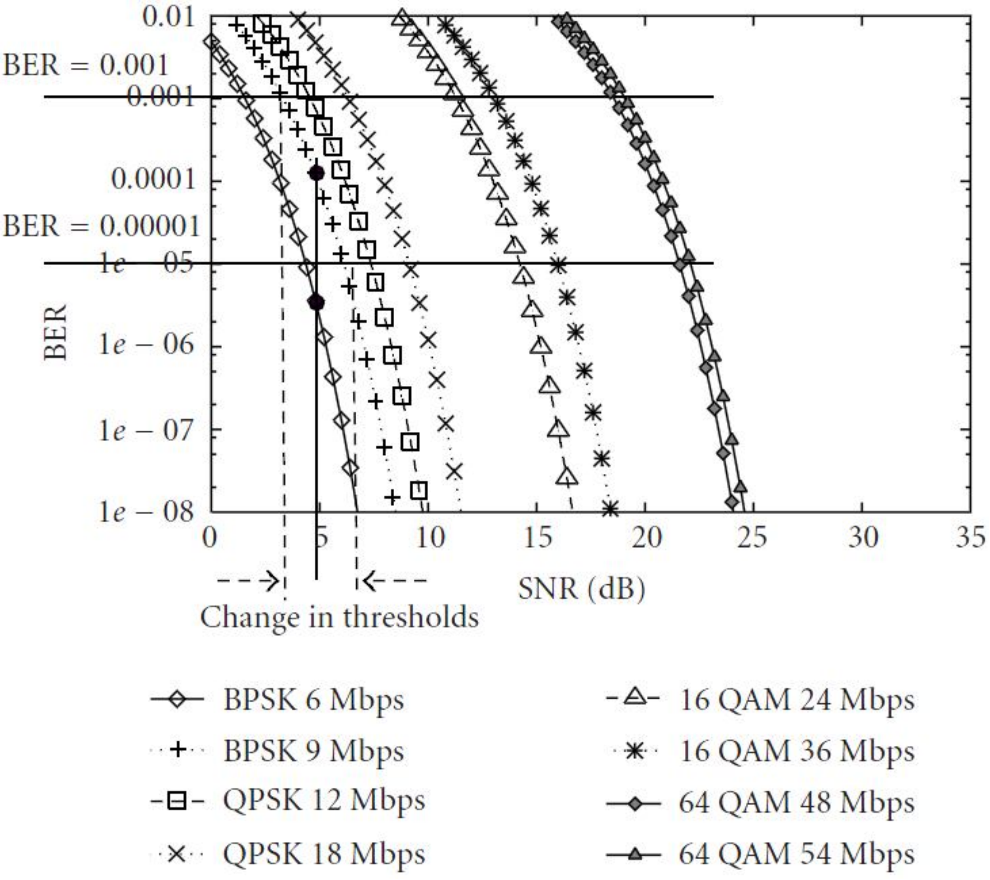

Figure 6.2. IEEE 802.11a BER vs. SNR [202]

The values of the physical parameters for the modulations schemes of 802.11b and 802.11g used in NS-2 are presented in Table 6.2.

TABLE 6.2. IEEE802.11B AND IEEE 802.11G PHY PARAMETERS

Parameter	Value 802.11b	Value 802.11g	Description
MAC dataRate_	11Mbps	54Mbps	*Theoretical Data Transmission Rate*
MAC basicRate_	1Mbps	6Mbps	*Theoretical Transmission Basic Rate*
CWmin	31	15	*Minimum Contention Window*
CWmax	1023	1023	*Maximum Contention Window*
SlotTime	9µsec	20µsec	*Slot Time*
SIFSTime	16µsec	10µsec	*SIFS Time*

In order to create a heterogeneous environment, the EURANE patch [204] was used. EURANE adds the support for UMTS network and it is available for NS-2.30. The patch was modified in order to work with NS-2.33. The wireless environment in NS-2 uses hierarchical addressing, this enables grouping of the nodes into clusters and domains in the same way as in the Internet IP addressing. However the EURANE patch comes with flat addressing making it incompatible to work with other IEEE 802.11g networks in a heterogeneous wireless scenario. For this reason EURANE was enhanced by adding the support for hierarchical addressing. The UMTS scenarios use some input trace files that can be generated with Matlab[1]. The trace files can be created for different realistic environments, modifying some of the physical layer parameters, like: environment (e.g., rural, urban, hilly terrain, etc.), velocity of the mobile user, distance from the BS, duration of the simulation, etc. The trace files provide the BLER (Block Error Rate) values and are meant to create a more realistic simulation environment.

6.1.2. Models and Algorithms Integration

As mentioned in Chapter 4, the overall proposed solution is structured in four main components:

(1) the **Power-Friendly Access Network Selection Mechanism (PoFANS)** which performs the selection of the best value network, based on user preferences, application requirements, and network conditions;

(2) the **Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy)** which adapts the multimedia stream based on network conditions in order to maintain acceptable user perceived quality levels;

(3) the **Adapt-or-Handover** mechanism which decides whether to adapt the multimedia stream or to handover to a new network in order to conserve the energy consumption of the mobile device;

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[1] Matlab - http://www.mathworks.co.uk/products/matlab/index.html

(4) the **Reputation-based Network Selection** mechanism which makes use of game theory in order to model the user-network interaction, and builds a reputation-based heterogeneous environment.

PoFANS and the reputation-based network selection mechanisms were developed as described in Section 4.2 and Section 4.5, respectively, and analyzed in Matlab. SAMMy and the Adapt-or-Handover solutions were developed as presented in Section 4.3 and Section 4.4 and integrated in NS-2.

The Adapt-or-Handover solution makes use of both PoFANS and SAMMy, and was deployed in NS-2 as an application containing both server-side and client-side components. A schematic integration of the solution architecture within NS-2 is illustrated in Figure 6.3. As the Adapt-or-Handover solution requires a multi-interface mobile node that can be connected to different wireless networks (e.g., WLAN, UMTS), the standard implementation of the wireless node in NS-2 had to be updated.

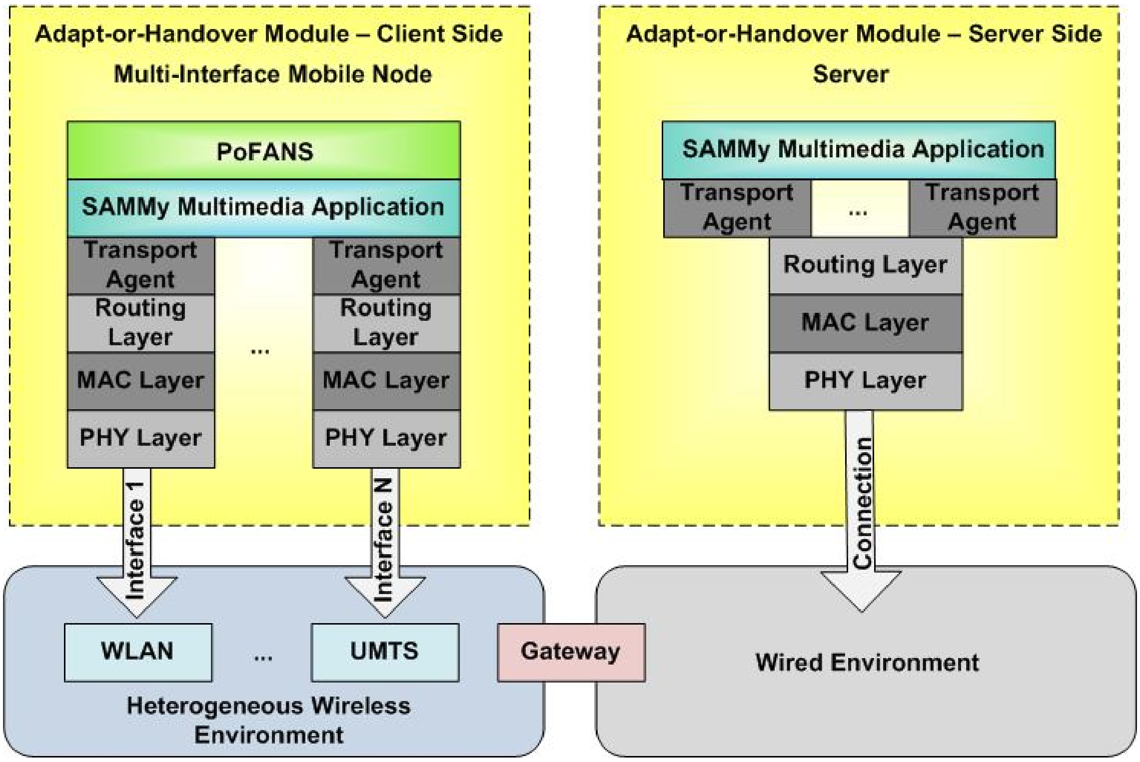


Figure 6.3. NS-2 Adapt-or-Handover Solution: Client Side and Server Side - Layered Model

As seen in Figure 6.3, each interface (one for each each network) will use a separate transport agent for multimedia delivery. The transport agent from the client-side will be connected to its corresponding agent at the server side. The Adapt-or-Handover mechanism will make use of PoFANS (as described in Chapter 4) in order to compute the score for each of the available networks and determine the corresponding interface and the suitable quality level for video delivery. All the input data required by PoFANS is assumed to be available at the client side.

At the client side, the SAMMy-enabled multimedia application (as describe in Chapter 4) will make use of the transport agent and its corresponding connection in order to receive the adaptive multimedia traffic from the server.

This SAMMy module sends feedback reports to the server containing: location information, packet loss information, received signal strength, maximum and minimum acceptable quality level (provided by the PoFANS module). The server side is represented by a wired node that has a single high bandwidth wired connection. The Gateway is represented by a node that connects the wired network to the wireless network. The SAMMy server side component determines the quality level (based on the received feedback) that has to be delivered to the mobile client over the existing connection. Note that in the simulation scenarios individual simulations for each interface were conducted. The detailed algorithm of each solution is provided in Chapter 4.

6.2. Validating the Wireless Environment

In order to validate the wireless environment integrated in NS-2, a simple scenario was created as illustrated in Figure 6.4.

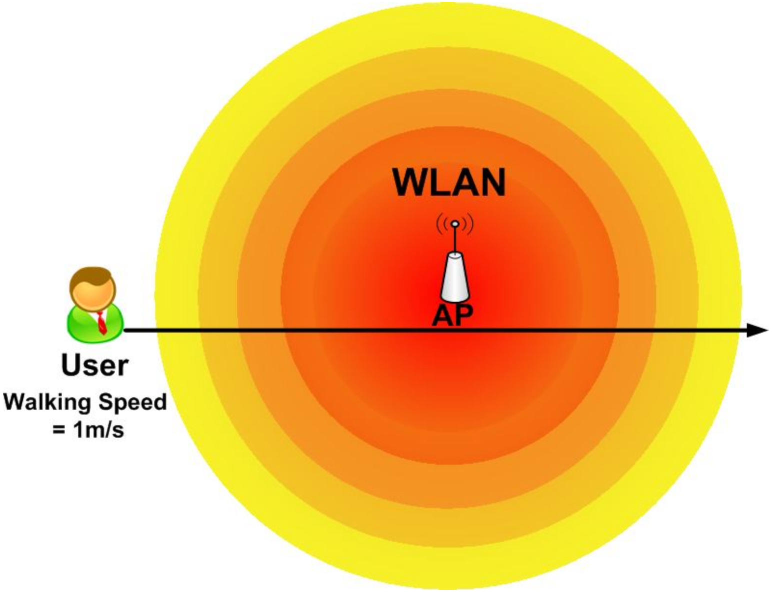
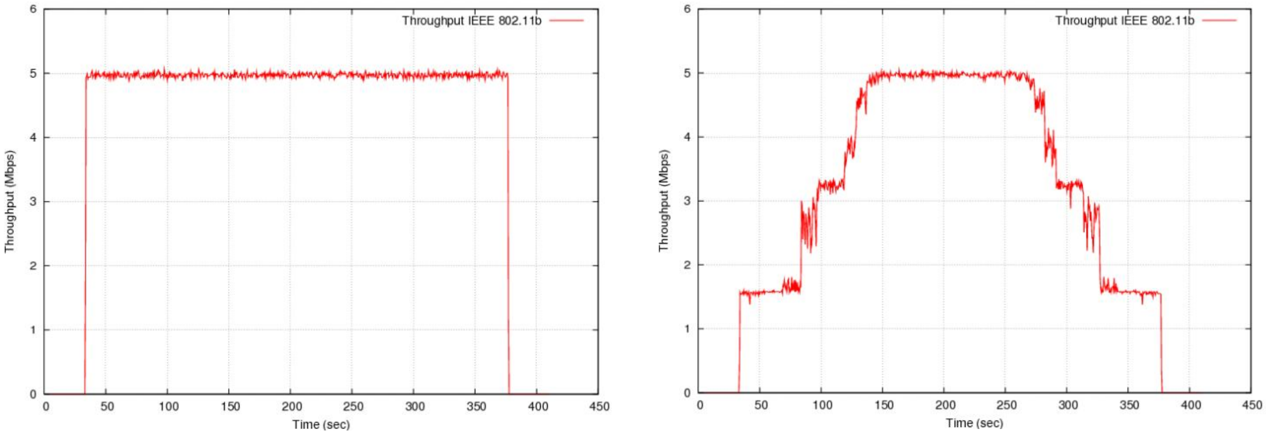


Figure 6.4. Validation Scenario – User moving towards and away from AP

The scenario is run for both IEEE 802.11b and IEEE 802.11g network types. A mobile user moves, at a walking speed of 1m/s, towards the AP and then away from the AP. The mobile user receives CBR (Constant Bit Rate) traffic at the highest data rate that can be provided (theoretically) by each network (i.e., 11Mbps for IEEE 802.11b and 54Mbps for IEEE 802.11g).

Figure 6.5 illustrates the user's received throughput during his/her path when simulating an IEEE 802.11b network using the standard version of NS-2.33 and when using NS-2.33 with the wireless update patch [199] integrated.



a) Standard NS-2.33

b) NS-2.33 plus wireless update patch

Figure 6.5. Received Throughput for User Moving Towards and then Away from an IEEE 802.11b AP

It can be noticed that the wireless update patch provides a more realistic model of an IEEE 802.11b wireless environment. As the mobile user moves towards and then away from the AP, in the standard version of the simulator the received throughput maintains the same value for the entire user's path, until the user moves out of the AP's coverage area. Whereas in the patched version of the simulator (with the wireless update patch), the throughput presents a step-wise increase as the user moves towards the AP and a step-wise decrease as the user moves away from the AP. The results are according to the IEEE 802.11b standard [12]. As noticed, the maximum throughput that can be achieved by the user in this scenario is 5Mbps even though the theoretical data rate for IEEE 802.11b is 11Mbps[2].

After the integration of the IEEE 802.11g network in NS-2.33, the same scenario was considered for its validation as for IEEE 802.11b (see Figure 6.4). Figure 6.6 illustrates the user's received power and received throughput as he/she is moving towards and then away from the AP at a constant speed of 1m/s.

As noticed in Figure 6.6(b), as the user is moving away from the AP, his/her received throughput is step-wise decreasing, as described in the standard [13]. The maximum received throughput in this scenario goes up to 22-23Mbps, even though the maximum theoretical throughput for IEEE 802.11g is 54Mbps[3].

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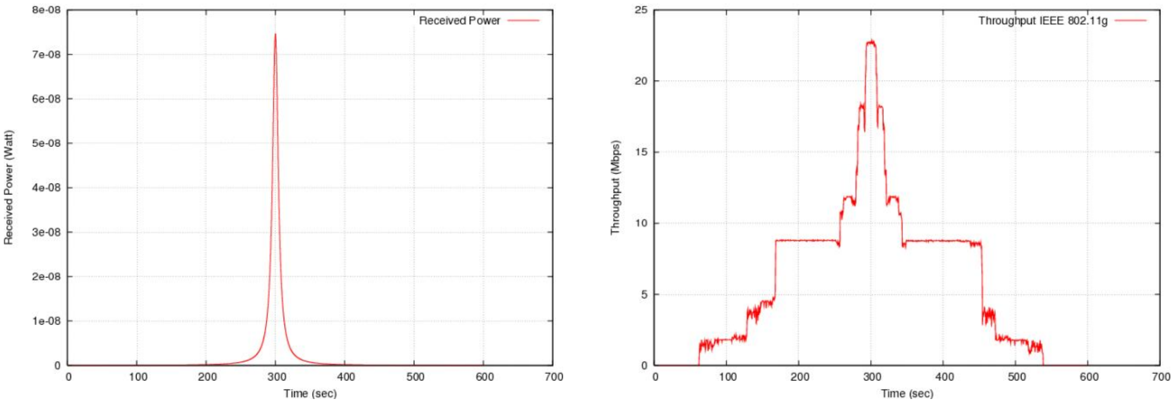
[2] Actual Speed of an IEEE 802.11b Wi-Fi Network http://compnetworking.about.com/od/wirelessfaqs/f/maxspeed80211b.htm

[3] IEEE 802.11g http://www.cisco.com/en/US/products/hw/wireless/ps4570/products_white_paper09186a00801d61a3.shtml



a) Received Power

b) Received Throughput

Figure 6.6. User Moving Towards and then Away from an IEEE 802.11g-based AP

6.3. IEEE 802.11 Performance Anomaly

The IEEE 802.11 standard uses the Distributed Coordination Function (DCF) based on the Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) access method in order to provide similar medium access priority to all the users. Previous studies have analyzed the performance of the IEEE 802.11 multi-rate WLANs and have shown the existence of a performance anomaly [205]. This anomaly occurs when multiple users share the radio channel of an IEEE 802.11 network. If there is at least one mobile node transmitting at a lower rate, the throughput of all the mobile nodes transmitting at a higher rate will be degraded below the level of the lower transmission rate.

In order to show this, two cases are analyzed, in which two mobile users are watching a video stream on their mobile devices:

(1) Case 1 - both users are located near an IEEE 802.11b AP, in the 11 Mbps zone (theoretical data rate);

(2) Case 2 - user 1 is located near the AP while user 2 is located far away from the AP, in the 1 Mbps zone (theoretical data rate).

Table 6.3 illustrates the average throughput achieved by each user when the two cases are simulated in NS-2.33. The results for **Case 1** are as expected. The combined throughput is around 5Mbps. However, the results for **Case 2** show that user 1 achieves almost the same low throughput rate as user 2, who is located at the edge of the network, in the 1 Mbps zone. It seems unfair that the mobile nodes located near the AP are penalized in terms of throughput because there are other mobile nodes badly located near the network edge. To overcome this problem many solutions have been proposed [206][207][208]. The main disadvantage of these solutions is that they require changes to the existing standards at MAC or network layers. The updates NS-2.33 simulator used for testing does not implement any such solution and obeys the IEEE 802.11 standard [14] as the results in Table 6.3 show.

TABLE 6.3. PERFORMANCE ANOMALY – EXAMPLE SCENARIO FOR IEEE 802.11B

	Average Throughput [Mbps]	
	User 1	**User 2**
Case 1	2.79	2.58
Case 2	0.87	0.84

6.4. Modeling the Quality Utility

This section shows the validation for the choice of the quality utility integrated in the network selection mechanism as described in Section 4.3.3.b. The quality utility is modeled as a sigmoid function, based on the idea that there is a minimum throughput required by a multimedia application in order to provide a minimum acceptable quality to the user. If the received throughput goes below this value, the quality becomes unacceptable and the quality utility is zero, meaning that the provided service is worth nothing to the user. On the other side, there is a maximum throughput required by a multimedia application in order to provide high quality levels to the user. The received throughput that goes above this maximum will not add much to the already existing high quality, but still it will increase the energy consumption and possibly it is wasted traffic on the operators' network.

In this work five different quality levels are considered, from QL1 (high quality) to QL5 (low quality). The five quality levels were chosen as described in Section 5.2.4 and their characteristics were illustrated in Table 5.2. The same quality levels presented in the experimental testing chapter (Chapter 5) will be used in the simulation-based testing (Chapter 6). After performing the subjective tests, described in Section 5.5.1, a Mean Opinion Score (MOS) was assigned for each considered quality level. Figure 6.7 shows the relationship between the quality utility, received throughput (Quality Levels) and MOS.

As can be noticed from Figure 6.7, the results obtained through subjective testing for the five quality levels, validate the choice of the sigmoid function.

Based on the quality levels' characteristics, the quality utility is modeled as in equation (6.1).

$$u_q(Th) = \begin{cases} 0 & , \quad Th < 0.120 \\ 1 - e^{\frac{-\alpha * Th^2}{\beta + Th}} & , \quad 0.120 <= Th < 1.920 \\ 1 & , \quad otherwise \end{cases} \qquad (6.1)$$

where α and β are two positive parameters that are determined knowing that: **(1)** for Th_{max} (1.920Mbps) the utility has its maximum value (e.g., $u_{max} = 0.99$ in order to avoid *ln(0)* which is invalid); **(2)** the second order derivate of u_q equals 0 for Th_{req} (0.480Mbps). The two conditions mentioned above will reduce to equation (6.2) and (6.3).

$$\alpha = \frac{\ln(1-u_{\max})(\beta + Th_{\max})}{-Th_{\max}^{2}} = 5.72 \qquad (6.2)$$

$$\begin{aligned}
&[1+2\ln(1-u_{\max})(\frac{Th_{req}}{Th_{\max}})^{2}]\beta^{3} + [Th_{req} + 2\ln(1-u_{\max})\frac{Th_{req}^{2}}{Th_{\max}} \\
&+ 2\ln(1-u_{\max})\frac{Th_{req}^{3}}{Th_{\max}^{2}}]\beta^{2} + [2\ln(1-u_{\max})\frac{Th_{req}^{3}}{Th_{\max}} + \ln(1-u_{\max})\frac{Th_{req}^{4}}{2Th_{\max}^{2}}]\beta \qquad (6.3)\\
&+ \ln(1-u_{\max})\frac{Th_{req}^{4}}{2Th_{\max}} = 0 \\
&\Rightarrow \beta = 2.66
\end{aligned}$$

where the positive solution of equation (6.3) is the value of β. In this particular case the values for α and β, after solving all the mathematical computations, are 5.72 and 2.66, respectively. For any other choice of quality levels, the procedure of identifying the parameters of the quality utility function is similar.

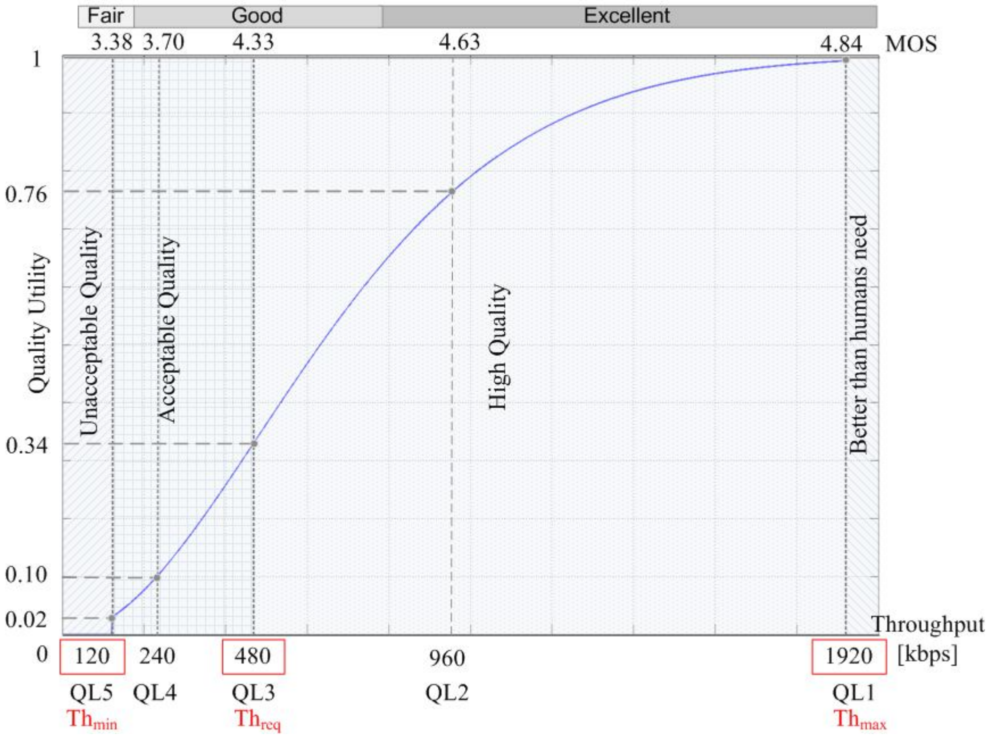


Figure 6.7. Quality Utility - Validation

6.5. Modeling the Energy Consumption Pattern

This section models the energy consumption pattern of the ***Google Nexus One Android mobile device***, by using the energy equation (4.1) and the energy measurements performed with the real experimental test-bed, presented in Chapter 5. Considering only the case of UDP-based video delivery, the r_t (the mobile device's energy consumption per unit of time), and r_d (energy consumption rate for data/received stream) are computed for five of the test scenarios presented in Section 5.3: **(1)** WLAN – No load, near AP; **(2)** WLAN – No load, far AP; **(3)** WLAN – Load, near AP; **(4)** WLAN – Load, far AP; **(5)** UMTS.

Following the mathematical calculations the values for r_t and r_d were computed and presented in Table 6.4, for each considered scenario.

TABLE 6.4. R_T AND R_D COMPUTED VALUES

	WLAN				**UMTS**
	No Load, Near AP	**No Load, Far AP**	**Load, Near AP**	**Load, Far AP**	**e-Mobile Network**
r_t	0.6341570	0.6690961	0.6641148	0.7115433	1.058
r_d	0.0003869	0.0002377	0.0003660	0.0004889	0.000388

By using these results the energy consumption pattern of the Google Nexus One can be modeled as a mathematical equation, illustrated below:

$$E = t(r_t + Th \cdot r_d) \qquad (6.4)$$

where *t* represents the transaction time, the multimedia stream duration taken from Chapter 5 for each of the test scenarios, r_t and r_d are taken from Table 6.4, for each considered scenario, *Th* is the received throughput.

In order to validate the energy equation, the Wireshark trace files, captured from the experimental test-bed, were used in order to extract the received throughput of the Google Nexus One during the video delivery of each quality level of the ten-minute video clip, and for each considered scenario. **Wireshark** captured the network conditions every **10 seconds**. The extracted throughput was then used in equation (6.4) in order to compute the energy consumption of the device.

During the experimental test-bed the energy consumption of the Google Nexus One was measured with the Arduino board, as explained in Chapter 5. The **Arduino** board measures the energy consumption of the device every **1 second**. The computed energy was then compared against the measured energy. Figure 6.8 and Figure 6.9 illustrate the received *Throughput (Wireshark)*, *Measured Energy (Arduino board)*, and *Computed Energy* (equation (6.4)) for QL1 and QL5, respectively in each considered scenario. Note that the throughput and the computed energy are represented by 60 points, while the measured energy by 600 points. This represents a reason, together with the possible synchronization issues between the trace files generated by different tools (Wireshark and Arduino), for which the plots might present slight variations. However, despite these issues, the energy equation provides a good approximation of the average energy consumption of the mobile device. The average values in all considered scenarios and for all the quality levels are presented in Table 6.5.

TABLE 6.5. MEASURED ENERGY VS. COMPUTED ENERGY [JOULE]

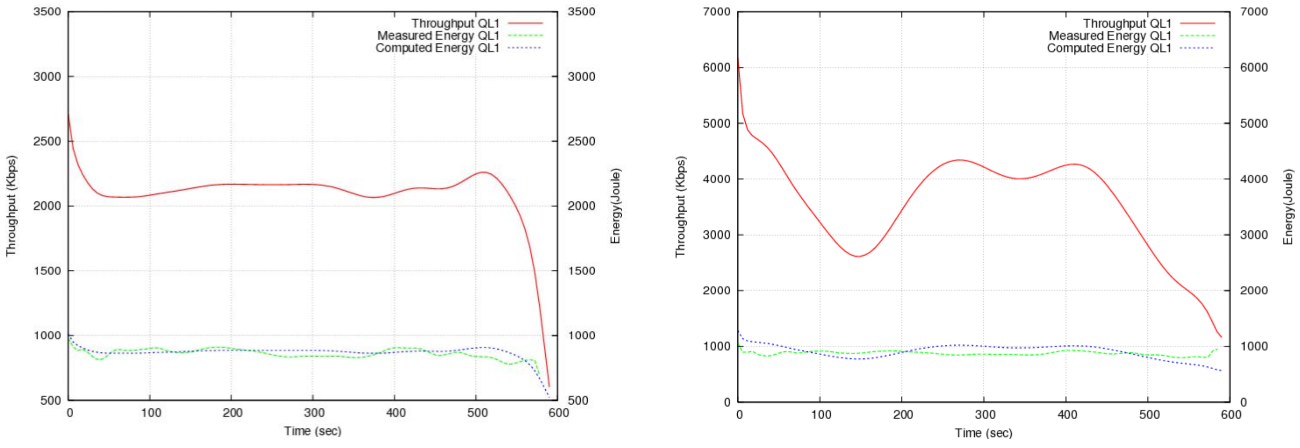
	WLAN								UMTS	
	No Load, Near AP		No Load, Far AP		Load, Near AP		Load, Far AP		e-Mobile Network	
	Measured Energy	Computed Energy	Measured Energy	Computed Energy	Measured Energy	Computed Energy	Measured Energy	Computed Energy	Measured Energy	Computed Energy
QL1	862	861.1	875	875	897	897	1300	1300	N/A	N/A
QL2	610	624.2	628	625	657	658	826	841	N/A	N/A
QL3	503	501.2	512	486	536	541	667	614	747	747
QL4	459	440.8	463	439	466	478	512	515	693	691
QL5	413	412.9	420	420	438	438	468	468	663	663

By performing t-tests on the *Measured Energy* and *Computed Energy* results for each multimedia quality level and for each considered scenario, it is shown that there is no statistical difference between the average values of the two sets of results. The t-tests compare the two sets of data assuming equal variances. The t-tests results are presented in Table 6.6. As noticed, in all cases the ***test statistic (t Stat) < critical value (t Critical)*** and the *p value > significant level (α)*. This accepts the null hypothesis and demonstrates that there is no statistical difference between the average results provided by the energy equation (Computed Energy) and the average values provided by the real test measurements (Measured Energy). This finding is stated with a very high level of confidence of 95% (the significant level, α = 0.05).

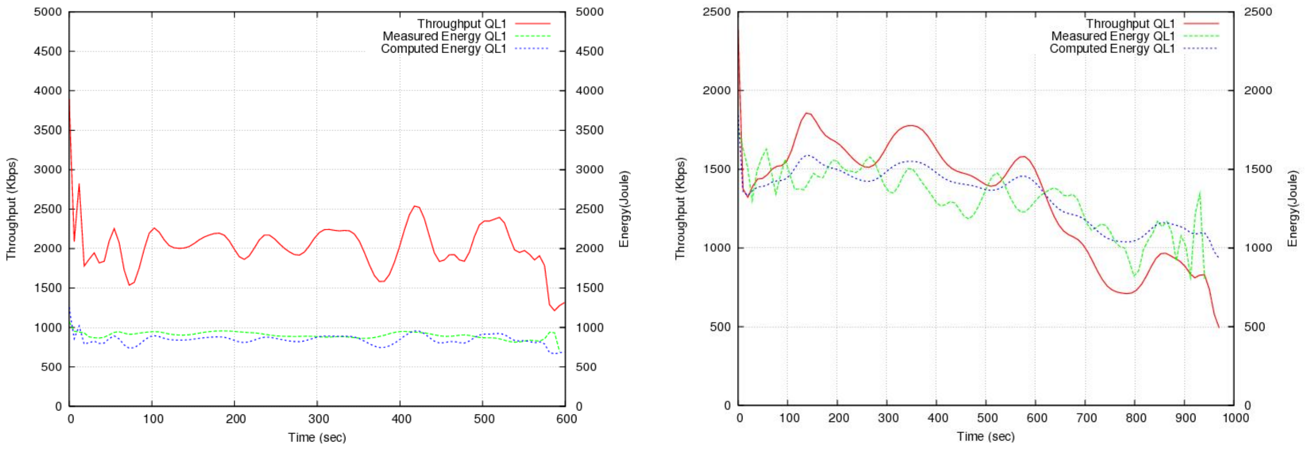
The results show that the proposed energy equation provides a good approximation of the average energy consumption of the Google Nexus One device. The r_t and r_d values will be mapped to the quality levels and the equation will be further used in the simulations in order to provide a more realistic environment.

TABLE 6.6. T-TEST RESULTS: TWO-SAMPLE ASSUMING EQUAL VARIANCES

	WLAN				UMTS
	No Load, Near AP	No Load, Far AP	Load, Near AP	Load, Far AP	e-Mobile Network
α	0.05	0.05	0.05	0.05	0.05
t Stat	0.011706	0.090233	-0.03065	0.032723	0.019135
P(T<=t)	0.990947	0.930321	0.976299	0.974697	0.985649
t critical	2.306004	2.306004	2.306004	2.306004	2.776445



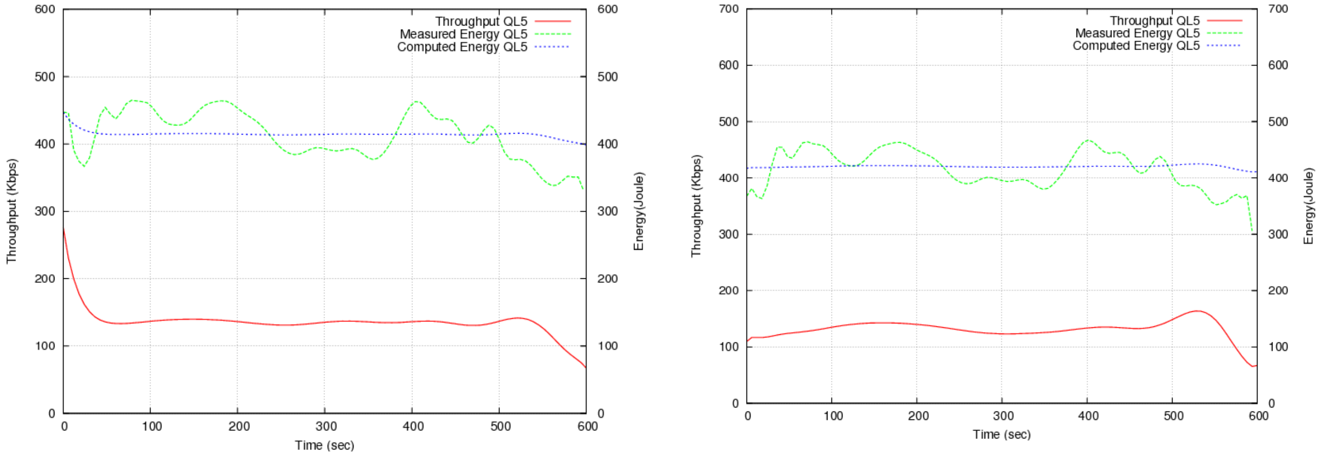
a) No Load, Near AP b) No Load, Far AP



c) Load, Near AP

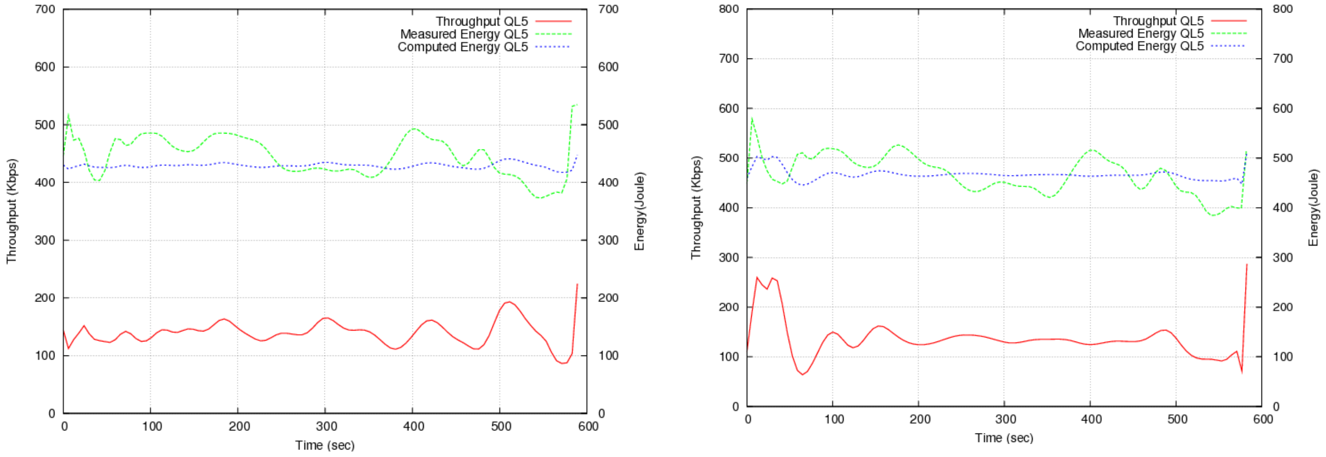
d) Load, Far AP

Figure 6.8. Throughput vs. Measured Energy vs. Computed Energy for QL1 for each of the four scenarios: a) No Load, Near AP; b) No Load, Far AP; c) Load, Near AP; d) Load, Far AP



a) No Load, Near AP

b) No Load, Far AP



c) Load, Near AP

d) Load, Far AP

Figure 6.9. Throughput vs. Measured Energy vs. Computed Energy for QL5 for each of the four scenarios: a) No Load, Near AP; b) No Load, Far AP; c) Load, Near AP; d) Load, Far AP

6.6. Evaluation of the Ranking Methods

This section evaluates four of the MADM methods: GRA, MEW, SAW, and TOPSIS, in order to analyze if they produce similar results under different conditions. The mathematical background to each method was introduced in Section 2.

The proposed network selection mechanism, PoFANS, is an energy efficient solution based on the Multiplicative Exponential Weighted method (MEW). For this reason the methods were analyzed in terms of energy-quality trade-off. In order to accomplish this, the candidate networks considered are the networks from the experimental test-bed described in Chapter 5. Despite the fact that the experimental testing was carried out with the same network but in different conditions, here it is assumed that each situation represents in fact a new candidate network with different conditions.

Based on this assumption the networks are as follows: **WLAN1 –** *No Load, Near AP*; **WLAN2** – *No Load, Far AP*; **WLAN3** – *Load, Near AP;* **WLAN4** – *Load, Far AP;* **UMTS** – *eMobile network.* Because in each network video at five quality levels (except three quality levels for UMTS) can be delivered, it is assumed that the network selection is performed between the quality levels and the five networks. A total number of 23 options are considered. The outcome will be the best value network that provides the best quality-energy trade-off.

Each ranking method will assign a score to each network and for each quality level. The network that has the highest score for a certain quality level will be selected as the target network.

In SAW and MEW the score for a given network *i* is calculated using additive and multiplicative operations, as defined in equation (6.5) and equation (6.6), respectively. Whereas GRA uses the best reference network in order to describe the similarity between each of the candidate networks, and TOPSIS scores the networks based on the distance from the best and worst reference networks. These methods formulas are presented in equation (6.7) and equation (6.8), respectively. The best reference network is defined as an ideal network formed with the best values of each parameter, whereas the worst reference network will be formed with the worst values of each parameter. In order to analyze the efficiency of each ranking method, the parameter utility functions were kept the same between them.

$$SAW_i = w_e \cdot u_{e_i} + w_q \cdot u_{q_i} + w_c \cdot u_{c_i} \quad (6.5)$$

$$MEW_i = u_{e_i}^{\ w_e} \cdot u_{q_i}^{\ w_q} \cdot u_{c_i}^{\ w_c} \quad (6.6)$$

$$GRA_i = \frac{1}{w_e \cdot |u_{e_i} - u_e^{\ b}| + w_e \cdot |u_{q_i} - u_q^{\ b}| + w_c \cdot |u_{c_i} - u_c^{\ b}| + 1} \quad (6.7)$$

$$TOPSIS_i = \frac{D_{w,i}}{D_{b,i} + D_{w,i}} \quad (6.8)$$

where w_e, w_q, and w_c represent the weights of the three parameters: energy, quality, and cost; u_e, u_q, u_c are the utility functions for each of the three parameters: energy utility, quality utility, and cost utility, as introduced in Section 4; u_e^b, u_q^b, and u_c^b are the utility values for the best reference network.

$D_{w,i}$ and $D_{b,i}$ represent the Euclidian distance of a network *i* from the worst and from the best, respectively, reference network and their values are given by equation (6.9) and equation (6.10), respectively:

$$D_{w,i} = \sqrt{w_e^{\ 2} \cdot (u_{e_i} - u_e^{\ w})^2 + w_e^{\ 2} \cdot (u_{q_i} - u_q^{\ w})^2 + w_c^{\ 2} \cdot (u_{c_i} - u_c^{\ w})^2} \quad (6.9)$$

$$D_{b,i} = \sqrt{w_e^{\ 2} \cdot (u_{e_i} - u_e^{\ b})^2 + w_e^{\ 2} \cdot (u_{q_i} - u_q^{\ b})^2 + w_c^{\ 2} \cdot (u_{c_i} - u_c^{\ b})^2} \quad (6.10)$$

where u_e^w, u_q^w, and u_c^w are the utility values for the worst reference network.

The quality utility, u_q was defined in Section 6.4, equation (6.1), whereas the energy utility and the cost utility were defined in Section 4, equation (4.3) and equation (4.4), respectively. The energy utility is described by the energy equation as modeled in Section 6.5, equation (6.4). E_{max} is computed as the average of the energy measurements presented in Table 6.5 for QL1 in each considered scenario, whereas E_{min} represents the average of the energy measurements for QL5 in each considered scenario. So that E_{max} = 983.4 Joule and E_{min} = 434.75 Joule (these values are used within the rest of the simulations scenarios presented in this thesis).

In order to analyze the energy-quality trade-off of each ranking method, the weight for the cost was considered to be zero whereas the weights for energy and quality are considered to be equal, such that: $\mathbf{w_e = 0.5}$, $\mathbf{w_q = 0.5}$, and $\mathbf{w_c = 0}$.

The best reference network is built from the best values of each parameter while the worst reference network, considers the worst value of each parameter. In this context, from the five networks, the best reference network is considered to be the one that provides the highest quality level QL1 ($u_q^b = 1$), with the lowest energy consumption of 413 Joule ($u_e^b = 1$), whereas the worst reference network is considered to provide the lowest quality level QL5 ($u_q^w = 0.0292$) with the highest energy consumption of 1300 Joule ($u_e^w = 0$).

The results of each ranking method (e.g., GRA, MEW, SAW, and TOPSIS) for each quality level and for each network are given in Table 6.7. The first three choices of each ranking method within each network are indicated by colors, such that: the first choice is represented in green, the second choice is marked by blue, and the third place is marked by orange.

TABLE 6.7. Ranking Method Results: GRA vs. MEW vs. SAW vs. TOPSIS

	WLAN1				**WLAN2**				**WLAN3**			
	No Load, Near AP				**No Load, Far AP**				**Load, Near AP**			
	GRA	**MEW**	**SAW**	**TOPSIS**	**GRA**	**MEW**	**SAW**	**TOPSIS**	**GRA**	**MEW**	**SAW**	**TOPSIS**
QL1	**0.7198**	**0.4706**	**0.6107**	**0.5612**	**0.7137**	**0.4445**	**0.5988**	**0.5525**	**0.7036**	**0.3968**	**0.5787**	**0.5386**
QL2	**0.7766**	**0.7103**	**0.7124**	**0.7048**	**0.7712**	**0.7005**	**0.7034**	**0.6948**	**0.7606**	**0.6804**	**0.6853**	**0.6746**
QL3	**0.7191**	**0.5480**	**0.6094**	**0.5818**	**0.7153**	**0.5433**	**0.6019**	**0.5770**	**0.7066**	**0.5323**	**0.5848**	**0.5654**
QL4	0.6879	0.3253	0.5462	0.5254	0.6847	0.3230	0.5395	0.5219	0.6770	0.3174	0.5228	0.5127
QL5	0.6732	0.1709	0.5146	0.5074	0.6732	0.1709	0.5146	0.5074	0.6719	0.1704	0.5116	0.5059

	WLAN4				**UMTS**			
	Load, Far AP				**e-Mobile Network**			
	GRA	**MEW**	**SAW**	**TOPSIS**	**GRA**	**MEW**	**SAW**	**TOPSIS**
QL1	0.6667	0	0.5000	0.4926	N/A	N/A	N/A	N/A
QL2	**0.7221**	**0.5960**	**0.6151**	**0.5982**	N/A	N/A	N/A	N/A
QL3	**0.6802**	**0.4957**	**0.5298**	**0.5223**	**0.6201**	**0.3847**	**0.3872**	**0.3805**
QL4	**0.6677**	**0.3104**	**0.5024**	**0.5006**	**0.5954**	**0.2394**	**0.3205**	**0.3487**
QL5	0.6598	0.1656	0.4843	0.4913	**0.5906**	**0.1306**	**0.3068**	**0.3563**

Looking at the results from a global point of view, all the methods select QL2 WLAN1 as their first choice. When looking at the results within one network only (e.g., WLAN1) it can be noticed that GRA and SAW provide similar results, as they rank the quality levels as follows: QL2, QL1, and then QL3, demonstrating that they are more quality-oriented methods. An aspect to note is that both of them provide very small differences between the scores. For example, between QL1 and QL3 for WLAN1, GRA score difference is 0.0007 only whereas SAW score difference is 0.0013. This makes them very sensitive to the changing conditions. For example, looking at WLAN2, WLAN3, and WLAN4, their quality levels order is QL2, QL3, and then QL1, but again the difference between scores is very small.

On the other hand, looking at the results provided by TOPSIS, the method provides a clear distance between the best solution and the rest for each individual RAN, but the differences between the scores of the remaining solutions are small for TOPSIS as well. The only method that provides a clear distance between all the quality levels is MEW. Also looking at the results provided for WLAN4, which can be considered the worst case scenario for WLAN choice, as the mobile user will be located in a poor signal area and a loaded network, GRA, SAW, and TOPSIS provide the same score order (QL2, QL3, QL4, QL1, QL5) whereas MEW totally eliminates the choice of QL1 (QL2, QL3, QL4, QL5). This is because QL1 has the highest energy consumption, and in extreme situations the user will be better off with a Fair quality (QL5) and moderate energy consumption than with high quality (QL1) and risking to reach the battery lifetime of his/her mobile device.

Figure 6.10 illustrates a comparison of the four ranking methods with varying quality weight (w_q) within the same network (WLAN1). For each method the total rank score vs. quality level vs. quality weight is illustrated in a colored 3D graph. The dark red color is associated with high score values while the dark blue color is associated with low score values.

The quality weight (w_q) is varied between 0 and 1 (quality-oriented) meaning that the energy weight will vary between 1 (energy-oriented) and 0. For example, $w_e = 0$ when $w_q=1$, which means that the user is quality-oriented, and does not care about the energy conservation at all. This is visible in Figure 6.10, as when $w_q = 1$, all the ranking methods will have the highest score (dark red color) for QL1.

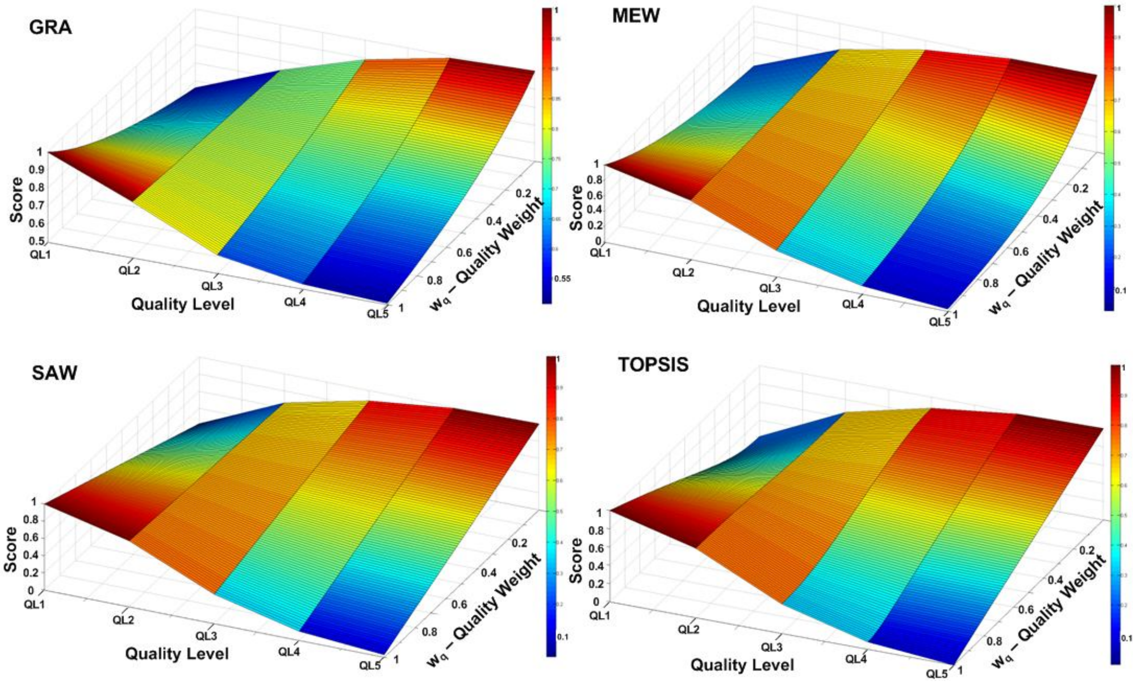


Figure 6.10. Ranking Methods Comparison with varying Quality Weight for QL within WLAN1 (No Load, Near AP), QL1 – highest quality level, QL5 – lowest quality level

Whereas $w_e = 1$ when $w_q=0$, which means that the user is highly energy-oriented, and wants to conserve the energy of the mobile device, no matter what the quality level is. In this situation the methods provide the highest score for QL5 (dark red color – see Figure 6.10). QL2 keeps, more or less, the same rank score (same range of color) for all quality weights and therefore indicates a more stable choice overall. It can be seen that MEW provides a more distinct difference between the choices of quality levels for the same value of the quality weight.

Considering a varying quality weight (w_q) but for a choice of different networks (e.g., WLAN1, WLAN2, WLAN3, and WLAN4) at the same quality level (QL1), the score results of each ranking method are illustrated in Figure 6.11. As it has beenseen in the experimental part (Section 5.5.7) the impact of the network conditions (WLAN4 - loaded network and far from the AP) is more visible on QL1 than other QL. This causes increase in the playout duration of the multimedia stream (because of re-buffering) and leads to an extreme increase in energy consumption and decrease in MOS. The increase in energy makes QL1 (WLAN4) the worst option among the 23 possible options. This is translated in u_e being zero. However, with all the presented disadvantages GRA, SAW, and TOPSIS all end-up selecting QL1 on WLAN4 as seen in Figure 6.11. MEW will select QL1 but only in the case that $w_q = 1$.

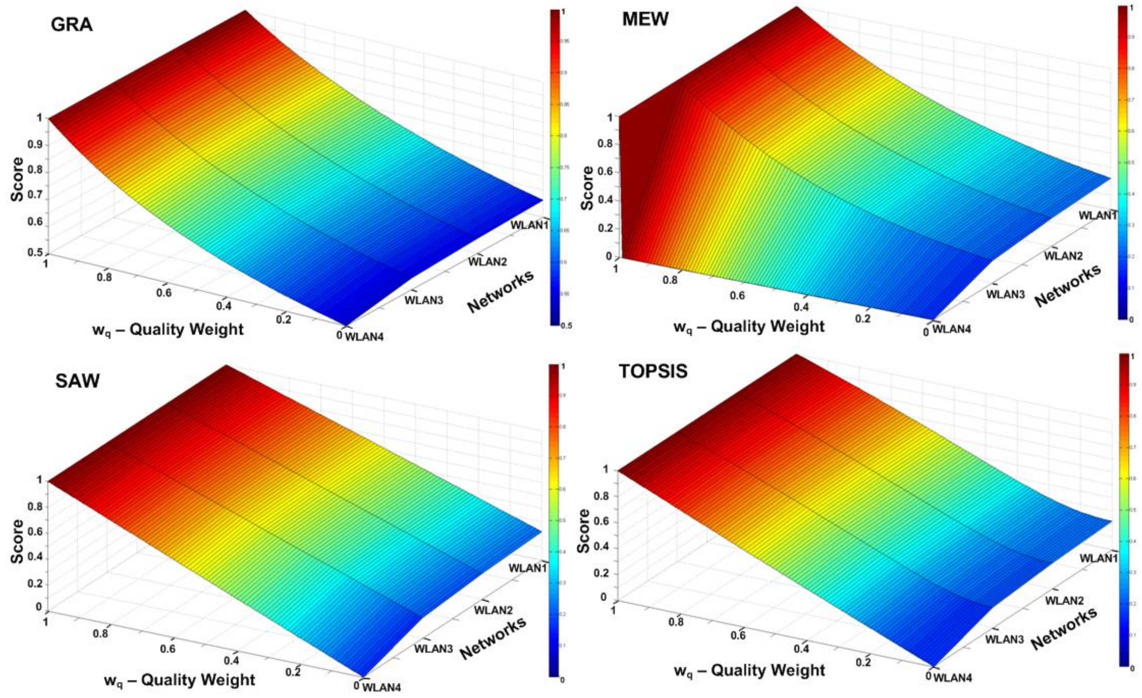


Figure 6.11. Ranking Methods Comparison with varying Quality Weight within WLANs for QL1 WLAN1 (No Load, Near AP), WLAN2 (No Load, Far Ap), WLAN3 (Load, Near AP), WLAN4 (Load, Far AP)

The analysis of the main ranking methods, presented in this section, have shown that MEW models the network selection in the best way, in comparison with other well-known ranking methods: GRA, SAW, and TOPSIS. The main advantages of MEW over the other methods, is that it provides a clear difference between the score results of each option, and that MEW penalizes alternatives/options with poor parameters/criteria values more heavily.

6.7. Chapter Summary

This chapter starts by presenting the simulation-based testing environment. The validation of the enhanced NS-2 environment is done by running and analyzing a simple wireless scenario. The quality utility used by the proposed network selection mechanism, as described in Section 4.3.3.b is then modeled based on the results obtained from the subjective tests for video quality assessment, as described in the previous chapter (Section 5.5.1). A mathematical model of the energy consumption pattern is built based on the real energy consumption measurements taken for a Google Nexus One mobile device, provided in the real experimental test-bed as introduced in Chapter 5.

Four of the well-known MADM ranking methods (e.g., GRA, MEW, SAW, and TOPSIS) are evaluated through mathematical performance analysis in order to examine if they produce similar results under different conditions. The results validate the choice of the score function introduced in Section 4.2.1.4, which is based on MEW. This analysis shows that MEW finds a better quality-energy trade-off and its main advantage is that provides distinct differences between the score results for each quality level. It also penalizes alternatives/options with poor parameters/criteria values more heavily.

Nowadays the network operators consider that if they offer individual high throughput that is translated into satisfied users. However, as this chapter shows, the excellent perceived quality of service does not always results from high throughput, and a good trade-off between quality-energy is needed in order to keep the user satisfied. Network operators need to integrate adaptive mechanisms in order to cater for the user preferences and enables a good balance between energy and quality.

Next chapter will further strengthen this conclusion by introducing the testing results and the results analysis.

Chapter 7

Testing Results and Results Analysis

This chapter presents the testing results and results analysis. Several simulation-based test case scenarios are such structured in order to analyze the performance of the four main contributions: (1) Power Friendly Access Network Selection Mechanism - PoFANS; (2) Signal Strength-based Adaptive Multimedia Delivery Mechanism - SAMMy; (3) Adapt-or-Handover Solution; and (4) Reputation-based Network Selection Mechanism using Game Theory. The performance of these solutions is compared against that of other state of the art schemes.

7.1. Simulation Test Case Scenarios

In order to analyze the performance of the proposed solutions, the case of Jack is brought up again. Recall that Jack is a business professional that likes to access multimedia content while walking everyday from Home to Office. On his travel path there are a number of available networks (e.g., UMTS, WLAN, etc.) that he can use as illustrated in Figure 7.1. As Jack leaves his home he starts up a multimedia session on his mobile device. In this call initiation phase, the selection of an access network is simple as there is only one available RAN (i.e., UMTS). As he moves further, he enters the coverage area of another RAN (i.e., WLAN). At Point A, Jack's device should detect the second RAN and the possibility to handover from UMTS to WLAN. After the decision is made according to the ***PoFANS*** suggested solution, and very likely the multimedia session is transferred to the WLAN, Jack's device may enable the adaptation of the multimedia stream to the increased rate offered by the WLAN network in comparison with UMTS. The ***Signal Strength-based Adaptive Multimedia Delivery*** mechanism copes with the wireless errors in order to maintain an acceptable user perceived quality level for Jack's multimedia session. When Jack enters the coverage area of a second WLAN and his mobile device battery lifetime is at risk, he will be facing the problem whether it is better to adapt the multimedia stream to a lower quality level or it is better to handover to a new network, in terms of energy efficiency. In this situation, the ***Adapt-or-Handover mechanism*** will help Jack in taking the best decision. Because Jack regularly takes the same path, he will usually be under the same coverage of the same RANs on his route. This enables Jack's device to record the history of the interactions with each RAN he visited, and to employ the ***Reputation-based Network Selection*** mechanism.

Jack's path from his home to his office in fact represents the roadmap for the overall solution. The reputation-based system, integrates the Adapt-or-Handover mechanism which in turn integrates SAMMy and PoFANS. Figure 7.1 marks the main points of interest that will be further analyzed, such that: **(1) Point A –** at this point Jack has a choice of two available RANs (e.g., UMTS and WLAN); the decision of the ***power friendly access network selection mechanism (PoFANS)*** is analyzed; **(2) Point B –** in order to cope with the errors of the wireless environment Jack can enable the adaptive multimedia mechanism, on his device; the performance of this ***signal strength-based adaptive multimedia delivery mechanism (SAMMy)*** is analyzed; **(3) Point C –** having a choice of three available RANs, Jack will be facing the problem: is it better for him to adapt the multimedia stream or to handover to a new network; the performance of the ***Adapt-or-Handover mechanism*** is analyzed in terms of energy efficiency; **(4) Point D** – as Jack follows the same path regularly the ***reputation-based system*** is built using Game Theory; the efficiency of this system is analyzed.

Note that the points marked in Figure 7.1 represent an illustrative example in order to better understand the roadmap of the overall proposed solution design phases, and they do not represent the exact location where the decisions take place.

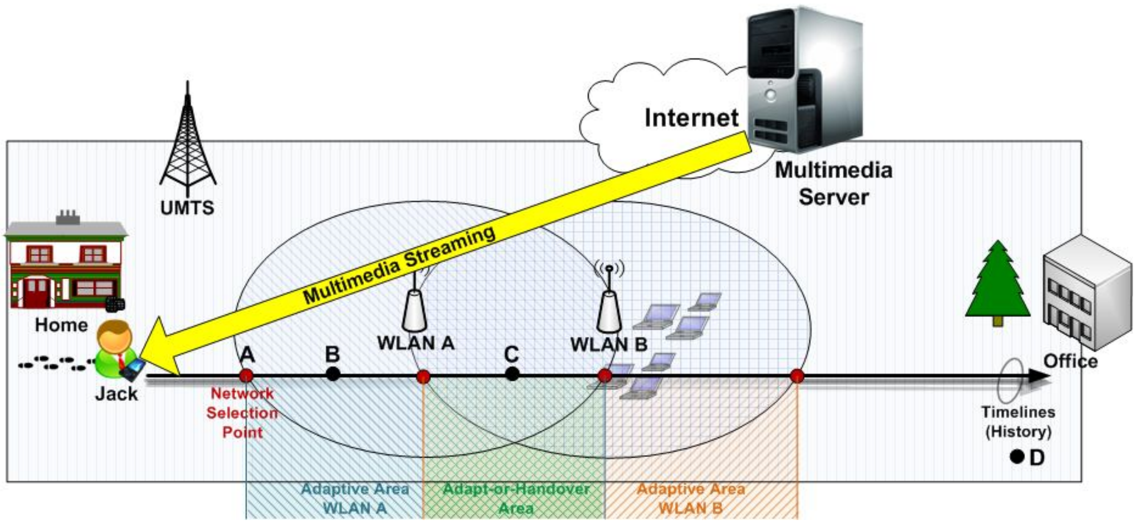


Figure 7.1. Example Scenario – Jack's path from Home to Office

7.2. Performance Analysis of PoFANS (Point A)

This section analyzes the performance of the Power-Friendly Access Network Selection Mechanism (PoFANS). The details of the PoFANS algorithm are described in Chapter 4. In this chapter, two aspects of PoFANS will be analyzed: **(1)** the ***energy-quality trade-off*** and **(2)** the ***energy-quality-cost trade-off.*** Two test case scenarios are considered:

(1) Test Case 1 Energy-Quality Trade-off – where Jack has a number of available wireless networks from which he can select. The networks differ only in terms of Quality Levels provided and Energy Consumption. All the networks are assumed to be free of charge. The trade-off between energy and quality is analyzed.

(2) Test Case 2 Energy-Quality-Cost Trade-off – the monetary cost parameter is also introduced so that the trade-off between energy, quality, and cost is analyzed.

The proposed network selection mechanism (PoFANS) is compared against the solution provided by Liu et al. [169]. The reason for using Liu's et al. solution as the comparison is that it also represents an energy efficient solution, and considers the same main parameters: available bandwidth, monetary cost, and the power consumption. This enables a fair comparison between the two schemes. Liu et al. propose the use of a SAW function (referred to as a Cost Function *C*) as given in equation (7.1).

$$C = w_B \ln \frac{1}{B} + w_P \ln P + w_c \ln c \qquad (7.1)$$

where *B* represents the available bandwidth, *P* represents the consumed power, and *c* represents the monetary cost. Note that when the monetary cost is zero (free network) then *ln c* = -∞. In order to allow for the Cost Function computation, in the simulations it is assumed a free network to have a cost of c=0.01 and therefore *ln c = -4.6*. As noticed, the main difference between the two approaches is the choice of score and utility functions, Liu et al. making use of logarithmic functions and PoFANS makes use of the utility functions defined in Chapter 4. Liu et al. Cost Function *C*, follows the principle '*the smaller the better'*, while PoFANS follows the principle '*the larger the better'* and is given by equation (7.2). In order to compare the two it is assumed that *B* can be linked to the received throughput and *P* to the energy consumption (E), as described by equation (6.4) in Section 6.5..

$$U_i = u_{e_i}^{\ w_e} \cdot u_{q_i}^{\ w_q} \cdot u_{c_i}^{\ w_c} \qquad (7.2)$$

where: *U* – overall score function for RAN *i*; u_e, u_q,and $u_c$are the utility functions defined for energy, quality in terms of received bandwidth, and monetary cost for RAN *i*, respectively. Also $w_e + w_q + w_c = 1$, where w_e, w_q, and w_c are the weights for the considered criteria, representing the importance of a parameter in the decision algorithm. As noticed the utility mobility is not considered, this is because Jack is moving at a walking speed meaning that u_m=1. This value will be further considered for the rest of the simulation scenarios.

7.2.1. Test Case 1 Energy-Quality Trade-off: Network Selection – Choice of five Networks

In this first test case scenario Jack is confronted with the problem of selecting the best network for his current application preferences from a pool of five available RANS as illustrated in Figure 7.2. The available RANs are set as the five networks from the experimental test-bed, that is: WLAN1 – No Load, Near AP; WLAN2 – No Load, Far AP; WLAN3 – Load, Near AP; WLAN4 – Load, Far AP; UMTS – eMobile network. It is also assumed that each of these RANs can provide any of the five quality levels (three quality levels in case of UMTS) of the multimedia stream stored at the server side without difficulties. Whenever new networks are available, Jack's device should detect a change in the candidate networks list and a network selection can be performed. Thus, the selection decision could be done between five (quality levels) x four (WLAN networks) + three (quality levels) x one (UMTS networks) = 23 options.

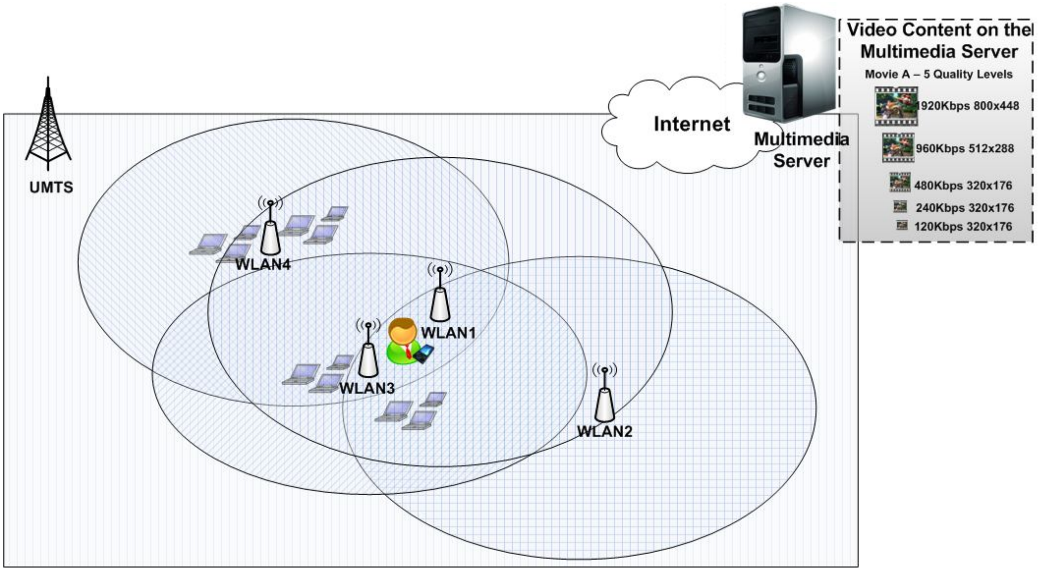


Figure 7.2. Test Case 1 – Network Selection – Choice of Five Networks

In order to compare the performance of the two network selection mechanisms in terms of the trade-off between quality and energy consumption, the weight value for the cost parameter, w_c, is set to zero. This means that Jack does not care about the monetary cost of the networks and is more interested in the quality of the multimedia stream and the energy consumption of the mobile device. For this reason the values for the three weights are set to: $\boldsymbol{w_e = 0.5}$, $\boldsymbol{w_q = 0.5}$, $\boldsymbol{w_c = 0}$. Considering these settings, the test-bed values for quality and energy were used to calculate the scores for both the Liu et al. Cost Function and PoFANS. The scores are illustrated in Table 7.1.

TABLE 7.1. TEST CASE 1 ENERGY-QUALITY TRADE-OFF RESULTS: COST FUNCTION VS. POFANS

	WLAN1		**WLAN2**		**WLAN3**		**WLAN4**		**UMTS**	
	No Load, Near AP		**No Load, Far AP**		**Load, Near AP**		**Load, Far AP**		**e-Mobile Network**	
	Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
QL1	**-0.4005**	0.4706	-0.3929	0.4445	-0.3805	0.3968	-0.1950	0	N/A	N/A
QL2	-0.2166	**0.7103**	-0.2088	0.7005	-0.1933	0.6804	-0.1375	0.5960	N/A	N/A
QL3	0.0232	0.5480	0.0313	0.5433	0.0494	0.5323	0.1032	0.4957	0.2208	0.3847
QL4	0.3064	0.3253	0.3147	0.3230	0.3346	0.3174	0.3580	0.3104	0.5285	0.2394
QL5	0.6180	0.1709	0.6264	0.1709	0.6474	0.1704	0.6805	0.1656	0.8544	0.1306

Looking at the results, from the 23 available options, when using PoFANS, Jack's device first choice is QL2 on WLAN1, whereas when using the Liu et al. Cost Function, the first selection choice is QL1 on WLAN1. This shows that PoFANS provides a better trade-off between quality and energy consumption than the Liu et al. Cost Function. In this situation, Jack equally cares about the energy consumption of the mobile device and the quality of the multimedia stream he is watching, so by selecting QL2, representing 'Excellent' quality (see Section 6.4), Jack can save up to 28% in energy consumption in comparison with selecting QL1. Jack's benefit for using PoFANS vs. Liu e al. Cost Function is highlighted in Table 7.2. The energy component was computed using equation (6.4). In terms of quality there is no significant perceived benefit as both QL1 and QL2 can be mapped to the 'Excellent' quality level on the ITU-T P.910 scale.

TABLE 7.2. TEST CASE 1 ENERGY-QUALITY TRADE-OFF: USER'S BENEFIT COST FUNCTION VS. POFANS

	Energy [Joule]	**Quality Level/MOS**
Liu et al. Cost Function	861.8	QL1/Excellent
PoFANS	622.48	QL2/Excellent
Benefit	28%	none

Moreover, looking at the results for each quality level for each network separately (e.g., WLAN1), QL1 will be only the third choice for PoFANS Whereas it will be the first choice for Liu et al. Cost Function. That is, for WLAN1-3 the order of selection for PoFANS will be: QL2, QL3, and only then QL1, while the order of selection for the Liu et al. Cost Function will be: QL1, then QL2, and QL3. For the UMTS network both algorithms ranked choice list will be the same, i.e., QL3, QL4, and then QL5.

Two further situations were considered:

(1) for **Quality-oriented** users, the weight for quality will have a higher value, for example: $w_e = 0.2, w_c = 0, w_q = 0.8$;

(2) for **Energy-oriented** users, the energy weight is higher than the quality weight, for instance: $w_e = 0.8, w_c = 0, w_q = 0.2$.

The results for these two situations are presented in Table 7.3. It can be seen that in the case of Quality-oriented users the ranked list for target quality level and network are the same as when equal Quality-Energy orientation was considered (e.g., $w_e = 0.5$, $w_c = 0$, $w_q = 0.5$). This means that the users would choose QL2 over QL1 as the first choice for PoFANS in comparison with the Liu et al. Cost Function, which still chooses QL1 as the first choice. The benefits for using PoFANS are the same benefits as presented in Table 7.2. The Quality-oriented users will benefit from an 'Excellent' quality level and a 28% decrease in energy consumption when compared with the case when the Liu et al. Cost Function is employed.

TABLE 7.3. TEST CASE 1: QUALITY-ORIENTED AND ENERGY-ORIENTED RESULTS: COST FUNCTION VS. POFANS

		WLAN1		**WLAN2**		**WLAN3**		**WLAN4**		**UMTS**	
		No Load, Near AP		**No Load, Far AP**		**Load, Near AP**		**Load, Far AP**		**e-Mobile Network**	
		Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
Quality Oriented	***QL1***	**-4.6962**	0.7397	-4.6932	0.7230	-4.6883	0.6909	-4.6140	0	N/A	N/A
	QL2	-4.2068	**0.7437**	-4.2037	0.7396	-4.1975	0.7310	-4.1751	0.6933	N/A	N/A
	QL3	-3.6950	0.4135	-3.6918	0.4121	-3.6845	0.4088	-3.6630	0.3973	-3.6159	0.3589
	QL4	-3.1658	0.1673	-3.1625	0.1668	-3.1546	0.1657	-3.1452	0.1642	-3.0770	0.1480
	QL5	-2.6253	0.0592	-2.6219	0.0592	-2.6135	0.0591	-2.6003	0.0585	-2.5307	0.0532
Energy Oriented	***QL1***	3.8953	0.2994	3.9074	0.2733	3.9272	0.2279	4.2241	0	N/A	N/A
	QL2	3.7736	0.6783	3.7861	0.6635	3.8109	0.6333	3.9002	0.5124	N/A	N/A
	QL3	**3.7414**	**0.7261**	3.7543	0.7162	3.7832	0.6933	3.8694	0.6185	4.0576	0.4122
	QL4	3.7786	0.6324	3.7919	0.6254	3.8237	0.6082	3.8612	0.5869	4.1340	0.3872
	QL5	3.8613	0.4932	3.8747	0.4932	3.9083	0.4909	3.9613	0.4692	4.2396	0.3210

In the case of Energy-oriented users both selection solutions provide similar ranking results both will select QL3 on WLAN1 as the first choice.

The results show that PoFANS score function more accurately models a good trade-off between quality and energy consumption in comparison with Liu et al. Cost Function for different user preferences on quality and energy. This is because Liu et al. Cost Function is based on the SAW method whereas PoFANS is based on the MEW method. In Chapter 6 it has been shown that the main disadvantage of SAW is that a poor value parameter can be outweighed by a very good value of another parameter, whereas MEW penalizes alternatives with poor parameters values more heavily. This can be noticed here in case of WLAN4, when the network is loaded and the mobile user is located in an area with poor signal strength. From the experimental test-bed measurements presented in Chapter 5 it has been seen that in this situation, streaming QL1 will significantly increase the energy consumption of the mobile device and will additionally more than double the playout duration of the multimedia stream (introducing re-buffering periods) which consequently will reduce the Mean Opinion Score. This makes QL1 (WLAN4) the worst option among the different QLs. This situation is captured by PoFANS which gives a zero score to QL1 whereas Liu et al. Cost Function will end up selecting QL1.

The results show that a weight of 0.5 for w_q can be mapped to a minimum quality level which is above QL4 ('Good' on the ITU-T P.910 scale). This means that with these settings, Jack's minimum acceptable quality would be QL3, so the options for QL4 and QL5 can be eliminated from the selection decision as they do not meet the minimum criteria. In this case PoFANS eliminates a number of candidate network choices reducing the list from 23 options to

16 options. This improves the performance and reduces the computational complexity of the solution in comparison with Liu et al.

7.2.2. Test Case 2 Energy-Quality-Cost Trade-off: Network Selection – Choice of Three Networks

Consider in this case, Jack as having a choice of three networks: WLAN2 – No Load, Far AP, WLAN3 – Load, Near AP, and UMTS, as illustrated in Figure 7.3. As the cost parameter is also considered additional to energy consumption and quality, for testing, the costs for each of the three networks are set to: WLAN2 – 0.2 cents per unit of data, WLAN3 – free hot-spot, and UMTS – 0.9 cents per unit of data. In this situation Jack cares also about his budget and he is willing to pay a certain amount while also maintaining a balance between the quality level he is getting the content at, and the energy consumption. However, he is not willing to pay anything if his requirements are not fulfilled. In these conditions the following weights for the three parameters are considered: $\mathbf{w_e = 0.4}$, $\mathbf{w_q = 0.4}$, and $\mathbf{w_c = 0.2}$. The results for this test case scenario are presented in Table 7.4. If Jack has enabled PoFANS on his mobile device, he will end-up selecting QL2 on WLAN2. If the Liu et al. Cost Function is enabled, then he will end-up with QL1 on WLAN3. It can be seen here the same phenomena as in Test Case 1 where the Liu et al. Cost Function selects the highest quality level (QL1), which in terms of energy conservation is the most power consuming, while PoFANS selects QL2 (WLAN2) achieving a 30% decrease in energy consumption as compared to QL1 (WLAN1). This shows again that PoFANS provides a good balance between quality level and energy consumption.

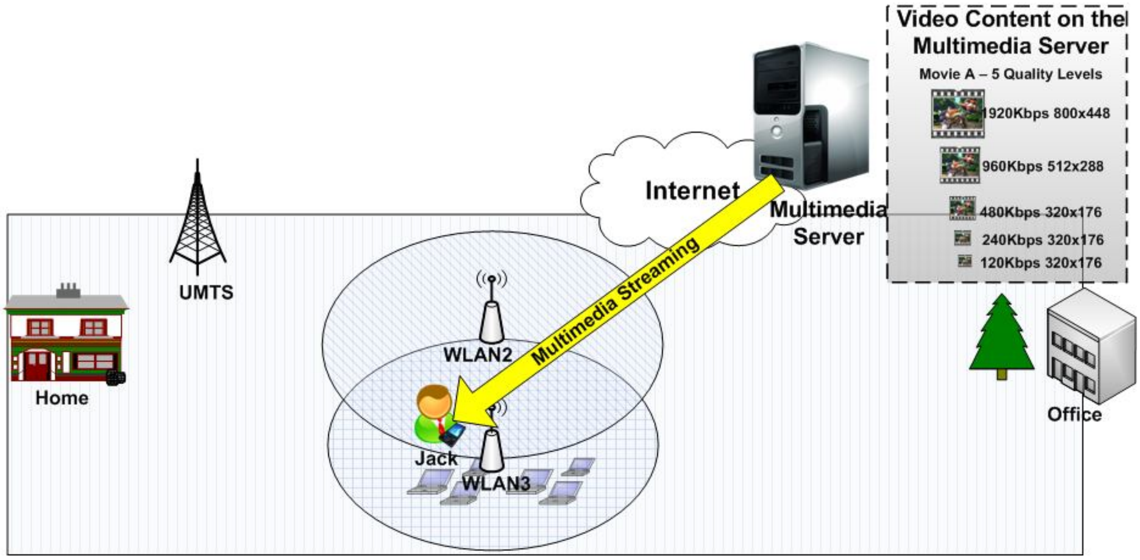


Figure 7.3. Test Case 2 – Network Selection – Choice of Three Networks

TABLE 7.4. Test Case 2 Energy-Quality-Cost Trade-off Results: Cost Function vs. PoFANS

	WLAN2		**WLAN3**		**UMTS**	
	No Load, Far AP		**Load, Near AP**		**e-Mobile Network**	
	Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
QL1	-0.6362	0.5119	**-1.2244**	0.4774	N/A	N/A
QL2	-0.4889	**0.7365**	-1.0746	0.7349	N/A	N/A
QL3	-0.2969	0.6010	-0.8805	0.6039	0.1556	0.4132
QL4	-0.0701	0.3965	-0.6524	0.3993	0.4017	0.2827
QL5	0.1792	0.2382	-0.4021	0.2427	0.6625	0.1741

When the cost parameter is also considered, PoFANS will select only QL2 and QL1 from the paid network (WLAN2) relative to QL2 and QL1, from the free network (WLAN3), respectively. Thus, Jack will be willing to pay the 0.2 cents per unit of data only if he is getting the 'Excellent' quality. If this quality level is not provided, then Jack is better off going for the free network (WLAN3) for QL3 to QL5. Looking at the results provided by the Liu et al. Cost Function, the free network will be always selected. Comparing the decisions for the quality levels from WLAN2 relative to the same quality levels provided by WLAN3, the Liu et al. Cost Function will never select the quality levels provided by the paid network. Even though for example for QL2 provided by WLAN2 there can be a 5% decrease in energy consumption when compared to QL2 provided by WLAN3. This shows that PoFANS finds a good trade-off between energy-quality-cost. Table 7.5 highlights the benefit obtained by Jack while using PoFANS in comparison with the case when he would use the Liu et al. Cost Function. As it can be noticed, the benefit in terms of energy is 30%, while there are no evident benefits in terms of quality, as both QL1 and QL2 are mapped to the 'Excellent' level on the ITU-T P.910 quality scale. When looking at the benefit in terms of cost, Jack will have to pay an additional amount of 0.2 cents per unit of data in order to get the 30% decrease in energy consumption.

TABLE 7.5. Test Case 2: User's Benefit: Cost Function vs. PoFANS

	Energy [Joule]	**Quality Level/MOS**	**Cost [cents/unit of data]**
Liu et al. Cost Function	897	QL1/Excellent	0
PoFANS	632.3	QL2/Excellent	0.2
Benefit	30%	none	-0.2

Other two situations are considered:

(1) for users with **Equal Interest** in energy, quality, and cost, the weights are set to: $w_e = 0.33$, $w_q = 0.33$, and $w_c = 0.33$;

(2) **Cost-oriented** users which could use, for example, the following weight distribution $w_e = 0.1$, $w_q = 0.1$, and $w_c = 0.8$;

The results for the two above situations are listed in Table 7.6. For both situations the outcome is the same. It can be noticed that the Liu et al. Cost Function has a stronger quality-orientation by selecting the QL1 on WLAN3, whereas PoFANS finds a trade-off between quality and energy by selecting QL2 on WLAN3. However both solutions select the free network in both situations. The benefit that Jack gets by using PoFANS vs. Liu et al. Cost Function is 26.6% decrease in energy consumption, while maintaining an 'Excellent' quality level for delivered content.

TABLE 7.6. TEST CASE 2 RESULTS: COST FUNCTION VS. POFANS

		WLAN2		**WLAN3**		**UMTS**	
		No Load, Far AP		**Load, Near AP**		**e-Mobile Network**	
		Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
Equal Interest	***QL1***	-0.7904	0.5656	**-1.7691**	0.5434	N/A	N/A
	QL2	-0.6689	0.7636	-1.6456	**0.7756**	N/A	N/A
	QL3	-0.5105	0.6457	-1.4854	0.6596	0.1110	0.4370
	QL4	-0.3234	0.4581	-1.2972	0.4689	0.3140	0.3195
	QL5	-0.1177	0.3009	-1.0907	0.3110	0.5292	0.2142
Cost - Oriented	***QL1***	-1.3661	0.7816	**-3.7561**	0.8312	N/A	N/A
	QL2	-1.3293	0.8560	-3.7187	**0.9259**	N/A	N/A
	QL3	-1.2813	0.8136	-3.6701	0.8815	-0.0401	0.5120
	QL4	-1.2246	0.7332	-3.6131	0.7949	0.0214	0.4657
	QL5	-1.1623	0.6455	-3.5505	0.7019	0.0866	0.4126

7.3. Performance Analysis of SAMMy (Point B)

This section analyzes the performance of the proposed Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy). After the network selection takes place and PoFANS selects one of the two available wireless networks (i.e., UMTS and WLAN), the multimedia session is transferred over the new network. Jack is now located in Point B as illustrated in Figure 7.4. In order to cope with the wireless errors and improve his quality of service, Jack will use an adaptive mechanism. In this context SAMMy is proposed. SAMMy is distributed and consists of a server-side and a client-side component, as described in Chapter 4. The server side will store a number of different quality levels of the same multimedia stream (e.g., five quality levels). The client (Jack's mobile device) monitors the network conditions (e.g., packet loss and signal strength) and sends feedback to the server. Based on the received feedback the server will then adapt the multimedia stream. The algorithm of SAMMy is detailed in Chapter 4.

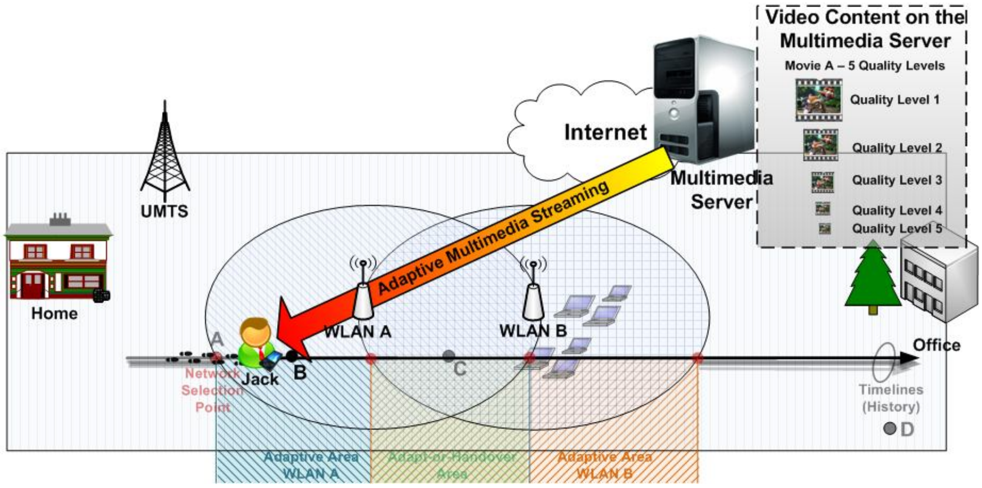


Figure 7.4. Adaptive Multimedia Delivery over a Wireless Network

When evaluating the performance of SAMMy the focus is on two main aspects:

(1) Single-User Environment - the performance of SAMMy is assessed in comparison with other multimedia delivery schemes when only one user is employing SAMMy in a wireless environment;

(2) Multi-User Environment - the performance of SAMMy in terms of fairness, when there are multiple simultaneous video delivery sessions in a wireless multi-user environment;

The performance of SAMMy is evaluated in comparison with three other multimedia delivery schemes: **(1)** a classic non-adaptive multimedia delivery solution referred to as **Non-Ad**; **(2)** a loss-based adaptive multimedia delivery scheme referred to as **Loss-Ad**; **(3)** TCP friendly rate control protocol referred to as **TFRC** [108]. All the solutions were modeled and integrated in NS-2.33 where the simulations were conducted.

The reasons for which the above solutions were selected are as follows:

- The Non-Adaptive (Non-Ad) solution represents the classical UDP-based video delivery method. By using this method the multimedia content is delivered at the encoded rate without taking the network conditions into considerations.
- Loss-based Adaptive Multimedia (Loss-Ad) solution[1] is a multiplicative decrease additive increase bitrate switching solution that reduces the multimedia quality level by half when congestion is detected, whereas when there is no packet loss detected the quality level is increased by one. This solution is very close to the ones deployed in the industry.
- TFRC represents a well-known network-based adaptive solution that computes the transmission rate based on the loss rate, round trip time, and video segment size. TFRC is known to be TCP friendly to the elastic traffic [108].

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[1] Multimedia Application - http://nile.wpi.edu/NS/

7.3.1. SAMMy – Performance Evaluation 1: Single-User Environment

In order to evaluate the performance of SAMMy in Single-User Environment, three scenarios are considered:

(1) Scenario 1: Mobility, No Load - Jack is moving, at a constant speed of 1m/sec, on a path towards the AP and then away from it. In this scenario the loss is mainly due to reduced received power with increased distance from AP;

(2) Scenario 2: No Mobility, Load – a number of other nodes generate background traffic while Jack is in a fixed position (five different positions are considered) so losses are mainly due to congestion;

(3) Scenario 3: Mobility, Load – the same background traffic from scenario 2 is used together with several mobility scenarios. A number of five different paths are considered such that losses may be due to reduced receive power, congestion, or both of these.

In each simulation scenario Jack is watching a multimedia stream on his mobile device. The video data is streamed from the multimedia server to Jack's mobile device through a WLAN (802.11b) network. The multimedia server stores five five-minute long multimedia clips encoded at five different rates. For these scenarios the following encoding rates, typical for high quality video content over WLAN, were considered: 0.5Mbps (QL5), 0.75Mbps (QL4), 1.0Mbps (QL3), 1.5Mbps (QL2), and 2.0Mbps (QL1). Video quality was estimated using the formula proposed in [55] which considers the effect of throughput and loss on the MPEG-encoded video stream.

7.3.1.1. Scenario 1: Mobility, No Load

Figure 7.5 illustrates the first scenario, where Jack is moving towards and then away from the AP at a constant speed of 1m/sec. There is no background traffic involved and the losses are mainly due to drop in signal strength.

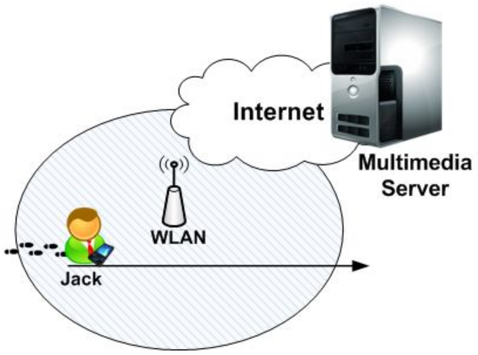

Figure 7.5. Scenario 1: SAMMy – Mobility, No Load

The simulation results for Non-Ad, Loss-Ad, TFRC, and SAMMy are presented in Table 7.7. The received throughput variation over time and distance relative to the AP is illustrated in Figure 7.6.

TABLE 7.7. RESULTS SCENARIO 1 – MOBILITY, NO LOAD

Scheme	Non-Ad	Loss-Ad	TFRC	SAMMy
Loss [%]	3.82	0.94	0.54	0
Average Throughput [Mbps]	1.91	1.90	1.90	1.62
Average PSNR [dB]	82	92	98	100

Results show that in case of SAMMy there is no loss at all, and this is because the video delivery rate (Quality Level) was adapted based on the signal strength, and as Jack moved away from the AP, the rate (Quality Level) gradually decreases. The multimedia stream adapts its rate smoothly, and in the absence of loss the user perceived quality remains very good and higher than that of the other solutions. The video quality estimated in terms of PSNR [55], shows how SAMMy is the best solution with 100dB. In this scenario the Non-Ad scheme presents the worst performance with a loss rate of 3.82% and the lowest PSNR, while TFRC reacts well to varying delivery conditions and achieves a good throughput and 0.54% loss rate only. Loss-Ad solution presents the same throughput as TFRC but 0.94% loss rate.

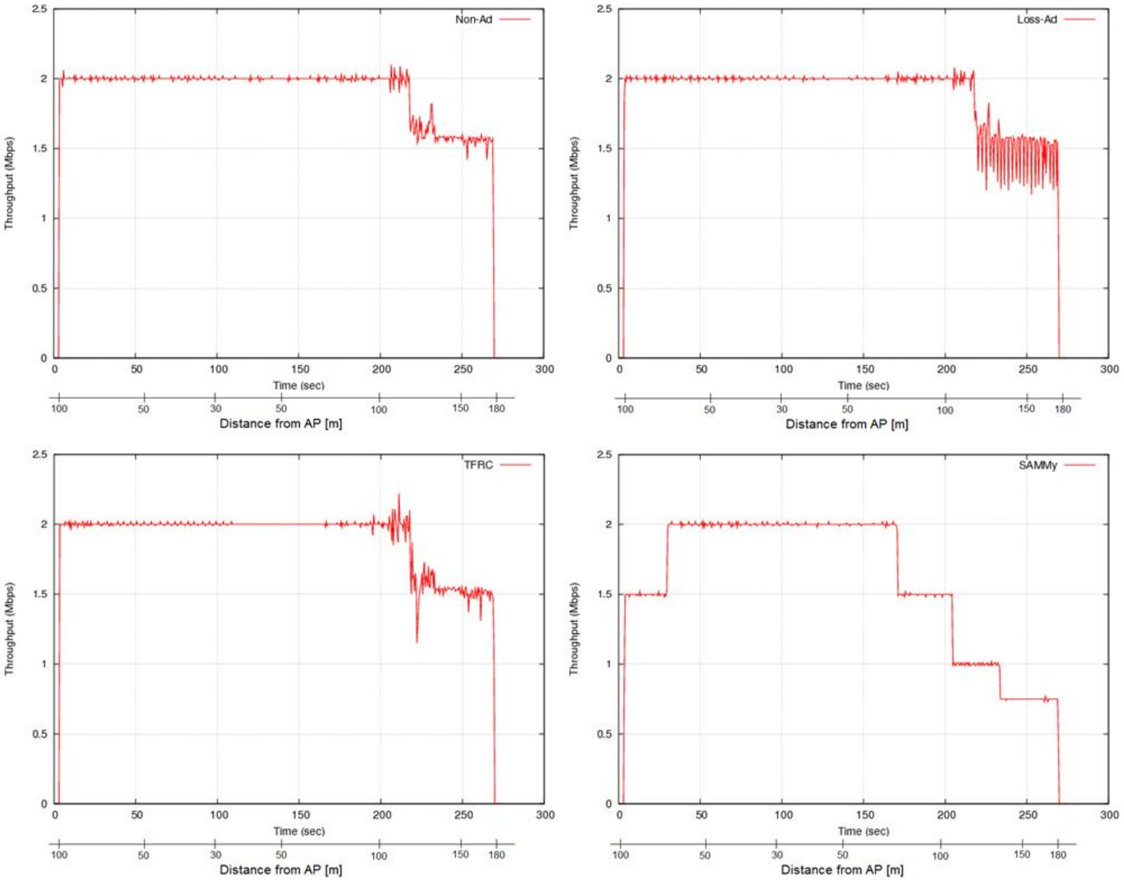

Figure 7.6. Throughput variation Scenario 1 (Mobility, No Load): Non-Ad, Loss-Ad, TFRC and SAMMy

7.3.1.2. Scenario 2: No Mobility, Load

In the second scenario, two other users were added that generate background traffic in order to load the wireless network: one receives FTP traffic over TCP, with a packet size of

1480 bytes, and the second one receives CBR traffic over UDP at a data rate of 1Mbps with packet size of 1000 bytes. Both users are located near the AP (within 17 meters), and do not move. In this scenario Jack is located in a fixed position in the network, so any loss is mostly due to congestion. As illustrated in Figure 7.7, in five different situations considered, Jack is located in five different positions relative to the AP: Position 1 – 42m, Position 2 – 89m, Position 3 – 20m, Position 4 – 10m, and Position 5 – 100m. The results for each scheme and mobile user position are listed in Table 7.8.

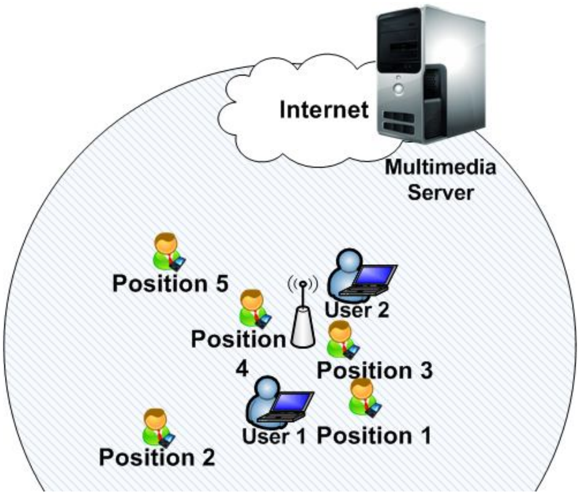

Figure 7.7. Scenario 2: SAMMy – No Mobility, Load

TABLE 7.8. RESULTS SCENARIO 2 – NO MOBILITY, LOAD

		Loss-Ad	TFRC	Non-Ad	SAMMy
Position 1	***Loss [%]***	1.93	2.64	21.01	0.90
	Average Throughput [Mbps]	1.56	0.64	1.55	1.40
	Average PSNR [dB]	76.2	59.03	51.14	81.30
Position 2	***Loss [%]***	6.10	3.30	22.98	2.98
	Average Throughput [Mbps]	0.97	0.43	1.51	0.85
	Average PSNR [dB]	49.52	59.73	47.22	66.42
Position 3	***Loss [%]***	2.45	1.48	3.56	1.42
	Average Throughput [Mbps]	1.5	0.90	1.90	1.07
	Average PSNR [dB]	61.67	66.38	51.08	72.42
Position 4	***Loss [%]***	4.37	2.39	4.37	1.76
	Average Throughput [Mbps]	1.04	0.71	1.54	1.15
	Average PSNR [dB]	50.44	60.35	48.48	74.43
Position 5	***Loss [%]***	13.04	3.79	29.37	1.97
	Average Throughput [Mbps]	0.64	0.37	1.38	0.65
	Average PSNR [dB]	35.65	53.5	19.69	71.45

The results show that when the user is located in a loaded network, where the loss is mainly due to congestion, SAMMy outperforms all the other schemes involved. When Jack is located at 100m away from the AP (Position 5), SAMMy records a 93%, 48%, and 84% decrease in loss, 263%, 34%, and 100% increase in PSNR, in comparison with Non-Ad, TFRC, and Loss-Ad. In terms of throughput, SAMMy presents a 52% decrease when compared with the Non-Ad solution, and 75% and 1.5% increase, when compared with TFRC and Loss-Ad.

When Jack is located at 10m away from the AP (Position 4), there is 60%, 26% and 60% decrease in loss, 54%, 23%, 48% increase in PSNR, in comparison with Non-Ad, TFRC, and Loss-Ad, respectively. In terms of throughput, SAMMy presents a 25% decrease when compared with Non-Ad, and 60% and 10% increase, when compared with TFRC and Loss-Ad, respectively.

7.3.1.3. Scenario 3: Mobility, Load

In the third scenario the network conditions are identical with those from the second scenario and node mobility is added. Five different movement paths for Jack are considered as shown in Figure 7.8. The paths differ in the distance from AP when the user moves towards and then away from the AP, crossing different coverage Areas. The simulations were run for each of these paths and each of the video delivery schemes. The results for this scenario are presented in Table 7.8. The results show that SAMMy performs very well in loaded networks and for all the paths considered. SAMMy has a better performance in terms of throughput, loss and estimated PSNR than any of the other schemes considered, increasing the user perceived quality.

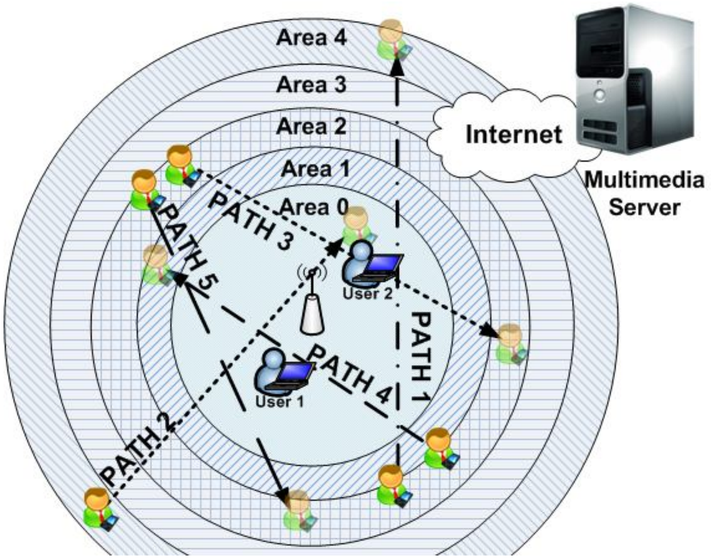

Figure 7.8. Scenario 3: SAMMy – Mobility, Load

PATH 1 combines the mobility used in the first scenario with the background traffic from the second one. The minimum distance between the mobile user and the AP that is achieved by the Jack in his path is 30m. The throughput variation over time and distance relative to the AP is illustrated in Figure 7.9. Also, Figure 7.10 presents the packet loss over time and distance relative to the AP, for each of the four schemes. Comparing the two figures it can be seen that in SAMMy's case, when two consecutive negative feedback reports are detected, the quality level decreases, fact which is reflected in a consequent throughput drop. In this particular case, when comparing with TFRC, there is a 28.8% decrease in loss and 15.47% increase in throughput, resulting in a 26.6% increase in PSNR. With respect to the Non-Ad and Loss-Ad solutions, SAMMy presents a 85% and 73%, respectively, decrease in loss rate and 64.7% and 47%, respectively, increase in PSNR.

TABLE 7.9. RESULTS SCENARIO 3 – MOBILITY, LOAD

		Loss-Ad	TFRC	Non-Ad	SAMMy
PATH 1	***Loss [%]***	4.68	1.80	8.52	1.28
	Average Throughput [Mbps]	1.21	0.84	1.81	0.97
	Average PSNR [dB]	51.3	59.7	45.9	75.6
PATH 2	***Loss [%]***	4.09	1.81	16.53	1.65
	Average Throughput [Mbps]	1.33	0.84	1.65	0.92
	Average PSNR [dB]	56.53	59.73	37.55	75.19
PATH 3	***Loss [%]***	6.71	1.83	9.41	1.45
	Average Throughput [Mbps]	1.10	0.81	1.79	1.04
	Average PSNR [dB]	42.97	58.55	47.12	75.68
PATH 4	***Loss [%]***	4.08	1.39	4.62	0.57
	Average Throughput [Mbps]	1.35	0.99	1.89	1.40
	Average PSNR [dB]	51.98	58.31	58.48	84.25
PATH 5	***Loss [%]***	5.85	1.68	28.8	1.42
	Average Throughput [Mbps]	1.09	0.82	1.41	1.15
	Average PSNR [dB]	46.33	61.42	18.00	78.42

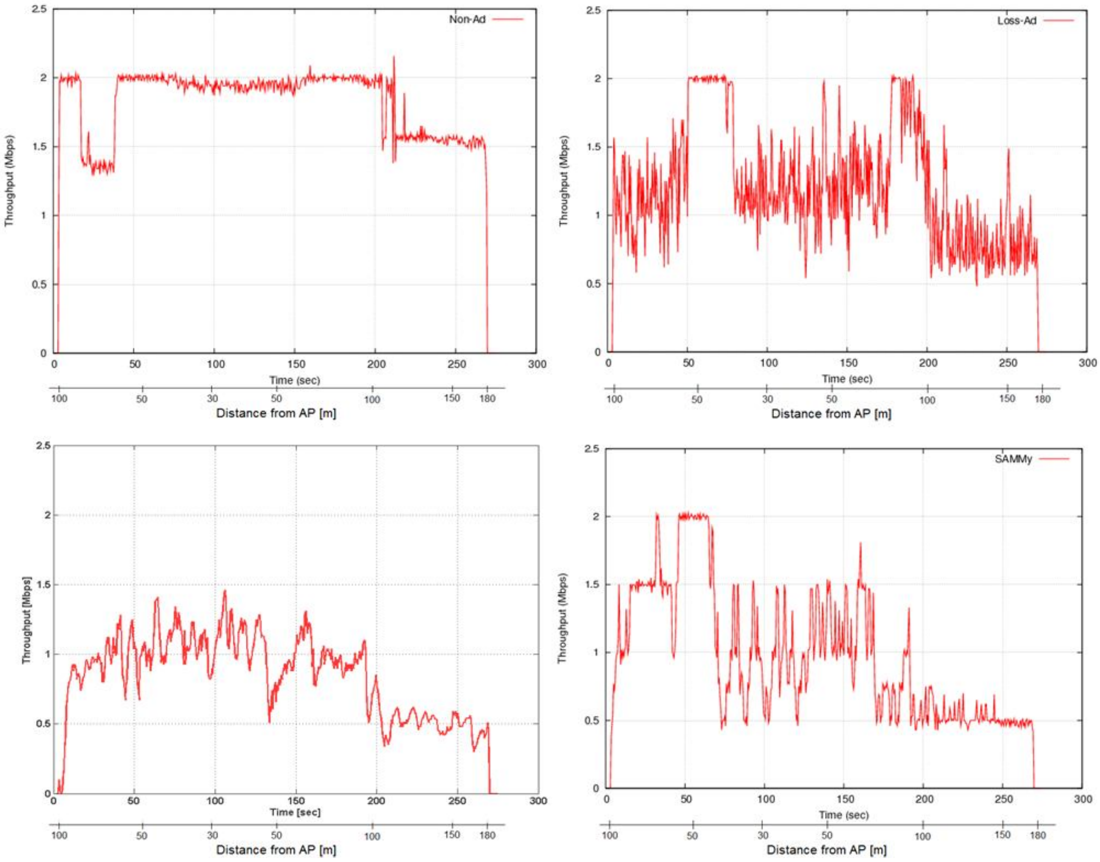

Figure 7.9. Throughput Non-Ad, Loss-Ad, TFRC and SAMMy – Path 1 - Scenario 3

Comparing an average of all five paths presented in this scenario, SAMMy performs 25% and 90%, respectively, decrease in loss, with an impact of 30.7% and 87.94% increase on PSNR relative to TFRC and Non-Ad, respectively. This is based on the average values computed as the means of the results obtained for each of the five paths, as presented in Table 7.9.

Figure 7.10 illustrates the lost packets during the video delivery over Path 1. As it can be noticed, SAMMy and TFRC have minimum loss and evenly spread throughout the path, whereas, Non-Ad and Loss-Add are affected more by sever loss at several distances.

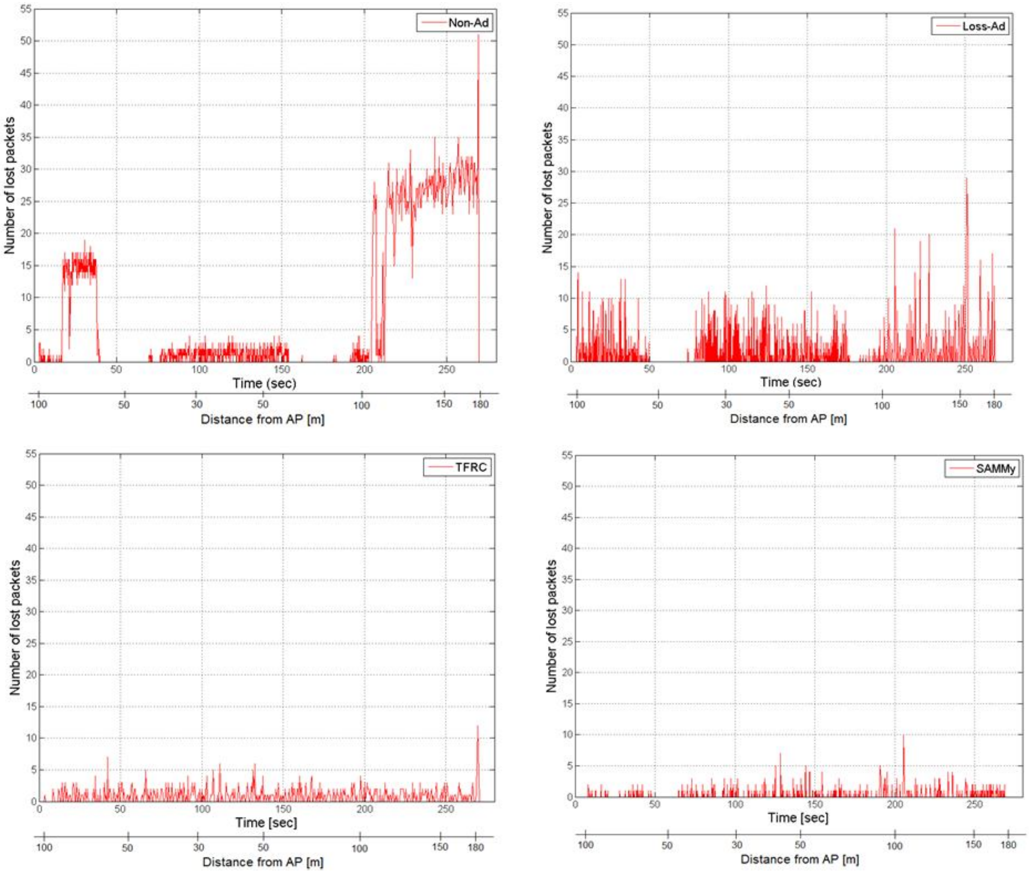

Figure 7.10. Packet Loss Non-Ad, Loss-Ad, TFRC and SAMMy – Path 1 - Scenario 3

7.3.1.4. SAMMy Single-User Environment - Conclusions

The simulation results show that SAMMy outperforms the other schemes involved in terms of throughput, loss, and estimated PSNR. For example, looking at the results presented in Table 7.9, for PATH 4, SAMMy achieves a 58.9% decrease in loss and 41.4% increase in throughput, leading to a 44.48% increase in PSNR, in comparison with TFRC.

The results have shown that signal strength can have a great impact in the user perceived quality, and must be considered in the adaptive schemes over wireless networks.

7.3.2. SAMMy – Performance Evaluation 2: Multi-User Environment

This section evaluates the performance of SAMMy in the presence of multiple simultaneous video streaming sessions in a multi-rate IEEE 802.11 network. As explained in Section 6.3, due to the characteristics of WLAN there is an existing issue with the fairness of the wireless resource distribution: users located near the AP transmitting at high data-rates are greatly impacted, in terms of throughput, by the introduction of a user at the cell border transmitting at a much lower rate. In this context, the goal of SAMMy is to reduce the impact of the low rate users on the nodes which are near the AP, maintaining a reasonable throughput for all users, relative to their locations in the network and their received signal strength.

In order to evaluate the performance of SAMMy in a Multi-User Environment, four scenarios are considered:

(1) Scenario 1 – 11&1Mbps Zones – four users are located in the 11Mbps zone and one user is located in the 1Mbps zone;

(2) Scenario 2 – 11&5.5&1Mbps Zones – two users are located in the 11Mbps zone, two users in the 5.5Mbps zone and two users in the 1Mbps zone – balanced user spread, high load;

(3) Scenario 3 – 1&11Mbps Zones – four users are located in the 1Mbps zone and one user in the 1Mbps zone;

(4) Scenario 4 – 11&5.5&2&1Mbps Zones – one user located in each zone, balanced user spread, low load.

The users present a random distribution within the zones. The zones are defined by the distance from the AP and the received signal strength, such that the 11Mbps Zone is within 78 meters from the AP, the 5.5Mbps Zone is within 108 meters from the AP, the 2Mbps and 1Mbps Zones are within 137 meters and 172 meters, respectively, relative to the AP.

In this section the performance of SAMMy was compared against TFRC only, because from the previous test case scenarios, TFRC resulted to be the best alternative solution. Moreover, TFRC is known to be TCP friendly to elastic traffic. All the mobile users start to watch a multimedia stream on their mobile devices with a 2 seconds delay interval between them. They all use the same adaptive multimedia mechanism (i.e., SAMMy or TFRC). The video data is streamed from a multimedia server to the users' mobile devices through an IEEE 802.11b AP. In these settings the multimedia server stores three-minute long multimedia clips encoded at five different rates corresponding to five quality levels: 0.2Mbps (QL5), 0.4Mbps (QL4), 0.6Mbps (QL3), 0.8Mbps (QL2), and 1Mbps (QL1).

7.3.2.1. Scenario 1 – 11&1Mbps Zones

In this first scenario five mobile users share the radio channel of a multi-rate IEEE 802.11b network. Four users are located near the AP in the 11Mbps zone, while one user is located at the edge of the AP's coverage area in the 1Mbps zone, as illustrated in Figure 7.11. The average throughput achieved by each user is illustrated in Figure 7.12 and listed in Table 7.10.

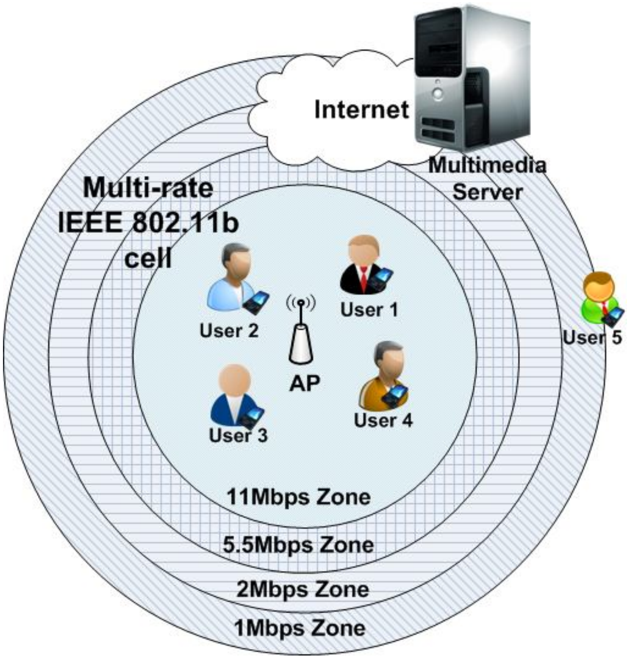

Figure 7.11. Scenario 1: SAMMy – 11&1Mbps Zone

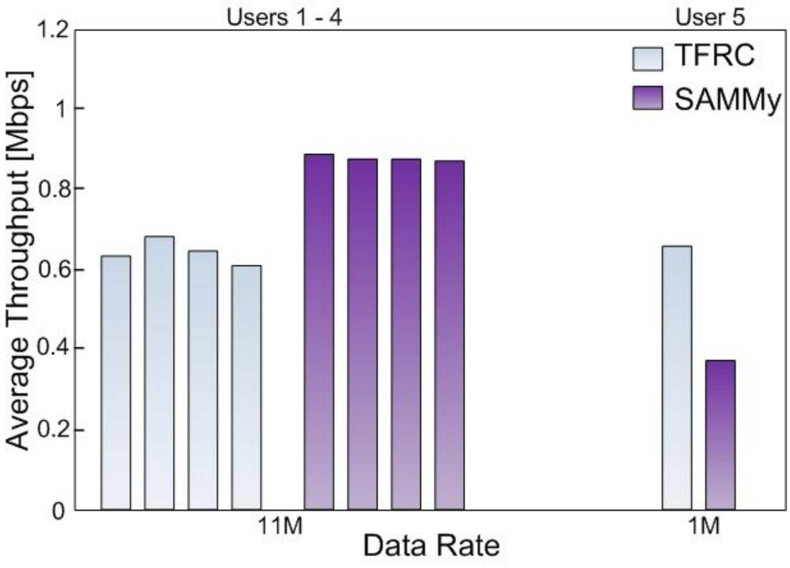

Figure 7.12. Scenario 1 – 11&1Mbps Zone - Throughput achieved by each mobile node

Looking at the results, it can be seen that when using TFRC, all the users located in the 11 Mbps zone, near the AP, are impacted by user 5, who is located at the edge of the cell (1Mbps Zone). Consequently all users receive almost the same throughput, an average of 0.65Mbps. On the other hand, SAMMy offers higher bandwidth share to the users near the AP (11Mbps Zone), while maintaining a reasonable throughput to user 5. Additionally, SAMMy achieves with 18% higher overall throughput in the IEEE 802.11b network when compared with TFRC.

TABLE 7.10. RESULTS SCENARIO 1 - 11&1MBPS ZONES

Scenario 1	User	User1	User2	User3	User4	User5	Total Throughput [Mbps]
	Zone	**11M**	**11M**	**11M**	**11M**	**1M**	
	Average Throughput [Mbps]						
	SAMMy	0.88	0.87	0.87	0.87	0.34	3.83
	TFRC	0.63	0.68	0.65	0.61	0.66	3.23

7.3.2.2. Scenario 2 - 11&5.5&1Mbps Zones

This scenario considers the case of six mobile users competing with each other for resources, with a balanced user spread within the 11, 5.5, and 1Mbps zones as illustrated in Figure 7.13.

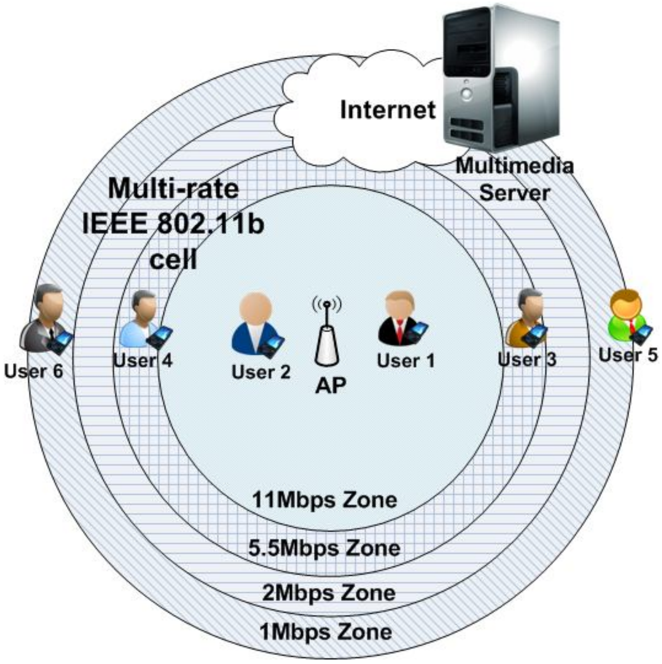

Figure 7.13. Scenario 2: SAMMy – 11&5.5&1Mbps Zone

Figure 7.14 and Table 7.11 present the average throughput achieved by each mobile node. The results confirm the conclusions drawn from Scenario 1. It is noticed that in case of TFRC, the users located in the 11 and 5.5Mbps Zones are impacted by the users with poor location, in the 1Mbps Zone (edge of cell). Consequently the users located in the 1Mbps zone achieve slightly higher throughput than the users with good location (11 and 5.5Mbps Zones). On the other hand, SAMMy offers higher bandwidth share to the users located in the 11 and 5.5Mbps Zones, while maintaining a reasonable throughput for the users in the 1Mbps Zone. In comparison with TFRC, SAMMy offers up to 66% increase in throughput for the users located in the 11Mbps Zone, and up to 36% increase in throughput for the users in 5.5Mbps Zone. Moreover, SAMMy achieves with 18% higher overall throughput in the IEEE 802.11b network when compared with TFRC.

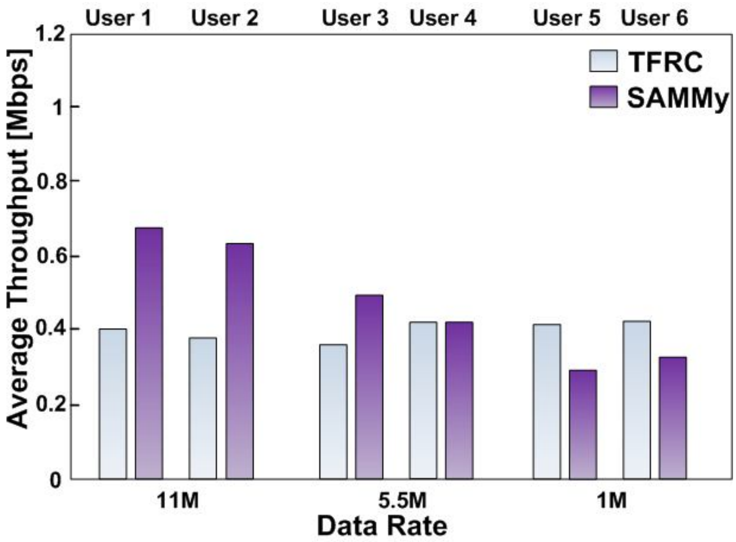

Figure 7.14. Scenario 2 – 11&5.5&1Mbps Zone - Throughput achieved by each mobile node

TABLE 7.11. RESULTS SCENARIO 2 - 11&5.5&2MBPS ZONES

Scenario 2	**User**	**User1**	**User2**	**User3**	**User4**	**User5**	**User6**	**Total Throughput [Mbps]**
	Zone	**11M**	**11M**	**5.5M**	**5.5M**	**1M**	**1M**	
	Average Throughput [Mbps]							
	SAMMy	0.67	0.63	0.49	0.42	0.29	0.32	2.82
	TFRC	0.40	0.38	0.36	0.42	0.41	0.42	2.39

7.3.2.3. Scenario 3 - 1&11Mbps Zones

The third scenario considers the case of five mobile users, with four users located in the 1Mbps Zone and only one user located in the 11Mbps, as illustrated in Figure 7.15.

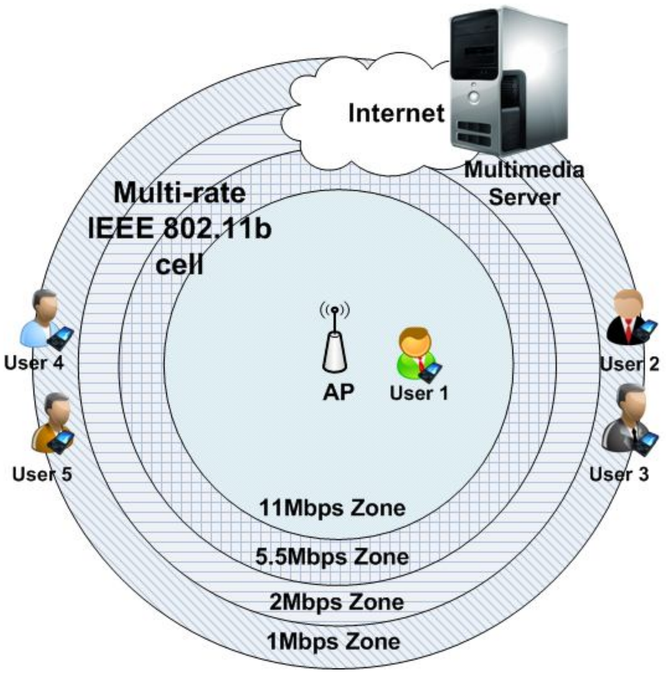

Figure 7.15. Scenario 3: SAMMy – 11&1Mbps Zone

The average throughput obtained by each mobile user is illustrated in Figure 7.16 and listed in Table 7.12. It can be noticed that in case of TFRC the users achieve more or less the same average throughput (i.e., 0.33Mbps). The mobile user located in a good area (11Mbps Zone) is greatly impacted by the users with poor location (1Mbps Zone). Whereas with SAMMy the throughput for the user located in the 11Mbps Zone is doubled (i.e., 0.64Mbps), in comparison with TFRC, whereas for the users located in the 1Mbps Zone SAMMy maintains more or less the same throughput as with TFRC. Consequently, SAMMy achieves with 15% higher overall throughput in the IEEE 802.11b network, in comparison with TFRC.

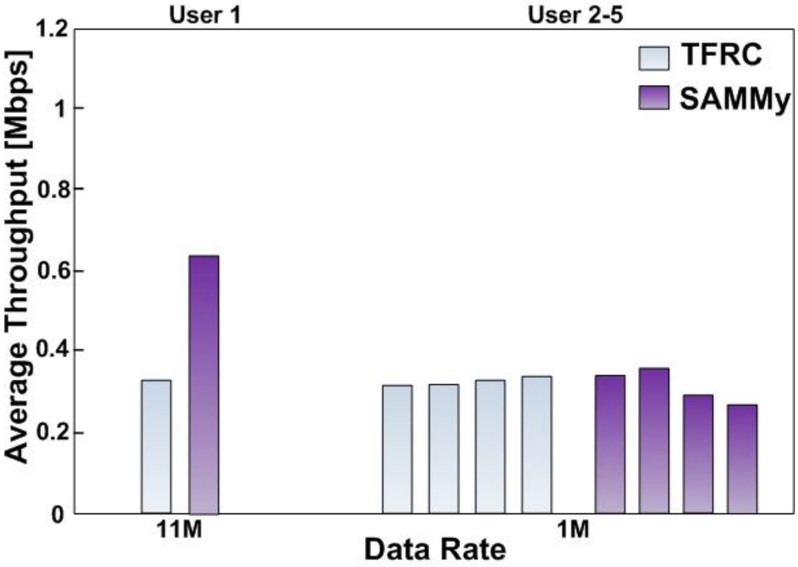

Figure 7.16. Scenario 3 – 11&1Mbps Zone - Throughput achieved by each mobile node

TABLE 7.12. RESULTS SCENARIO 3 - 1&11MBPS ZONES

Scenario 3	User	User1	User2	User3	User4	User5	Total Throughput [Mbps]
	Zone	11M	1M	1M	1M	1M	
		Average Throughput [Mbps]					
	SAMMy	0.64	0.34	0.36	0.29	0.27	1.9
	TFRC	0.33	0.32	0.32	0.33	0.34	1.64

7.3.2.4. Scenario 4 – 11&5.5&2&1Mbps Zones

In the fourth scenario, four mobile users share the radio channel of a multi-rate IEEE 802.11b network, with each user being located in one of the four transmission rate zones (11, 5.5, 2, and 1 Mbps Zones) as illustrated in Figure 7.17.

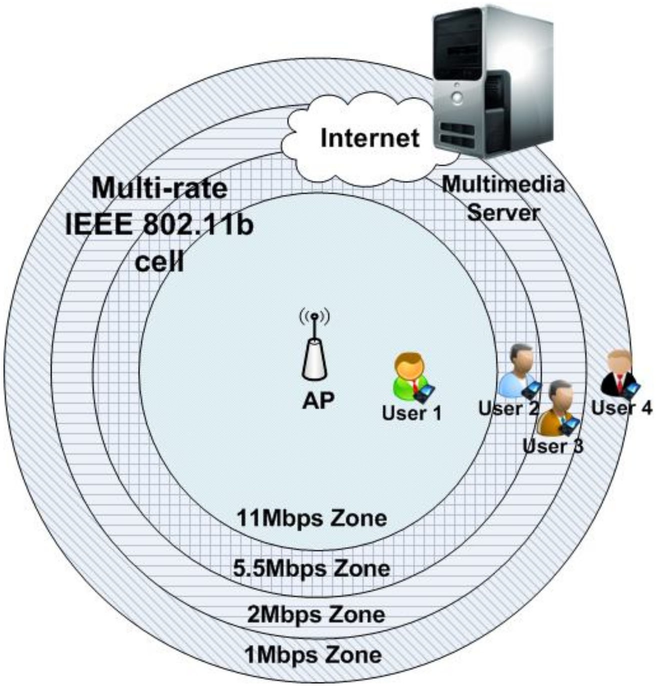

Figure 7.17. Scenario 4: SAMMy – 11&5.5&2&1Mbps Zone

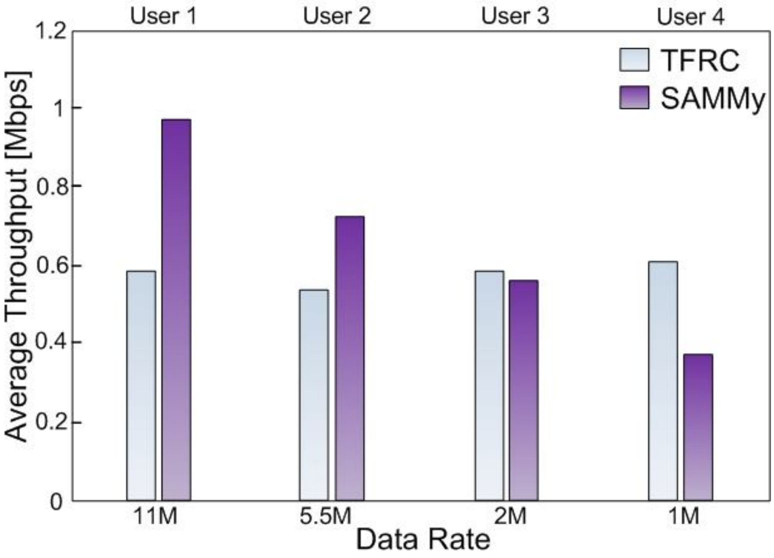

Figure 7.18. Scenario 4 - 11&5.5&2&1Mbps Zone - Throughput achieved by each mobile user

The results are listed in Table 7.13 and Figure 7.18 illustrates the average throughput of each user. It can be seen how, in comparison with TFRC, SAMMy provides bandwidth shares based on user location and their corresponding received signal strength. It can be seen that in SAMMy's case the users located near the AP have high priority and achieve high throughput, while the users located far away from the AP have low priority. In this way the user located near the AP is not severely affected by the user located in the 1 Mbps zone achieving 68% increase in throughput, in comparison with TFRC. Additionally, the overall throughput of SAMMy, in the IEEE 802.11b network, is 15% higher than that achieved by TFRC.

TABLE 7.13. RESULTS SCENARIO 4 – 11&5.5&2&1 MBPS ZONES

Scenario 4	User	User1	User2	User3	User4	Total Throughput [Mbps]
	Zone	11M	5.5M	2M	1M	
		Average Throughput [Mbps]				
	SAMMy	0.96	0.72	0.56	0.37	2.61
	TFRC	0.57	0.5	0.64	0.61	2.3

7.3.2.5. SAMMy Multi-User Environment - Conclusions

The results show that when using TFRC the throughput experienced by users located near the AP decreases in the presence of users located at the edge of the network. SAMMy reduces the impact of the low rate users on users located near the AP, while maintaining a reasonable throughput for all users relative to their proximity to the AP. In comparison with TFRC, SAMMy achieves significant increases in overall throughput (up to 18%) of a multi-rate IEEE 802.11b network.

7.4. Performance Analysis of Adapt-or-Handover (Point C)

Recall Jack's path from his home to his office, as introduced in Section 7.1. Jack enters now the coverage area of the second WLAN (i.e., WLAN B), as represented by point C in Figure 7.19.

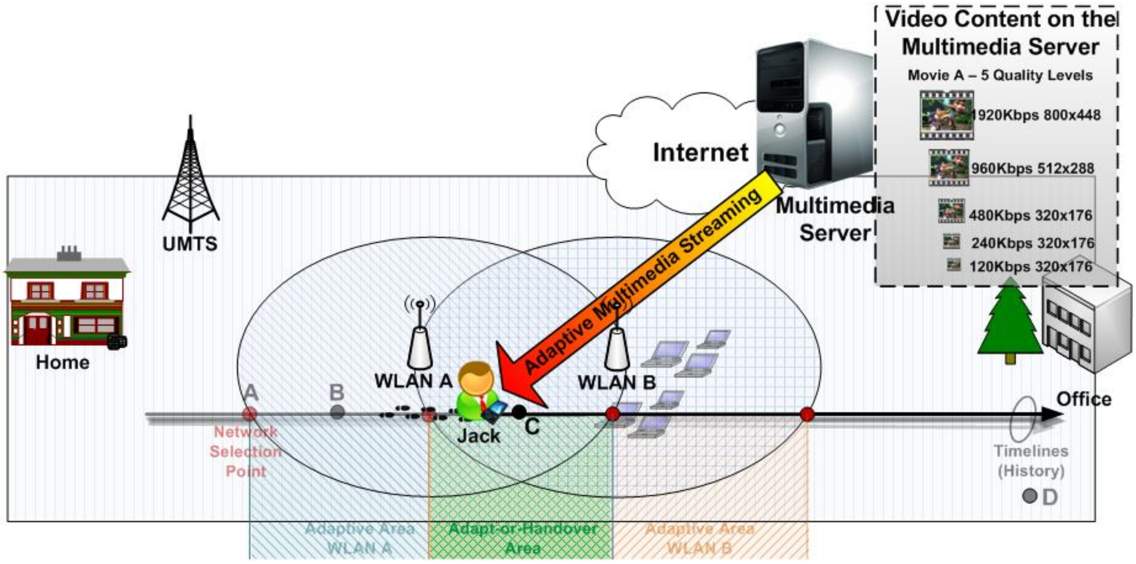

Figure 7.19. Adapt or Handover Scenario

At this point, having a number of three available wireless networks (i.e., UMTS, WLAN A and WLAN B), Jack will be facing a problem in terms of energy efficiency: is it better to adapt the multimedia stream or is it better to handover to a new network. In this situation, the Adapt-or-Handover mechanism will help Jack in taking the best decision.

This section analyzes the performance of the Adapt-or-Handover solution in terms of energy efficiency. Two scenarios are considered:

(1) Critical Test-Case Scenario – in which Jack's mobile device is running out of battery;

(2) Regular Test-Case Scenario – in which Jack's full travel path (from his house to his office) is analyzed in terms of energy efficiency.

7.4.1. Critical Test-Case Scenario – Low Battery Lifetime

Consider that Jack is located in the area where he has a number of three available networks to choose from, as illustrated in Figure 7.20. Assuming that Jack is willing to pay any amount in order to ensure a good quality-energy trade-off, the weights for the three parameters are set to: $w_e = 0.5, w_q = 0.5, w_c = 0.$

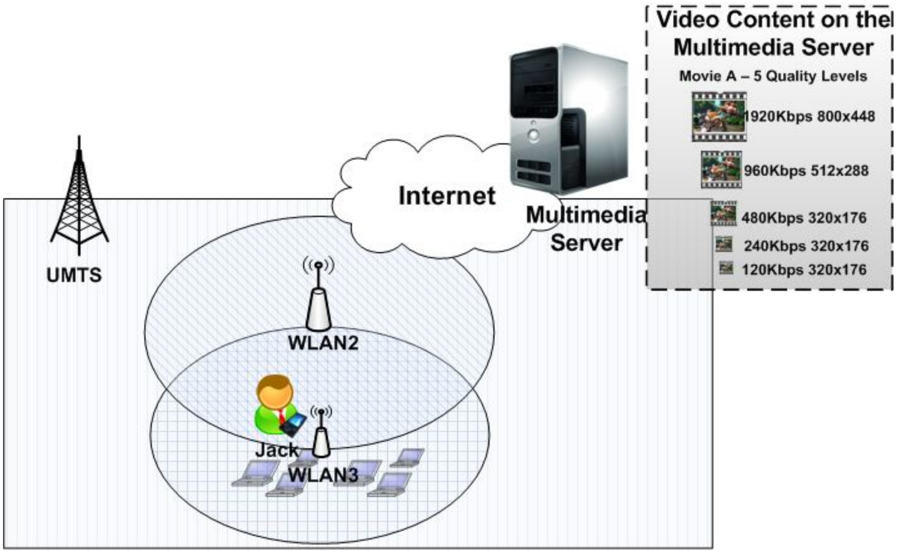

Figure 7.20. Adapt-or-Handover – Critical Test-Case Scenario

This section assumes a critical scenario in which Jack's mobile device is running out of battery. The battery lifetime of his device is just enough to play five minutes of the ten-minute QL1 video clip stored on the server, and this in ideal network conditions (e.g., No Load, Near AP – from the experimental test-bed). In this situation the efficiency of the Adapt-or-Handover mechanism is analyzed. The Adapt-or-Handover algorithm is detailed in Section 4.4.3.

First step is for the network selection mechanism, PoFANS, to select the best network and quality level. The results of the PoFANS mechanism in comparison with the Liu et al. Cost Function (previously introduced in Section 7.2) for WLAN 1, WLAN 3 and UMTS, are listed in Table 6.17. The results are obtained based on the data provided from the experimental test-bed, as explained in Section 7.2.

TABLE 7.14. ADAPT-OR-HANDOVER RESULTS: COST FUNCTION VS. POFANS

	WLAN2		**WLAN3**		**UMTS**	
	No Load, Far AP		**Load, Near AP**		**e-Mobile Network**	
	Cost Function	**PoFANS**	**Cost Function**	**PoFANS**	**Cost Function**	**PoFANS**
QL1	**-0.3929**	0.4445	-0.3805	0.3968	N/A	N/A
QL2	-0.2088	**0.7005**	-0.1933	0.6804	N/A	N/A
QL3	0.0313	0.5433	0.0494	0.5323	0.2208	0.3847
QL4	0.3147	0.3230	0.3346	0.3174	0.5285	0.2394
QL5	0.6264	0.1709	0.6474	0.1704	0.8544	0.1306

As it can be seen, PoFANS will select QL2 WLAN2 while Liu et al. Cost Function, will select QL1 WLAN2. Because the solution provided by Liu et al. Cost Function, does not provide a dual adaptation approach (network selection + video delivery adaptation), after the best network is selected the session is transferred at the corresponding quality level (i.e. QL1).

In case of PoFANS, immediately after the selection of the best quality level and network, the Adapt-or-Handover algorithm kicks off by checking if the *Battery Lifetime* of the mobile device is less than the *Stream Playing Duration*. If this is the case, the energy conservation gets higher priority over the quality so that the device's battery lifetime will last longer (ideally until the end of the multimedia playout) and the adaptive video delivery mechanism, SAMMy, is employed which reduces the current video quality level to the next lower quality level. The detailed algorithm of each of the mechanisms was introduced in Chapter 4.

In this particular case with Jack's mobile device having only five minutes left of its battery (for playing QL1 in ideally No Load, Near AP network) while the video stream playing duration is ten minutes, the Adapt-or-Handover mechanism, after selecting the best target network will adapt the stream to the quality level for which the battery lifetime of Jack's mobile device will be the closest or higher than the stream playing duration. In this case, the Adapt-or-Handover mechanism will adapt the quality level to QL5, so Jack will be able to watch the full multimedia stream. Figure 7.21 and Table 7.15 illustrate what would be the playing durations for each of the quality levels in each network. The results are estimated based on the results obtained in the real experimental test-bed scenarios as described in Chapter 5 with the playout duration of QL1 in a No Load, Near AP taken as reference. Figure 7.21 illustrates the throughput (quality level) for each situation, with the throughput falling to zero when the device runs out of battery. The results show that only when transmitting at QL5 in WLAN2 Jack will be able to finish watching the multimedia stream.

By employing the Liu et al. Cost Function the multimedia will be streamed at QL1 on WLAN 2. As seen in Table 7.15, in this situation Jack's mobile device battery lifetime will last for 4:57 minutes only, Jack being able to watch less than half of the multimedia playout.

From Table 7.15 it can be seen that, in this situation, the Adapt-or-Handover solution, by employing the adaptation mechanism (SAMMy), will more than double the battery lifetime of Jack's mobile device as compared with the Liu et al. Cost Function-based solution.

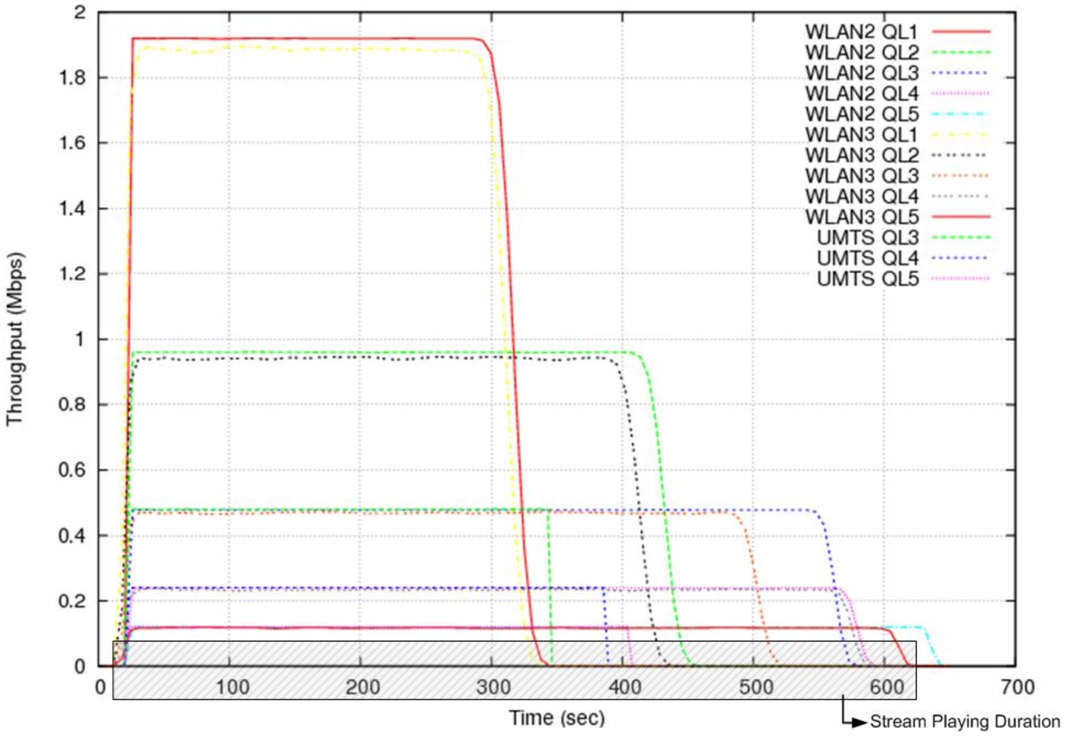

Figure 7.21. Stream Playing Duration for different QL and networks

TABLE 7.15. ADAPT-OR-HANDOVER COMPARISON OF STREAM PLAYING DURATIONS

	WLAN2	**WLAN3**	**UMTS**
	No Load, Far AP	**Load, Near AP**	**e-Mobile Network**
	Stream Playing Duration [min:sec]	**Stream Playing Duration [min:sec]**	**Stream Playing Duration [min:sec]**
QL1	4:57	4:51	N/A
QL2	6:52	6:33	N/A
QL3	8:26	8:05	5:26
QL4	9:19	9:15	6:09
QL5	**10:16**	9:51	6:27

7.4.2. Regular Test-Case Scenario

This section analyzes the performance of the proposed Adapt-or-Handover solution in terms of energy efficiency, over Jack's full travel path (from Home to Office). The Adapt-or-Handover solution is compared against the Liu et al. Cost Function-based solution. Figure 7.22 and Figure 7.23 illustrate the received throughput and the energy consumption of Jack's mobile device, respectively. The weights for the three parameters are: $w_e = 0.5$, $w_q = 0.5$, $w_c = 0$. As mentioned in Section 7.2, a weight for quality of 0.5 will result in minimum acceptable video quality above QL4.

As noticed in Figure 7.22 on his way to his office Jack has a number of three available networks (i.e., UMTS, WLAN A and WLAN B). WLAN A is not loaded, whereas WLAN B is loaded. This scenario incorporates all the situations covered in Section 7.2.1 and the results provided in Table 7.1. For example, WLAN A incorporates WLAN2 (No Load, Far AP) when Jack is located far from the AP, and as he goes towards the AP the scenario of WLAN1 (No Load, Near AP) is considered. The same applies for WLAN B (WLAN3 – Load, Near AP and WLAN 4 – Load, Far AP). These aspects were considered when computing the energy consumption for this scenario. The network conditions from the experimental test-bed for all five networks were modeled in the NS-2 simulator.

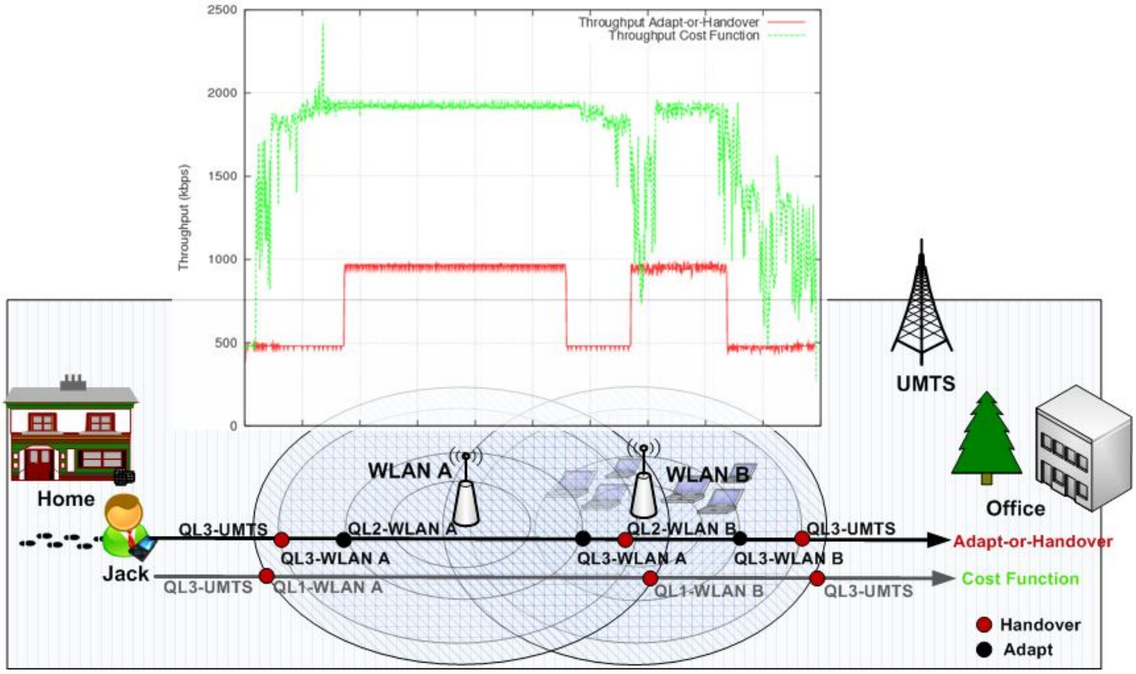

Figure 7.22. Throughput Jack’s Full Travel Path: Adapt-or-Handover vs. Cost Function Analysis

In this scenario, initially Jack receives video at QL3 over the UMTS network, and as he goes further, he enters the coverage area of WLAN A (incorporates the two experimental scenarios WLAN2 – no load, far from AP and WLAN1 – no load, near the AP). The Liu et al. Cost Function performs a handover to WLAN A (QL1 – WLAN2) whereas Adapt-or-Handover solution decides to stay in UMTS. This is because, Jack would be located in an area with poor signal strength within WLAN A (Area 3), meaning that SAMMy could provide QL4 as the maximum QL in that area, which is not acceptable for Jack that prefers a video quality above or equal to QL3. When Jack enters Area 2 (maximum QL of SAMMy = QL3) of WLAN A the Adapt-or-Handover mechanism will handover (a smooth handover is assumed) to WLAN A

(QL3- WLAN2). Moving further towards the AP, SAMMy will adapt to a higher quality level (QL2-WLAN1). QL2 is the maximum quality level that Jack could receive as decided by PoFANS (see Table 7.1). When Jack crosses in Area 2 of WLAN A again, SAMMy will adapt to a lower quality level (QL3-WLAN2). When leaving area Area 2 of WLAN A, the Adapt-or-Handover mechanism will trigger PoFANS and will handover to WLAN B (QL2-WLAN3) (Area 1 of WLAN A is not acceptable in terms of quality as already explained). Moving further away from the AP, SAMMy will adapt the multimedia stream to a lower quality level (QL3-WLAN4), and when leaving Area 3 of WLAN B, PoFANS will decide to handover to the UMTS network again.

The Liu et al. Cost Function has three handover decision points, when entering and leaving the coverage area of an AP, only. It does not take any adaptation decision and transmits the highest video quality level at all times.

The average throughput and average energy consumption for both Adapt-or-Handover solution and Liu et al. Cost Function –base solution, in this scenario, are listed in Table 7.16. It can be seen how Jack, by using the Adapt-or-Handover solution, can reduce the energy consumption of his mobile device with 31% in comparison with when the Liu et al. Cost Function is employed. Note that the cost of handover in terms of energy consumption has been neglected in this scenario. However it does not have any impact in the comparison of the methods as both methods have the same number of handover executions.

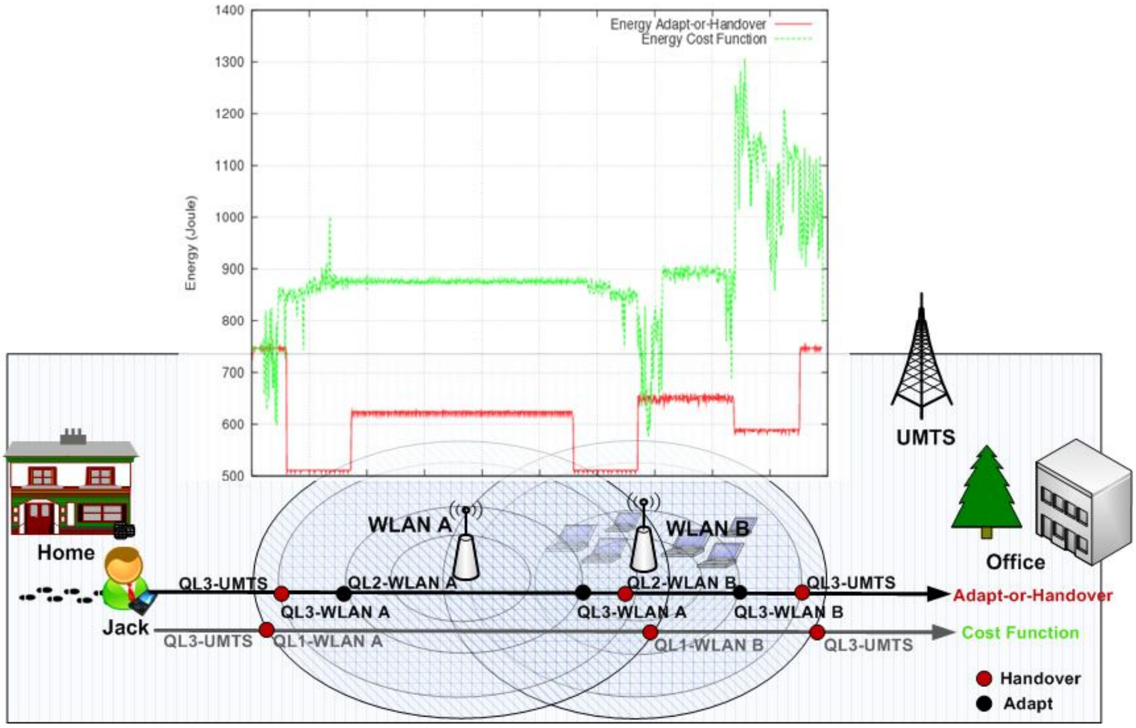

Figure 7.23. Energy Consumption Jack's Full Travel Path: Adapt-or-Handover vs. Cost Function

TABLE 7.16. REGULAR TEST-CASE SCENARIO – JACKS'FULL TRAVEL PATH RESULTS

Solution	Average Throughput [Kbps]	Average Energy Consumption [Joule]
Adapt-or-Handover	740	891
Liu et al. Cost Function	1710	610

7.5. Analysis of the Reputation-based Network Selection Mechanism using Game Theory (Point D)

As Jack is traveling every day from his Home to his Office, as illustrated in Figure 7.24, he is passing across several available wireless networks which may belong to the same, or to different network operators. Because Jack is taking the same path every day, it can be considered that he has a history of the interaction with the different wireless networks he is accessed on his way. This user-network interaction is modeled as a repeated cooperative game, following the repeated Prisoner's Dilemma game as described in the Game Theory. The outcome of each user-network interaction game is a reputation factor for each visited network. This enables a reputation-based network selection mechanism to be built.

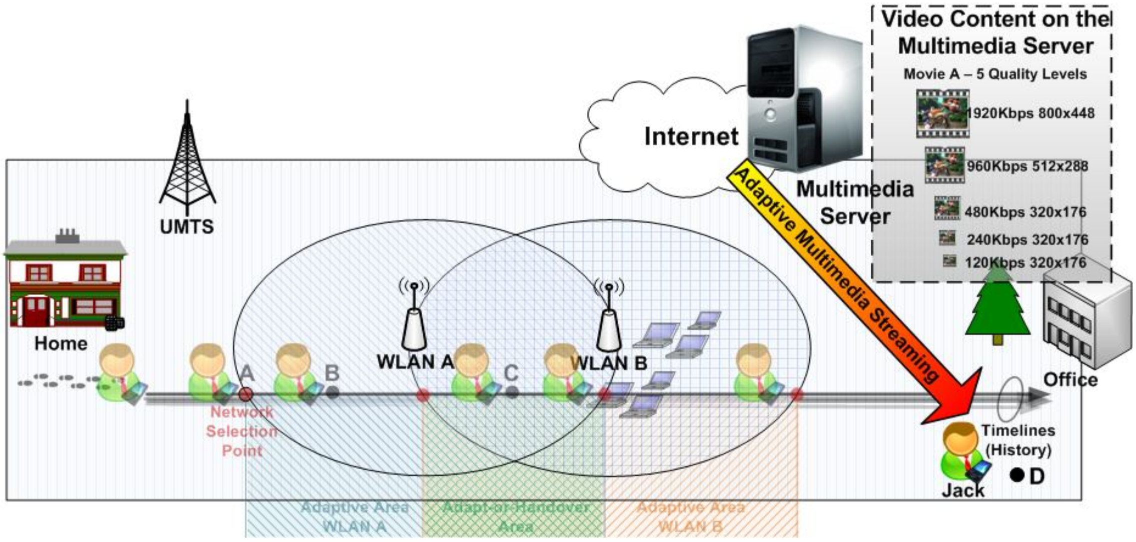

Figure 7.24. Reputation-based Network Selection – Example Scenario

This section analyzes the performance of the reputation-based network selection mechanism proposed and described in Chapter 4. Three main aspects are considered:

(1) mathematical **analysis of the Equilibrium**;

(2) impact of different strategies and payoffs on the user-network interaction;

(3) impact of user preferences on the network reputation factor.

Next, these aspects are presented in details.

The user-network interaction game was modeled and described in Chapter 4. As mentioned, the players in this game are ***the user*** and ***the network***. Following the model of repeated Prisoner's Dilemma, there are three strategies involved: *Cooperate*, *Defect*, and *GRIM*. By *Cooperation* it is meant that the network fulfills the user requirements, and the user is satisfied, deciding to stay within the same network. By playing *GRIM* the network will always cooperate as long as the user cooperates. *Defecting* means that the network does not fulfill the user's QoS requirements anymore and the user decides to leave.

7.5.1. Analysis of the Equilibrium

After the network selection decision takes place, and the target network is selected, the two-player repeated cooperative game starts. It is assumed that the game starts with the network's *Cooperate* strategy. If the user's response will be *Cooperate*, then the network will switch to playing *GRIM*. Even though the network's strategy is *Cooperate*, it might happen that the user perceives degradation in the quality of service because of the wireless environment where connections are prone to interference, high data loss rates, and/or disconnection. In general, the errors in the wireless environment are random and can be represented by the Nature player. Figure 7.25 illustrates an example of an extensive form of the one-shot user-network game where the Nature player is integrated.

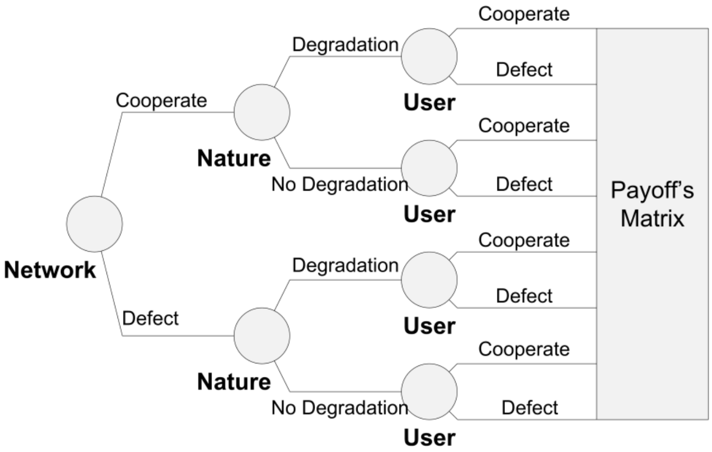

Figure 7.25. Extensive form of the one-shot user-network game

An approach on explaining how cooperation can survive in long-term relationships without the need for external enforcement is finding *a Pareto-efficient Nash Equilibrium* in the user-network repeated game.

Usually a repeated game has a huge number of strategies, leading to an infinite number of Nash Equilibrium. The general payoff table of the game is illustrated in Table 7.17. Each player $k \in \{1,2\}$ has a payoff such that $A_k>B_k>C_k>D_k$.

TABLE 7.17. GENERAL PAYOFFS USER-NETWORK REPEATED GAME

Player 1 - User	Player 2 - Network			
		Cooperate	**GRIM**	**Defect**
	Cooperate	B_1B_2	B_1B_2	D_1A_2
	GRIM	B_1B_2	$\boxed{B_1B_2}^{NE}$	C_1C_2
	Defect	A_1D_2	C_1C_2	$C_1C_2^{NE}$

Observing the payoff table, it can be noticed that the user gets the highest payoff if the network *Cooperates* and he/she *Defects*. This can happen when another better offer is available and the user decides to switch to that network. On the other side, the network gets the highest payoff when the user decides to *Cooperate,* but the network *Defects*. This happens when the network operator acts selfishly, trying to maximize the short-term increase in its own payoff by squeezing in extra users which finally will lead on low QoS for the user. The meaning of the general payoffs is illustrated in Table 7.18.

TABLE 7.18. USER-NETWORK REPEATED GAME PAYOFFS - MAPPING TABLE

User Payoffs	Description
A_1	The payoff the user gets when the network *Cooperates* but another better offer is available, expressed as the difference between the benefit the user gets from the service and the cost incurred in the new network (*the payoff of the new network > the payoff of the current network*).
B_1	The payoff the user gets when both players *Cooperate* or play *GRIM*, expressed as the difference between the service quality and the cost of the current network.
C_1	The payoff the user gets when both players *Defect* or one plays *GRIM* and the other one *Defects*, expressed as the difference between the service utility when the network does not offer the requested QoS and the cost incurred when the user decides to leave.
D_1	The payoff the user gets when he/she *Cooperates* but the network acts selfishly by trying to maximize its own payoff and *Defects*, expressed as the difference between the quality utility when the network is not offering the requested QoS to the user and the cost utility charged as for receiving the requested QoS.
Network Payoffs	**Description**
A_2	The payoff the network gets when the user *Cooperates* but the network *Defects* seeking short-term maximization of its own revenue, expressed as the difference between the compensation received by accepting other users, and the cost incurred in supporting the requirements.
B_2	The payoff the network gets when both players *Cooperate* or play *GRIM*, expressed as the difference between the compensation received from the user and the cost incurred in supporting the requirements.
C_2	The payoff the network gets when both players *Defect* or one plays *GRIM* and the other one *Defects*, expressed as the difference between the compensation received after the user decides to leave the network and the cost incurred in supporting lower QoS requirements.
D_2	The payoff the network gets when *Cooperates* but the user decides to leave the network as a better offer is available, expressed as the difference between the compensation received after the user decides to leave and the cost incurred on offering the requirements.

From the payoff described in Table 7.17 it can be noticed that if the user-network repeated game would have had only *Cooperate* and *Defect* strategies it would be reduced to one-shot version of the game. Two *Nash Equilibrium* cases can be identified from the payoff table, one for punishment when both players *Defect*, and one for reward when both players play *GRIM.*

Usually if a repeated game has more than one *Nash Equilibrium*, then the prospect of playing different equilibrium in the next stage is used, in order to provide incentives (rewards and punishments) for cooperation in the current stage.

In order to sustain *Nash Equilibrium* in the game it has to be shown that the user would earn more if he/she plays *Cooperate* rather than *Defect*. If the user selects to *Cooperate* in the first stage then his/her payoff would be B_1 plus the payoff from the next stage when both will play *GRIM* which is B_1, leading to a total payoff of $2B_1$. If the user decides to *Defect* in the first stage, then his/her payoff would be A_1 plus the payoff from the next stage when both players *Defect*, leading to a total payoff of $A_1 + C_1$. In order to sustain *Nash Equilibrium* the condition $2B_1 \geq A_1 + C_1$ has to hold.

Another way of showing this is by comparing the temptation to *Defect* in the current stage with the value of rewards and punishment in the next stage. In this case, the following condition defined by equation (7.3) has to be true:

temptation to Defect in the ***current stage*** ≤

the value of reward – value of punishment in the ***next stage*** (7.3)

The temptation to *Defect* in the current stage is given by the difference between the payoff the user gets by playing *Cooperate* and the payoff the user gets by playing *Defect*: $A_1 – B_1$. The value of reward in the next stage is given by the payoff the user gets when both players play *GRIM*, which is B_1. The value of punishment in the next stage is given by the payoff the user gets when both players *Defect*, which is C_1. Putting it all together: $A_1 - B_1 \leq B_1 - C_1$ => in order to enable Cooperation the same condition $2B_1 \geq A_1 + C_1$ has to be true. By using the two *Nash Equilibrium cases*, one for punishment and one for reward, enables us to sustain *Cooperation.*

Usually, when the duration of the game is known, the players tend to play *Defect* in the last period. In this work the game between the user and the network has no known end, but a probability of continuity δ is defined. In order to sustain *Nash Equilibrium* in a game with unknown end, the condition given by equation (7.3) has to be true. The value of temptation to *Defect* in the current stage is the same as before, but the value of reward in the next stage is given by the payoff earned when playing *Cooperate* for the entire period of the rest of the game, until the game ends. The value of punishment in the next stage is given by the payoff earned when playing *Defect* until the game stops. The difference of the two values is multiplied by δ, where $\delta < 1$ as the game may end and the next period might not happen.

$$A_1 - B_1 \leq [B_1 \text{ for the rest of the game} - C_1 \text{ for the rest of the game}] \times \delta;$$

$$B_1 \text{ for the rest of the game} = B_1 + B_1\delta + B_1\delta^2 + \ldots \cong B_1/(1-\delta);$$

$$C_1 \text{ for the rest of the game} = C_1 + C_1\delta + C_1\delta^2 + \ldots \cong C_1/(1-\delta);$$

$$\Leftrightarrow$$

$$A_1 - B_1 \leq [\, B_1/(1-\delta) - C_1/(1-\delta)\,] \times \delta$$

This analysis shows that **cooperation can be obtained by using the GRIM trigger** as a sub-game perfect equilibrium provided $\delta > (A_1 - B_1)/(A_1 - C_1)$. For continuous interactions, to provide incentives for cooperation, it helps to have a future, meaning that the probability that the interaction will continue in the next period is high. The continuity probability represents the weight it is put on the future interactions. It is needed that the probability of interaction to continue to be reasonable high in order to overcome the temptation to *Defect*.

7.5.2. Impact of Different Strategies on the Payoffs

In order to examine how different strategies (for the user and for the network) impact the payoffs of the user-network interaction game, an analytical model of the repeated game was implemented in Matlab. Three strategies were implemented for the **Network**: *GRIM* – the network cooperates as long as the user cooperates, *Always Defect* – the network defects in each round, and *Random Behavior* – there is a random chance for the network to defect or to cooperate. On the other side, the **User**, Jack, can make use of four strategies: *GRIM* – the user cooperates as long as the network does the same, *Tit for Two Tats* – the user will defect if the network defects two consecutive times, *Tit for Random Tats* – the user will defect if the network defects a random number of consecutive times, and *Always Cooperate* – the user will cooperate in each round. The payoffs for the user and the network were selected in order to simplify the analysis of different strategies and they are based on the previously mentioned relationship: A > B > C > D (see Chapter 4). Two sets of simulations using different payoffs and the same combination of strategies were run. A simulation set consists of 100 simulation runs. The payoffs are illustrated in Table 7.19.

TABLE 7.19. USER/NETWORK PAYOFFS

		Simulation Set 1		**Simulation Set 2**	
		Network		**Network**	
		Cooperate	**Defect**	**Cooperate**	**Defect**
User	**Cooperate**	3 / 3	1 / 4	60 / 60	1 / 100
	Defect	4 / 1	2 / 2	100 / 1	40 / 40

For example, in the first simulation set, if the user Cooperates and the network Defects, the user will get a payoff of 1 while the network gets 4. In the second simulation set the gap between the payoffs received when Cooperating and the payoffs received when Defecting was increased. In this case the cooperating user will get a payoff of 1 and the defecting network will get 100. When the user Defects, it means that the user leaves the network for a random number of rounds. It is assumed that another better network that fulfils his/her requirements is available. The user's total accumulated payoff will include the payoff for the current round and the previous rounds. The payoff for the rest of the rounds (where he/she has left the network) is zero. A new random number is generated every time the user comes back, and is different for each of the strategies and simulation sets.

For each simulation set and strategy combination, 100 simulations were run, with random number of rounds per simulation (between 1 and 1000) so that the behavior when the user-network interaction is both short-term and long-term is covered. The minimum number of rounds generated was 3 and the maximum number was 935. Based on the cumulative user and network payoffs per simulation the average cumulative payoffs from all the simulations runs, for an average of 258.46 rounds, was computed. Table 7.20 illustrates the results of both simulation sets.

TABLE 7.20. AVERAGE CUMULATIVE PAYOFFS FROM ALL STRATEGY COMBINATIONS

			Network			
			GRIM	**Always Defect**	**Random**	
Simulation Set 1	**User**	**GRIM**	**775.38 / 775.38**	3 / 6	131.29 / 209.71	49.9% ND & 20.2% UC
		Tit for 2 Tats	**775.38 / 775.38**	4 / 10	233.6 / 396.35	49.8% ND & 41.8% UC
		Tit for R Tats	**775.38 / 775.38**	8.37 / 27.6	493.59 / 861.78	49.9% ND & 95.13% UC
		Always Cooperate	**775.38 / 775.38**	258.46 / **1030**	515.98 / 905.08	50.17% ND & 100% UC
Simulation Set 2		**GRIM**	**15500 / 15500**	41 / 140	2170 / 4765	49.6% ND & 20.49 UC
		Tit for 2 Tats	**15500 / 15500**	42 / 240	3600 / 8980	49.8% ND & 41.49% UC
		Tit for R Tats	**15500 / 15500**	45.81 / 660.60	7640 / 19900	49.7% ND & 96% UC
		Always Cooperate	**15500 / 15500**	258.46 / **25846**	7900 / 20700	49.9% ND & 100% UC

It can be seen that in both cases the Network gets the best score when it plays Always Defect and the user plays Always Cooperate. This means that the Network offers a quality to the user, which is below the minimum acceptable threshold, and the user accepts it. This will not happen in real life, as usually the users expect to get the service quality they are paying for. When the network plays Random it can be seen the different behavior of the user for each strategy. For example, when the user plays GRIM, the network defects (ND) 49.9% of the rounds and the user cooperates (UC) only 20.2% of the rounds, getting a smaller payoff. This payoff reflects only the payoff the user gets from this particular user-network interaction, without considering the payoff he/she gets from the other network that he/she connects to when leaving the current network. This means that his/her actual payoff is greater. In this case, when the user plays GRIM and the network defects almost 50% of the rounds, the situation in which the user is not willing to accept poor quality is reflected. If the user plays Tit for Random Tats, even though his/her payoff will be higher by cooperating 95.13% of the rounds, the network still defects 49.9% of the rounds. So the user is suffering the poor service quality offered by the network.

The situation that satisfies both parties, and is the most convenient for both the network and the user is when the network plays GRIM and the user plays any of his/her strategies. Only then they will both gain from the user-network interaction.

7.5.3. Impact of User Preferences on the Network Reputation

Different users, having different preferences will generate different reputation factors for the networks that they visit. The network reputation depends on a particular user profile and whether they are using the current application for business or for personal use. For example, a network that generally offers good quality levels for a reasonable price can have a better reputation for a user that prefers quality over energy conservation or cost, than for a user that can accept a lower quality level for a cheaper price. This section studies the impact of different user preferences on the network reputation.

The repeated game was implemented in Matlab as a proof of concept. A throughput trace file was used as input data. The trace file was generated from NS-2, considering the scenario of a mobile user performing video delivery (QL1 - CBR traffic – 1920kbps data rate) over a WLAN network that becomes overloaded in time. The throughput trace file contains throughput values that range from very high values to very low values, for simulation purpose in order to cover all different possible network loads (network operators' attitudes). Based on the throughput trace file and equation (6.4), which models the energy consumption pattern of a Google Nexus One mobile device, the energy consumption was computed considering a loaded, near AP scenario. The resulted throughput and energy consumption are illustrated in Figure 7.26. It can be noticed that as the throughput decreases, the energy consumption decreases as well.

In order to study the impact of different user preferences, three cases were considered:

(1) Quality-Oriented User – the user prefers high quality over low energy and cost: $w_q = 0.6, w_e = 0.2, w_c = 0.2$;

(2) Energy-Oriented User - the user prefers low energy over high quality and low cost: $w_q = 0.2, w_e = 0.6, w_c = 0.2$;

(3) Quality & Energy Focused User - the user equally prefers quality and energy over cost: $w_q = 0.4, w_e = 0.4, w_c = 0.2$.

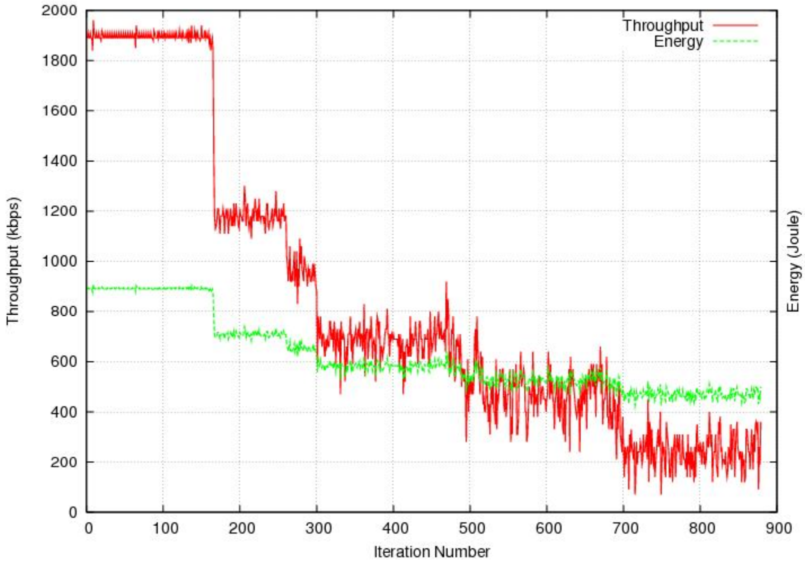

Figure 7.26. Throughput trace and Energy Consumption

The utility functions used in these test-case scenarios were previously introduced and described in Section 4, such that: the quality utility (u_q) defined in equation (4.4), energy utility (u_e) defined in equation (4.3), the cost utility (u_c) defined in equation (4.8), and the overall score function (U) defined in equation (4.2).

It is assumed that the user has a budget of 10 eurocents per KByte, meaning that he/she is willing to spent up to B = 10c/KB. Moreover, a flat rate cost is assumed. The cost of the network is selected based on the current offers on the market for pay as you go option: C = 2c/KB (Meteor Ireland[2]).

The payoff for the user and for the network were introduced and defined in Section 4.5.3 and reminded here in equation (7.3) and equation (7.4), respectively:

$$\pi_M = U_i * B - C_i + P_{new} - C_{HO} \qquad (7.3)$$

where: π_M - user's payoff (euro), U_i - the score function of the current network i (values within [0,1]), B – the user's budget (euro), C_i – the cost of the current network i (euro), P – the user's payoff if he/she would handover to a new network (is 0 when the user Cooperates) (euro), C_{HO} – the cost of handover to a new network (is 0 when the user Cooperates) (euro).

$$\pi_N = G - C_{QoS} - L_{rev} \qquad (7.4)$$

where: π_N – network's payoff (euro), G – the network gain (money gained from user payments for the services used in the network) (euro), C_{Qos} – the cost paid by the network for the current QoS provisioning (euro), L_{rev} – the loss of revenue in case the user decides to defect/leave the network (is 0 if the user Cooperates) (euro).

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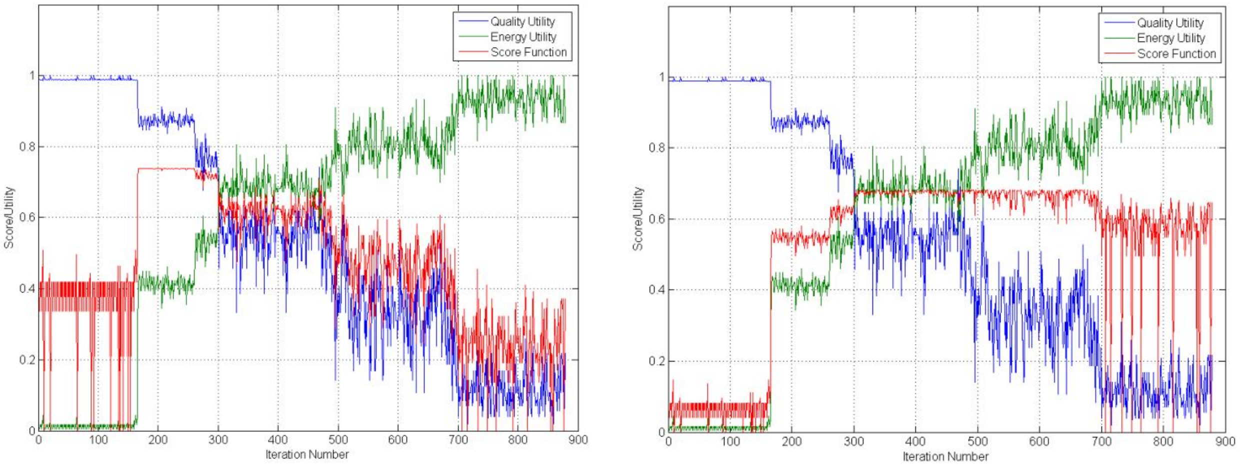
[2] Meteor Ireland - www.meteor.ie

The cost paid by the network for the current QoS provisioning, can be obtained from the network operator. In order to simplify the analysis, in this work it is assumed that the network has a 60% profit, consequently the network cost for QoS provisioning is $C_{QoS} = u_q \cdot 40\% \cdot G$. Where, G represents the network gain, which is in fact the cost paid by the user for the current services. Moreover, it is assumed that as the network offers a lower QoS, its cost for provisioning is decreasing, therefore increasing its revenue. For example, considering that the network advertises data rates of 2Mbps for a price of 2c/KB while actually offering 0.48Mbps for the same price, its payoff will be 2 – 0.34*0.4*2 = 1.728c. For the purpose of this study it is assumed that the values for the C_{HO} and L_{rev} are random values in the [0,1] interval. The payoff of the user in case he/she handovers to a new network, P_{new} is assumed to be the payoff the user gets for U_{req} (the score function computed for Th_{req}=0.48Mbps) having the same budget and same network cost.

The quality utility (u_q), energy utility (u_e) and overall score function (U), for all three cases considered in the simulation, are illustrated in Figure 7.27. It is clear that the quality utility is high when the throughput is high and decreases as the throughput decreases; on the other side, the energy utility is low when the throughput is high, as the energy consumption will also be high, and increases as the throughput decreases. By varying user preferences it can be seen that when the user is quality-oriented (prefers more the quality) although the quality utility is high, the overall utility is low because the energy consumption is very high and this does not represent a good trade-off for the user. If the throughput is very high, better quality is supported but more energy is consumed, and if the user will not be able to watch the full multimedia stream due to possible battery depletion then, it is not worth to the user that the quality was high.

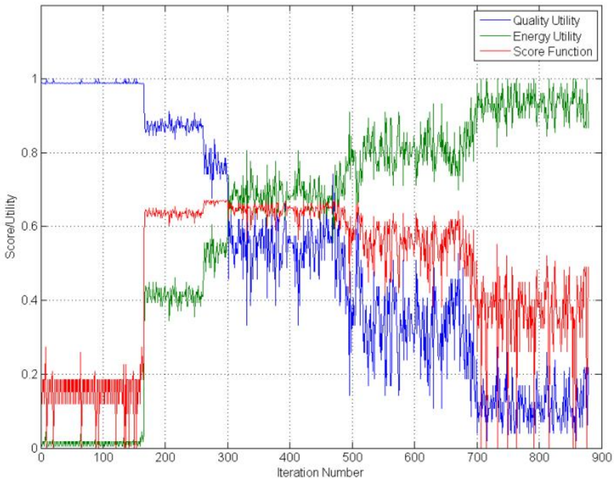
These shows again the need of an adaptive mechanism that controls the received throughput based on the user preferences. In the real world, the network operators have the idea that high quality means as much throughput as possible. But this is not the case, as it can be seen, when the network offers high throughput values, but the user prefers energy conservation (suggesting lower throughput). As mentioned, in this work this example is used only as proof of concept.

A good trade-off between the energy and throughput is needed, and this is obtained through the overall score function as illustrated in Figure 7.27(a,b, and c). In Figure 7.27b, when the user prefers the energy conservation, the overall score function is very low for high values of quality utility as the energy consumption is significant.



a) Quality-Oriented User ($w_q = 0.6$, $w_e = 0.2$, $w_c = 0.2$)

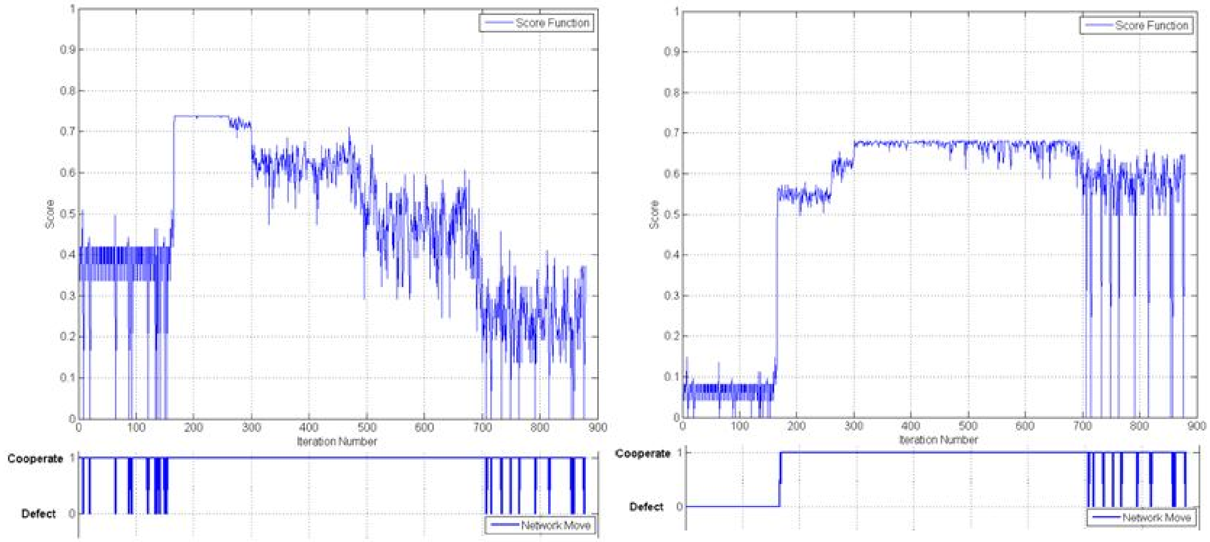
b) Energy-Oriented User ($w_q = 0.2$, $w_e = 0.6$, $w_c = 0.2$)



c) Quality & Energy Focused User ($w_q = 0.4$, $w_e = 0.4$, $w_c = 0.2$)

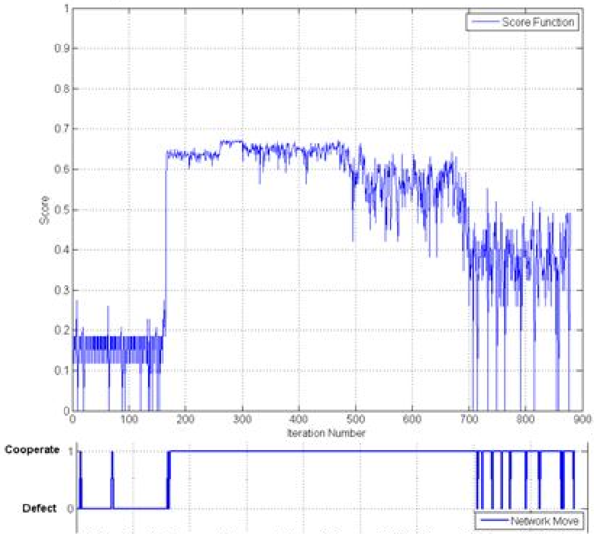
Figure 7.27. Quality Utility, Energy Utility, and overall Score Function for the three cases

For the three different cases the network will have different reputation factors. It is considered that the network Defects when its offered utility (overall score function) goes below the minimum acceptable utility (score function) of the user. Because user preferences are different, every user will have different minimum acceptable scores. When the user is quality-oriented (prefers higher quality), its minimum acceptable score function and the required score function values are: $U_{min} = 0.1167$ and $U_{req} = 0.4786$, respectively. For the second case $U_{min} = 0.4743$ and $U_{req} = 0.6737$ and for the third case $U_{min} = 0.2350$ and $U_{req} = 0.567$. Where U_{min} and U_{req} were computed for Th_{min} and Th_{req}, respectively. The overall score function *(U)* and the network's move (1 denotes Cooperation and 0 denotes Defection) are illustrated in Figure 7.28.



a) Quality-Oriented User (U_{min} = 0.1167 and U_{req} = 0.4786)

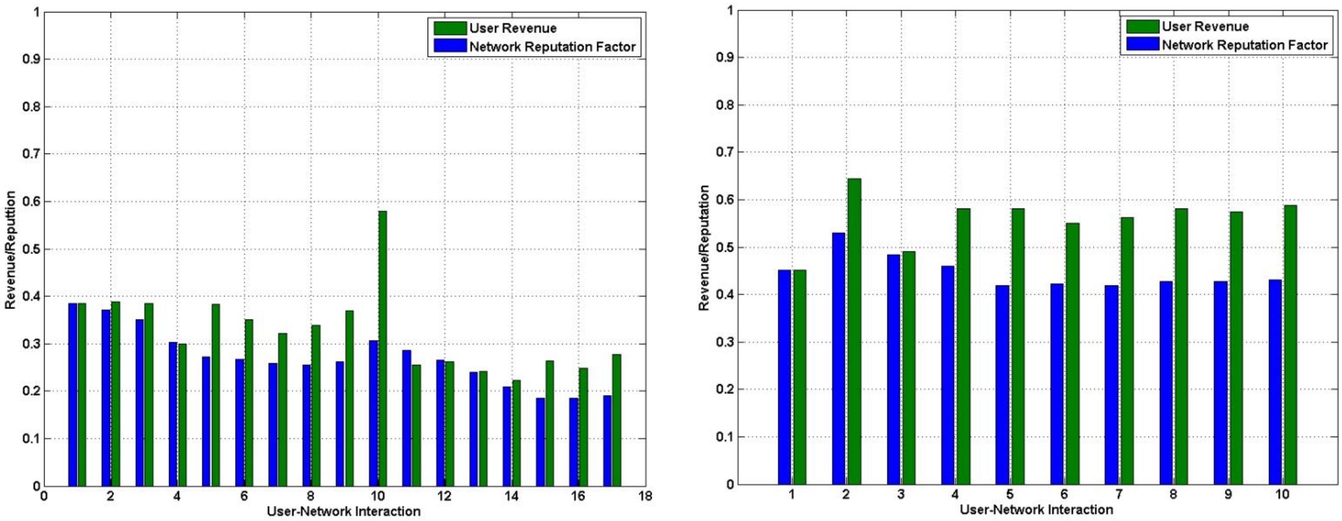
b) Energy-Oriented User (U_{min} = 0.4743 and U_{req} = 0.6737)



c) Quality & Energy Focused User (U_{min} = 0.2350 and U_{req} = 0.567)

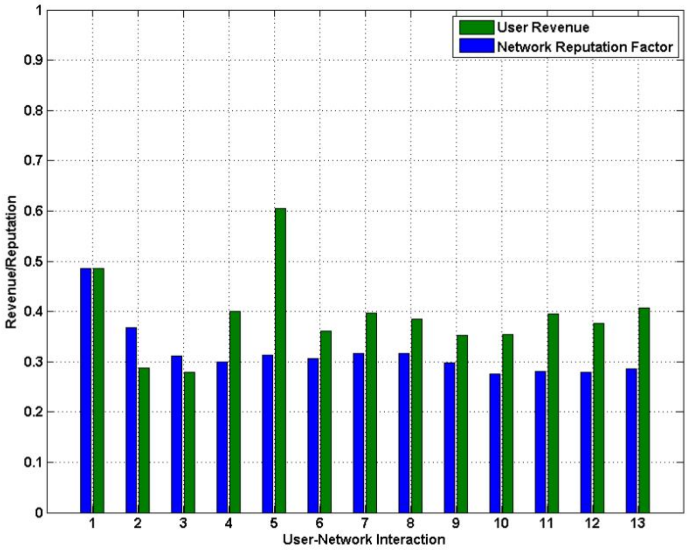
Figure 7.28. Overall Score Function and Network Moves (1 for Cooperation and 0 for Defection) for the three cases

As mentioned before, for the first type of user even though the network offers high quality utility, the trade-off quality-energy represented by the overall score is not acceptable, and therefore the network is considered by the user to be Defecting. In the second case, when the user prefers more the energy conservation, for the high values of the quality utility the network will be defecting for this user, and only when its overall utility goes above U_{min} = 0.4743, the network starts Cooperating.



a) Quality-Oriented User ($w_q = 0.6$, $w_e = 0.2$, $w_c = 0.2$)

b) Energy-Oriented User ($w_q = 0.2$, $w_e = 0.6$, $w_c = 0.2$)



c) Quality & Energy Focused User ($w_q = 0.4$, $w_e = 0.4$, $w_c = 0.2$)

Figure 7.29. User Average Revenue and Network Reputation for the three cases

In all the above cases the network cooperates only when a good trade-off quality-energy is reached. This is based on the user preferences. In all the cases the user plays GRIM. It is considered that a user-network interaction is the period in which the user and the network are cooperating. The average revenue for each interaction is computed as well as the reputation factor of the network at the end of each interaction. The reputation factor was previously introduced and described in Section 4.5.4 and is computed using equation (4.16), considering the history of five past interactions with the network. The weight of each interaction is computed using equation (4.17) with $\rho = 2.5$. The recent interactions are given higher importance than older ones. The average user revenues and the network reputation factor variation for the three cases are illustrated in Figure 7.29.

The results show that for the same network, considering different user preferences, each user will score the network different, and they will have different reputation factors based on their requirements. In all three cases, as the average revenue of the user is increasing so is the reputation. If user's average revenue is decreasing, the reputation is decreasing as well.

After the computation of the network reputation factor, it will be considered in the overall score function. Consequently when the next network selection takes place, if a network had a fraudulent behavior in the past, because of its good behavior in recent interactions, it may be selected as the target network. This despite the fact that there might be another network with a good behavior in the past, out its recent fraudulent behavior will have a greater impact in the decision, and may not determine its selection as the target network.

7.6. Chapter Summary

This chapter presents the simulation-based testing results and their analysis. The simulation test case scenarios were structured in order to analyze the performance of the four major contributions:

- Network Selection Mechanism – PoFANS which was analyzed on two main aspects: **(1) energy-quality trade-off**; and **(2) energy-quality-cost trade-off**. The proposed PoFANS solution was compared against another energy-efficient solution proposed by Liu et al. and referred to as the Cost Function.

- Adaptive Multimedia Mechanism – SAMMy –its performance analysis was divided in two main categories: **(1) Single-User Environment** – where only one user has enabled SAMMy in a wireless environment. Three scenarios are considered: (1) Mobility, No Load; (2) No Mobility, Load; and (3) Mobility, Load. The second category **(2) Multi-User Environment –** the performance of SAMMy is analyzed in terms of fairness when there are multiple simultaneous video delivery sessions in a wireless multi-user environment. Four scenarios are considered, based on the users' location within the AP's coverage area: (1) Scenario 1 – 11&1Mbps Zones; (2) Scenario 2 – 11&5.5&1Mbps Zones; (3) Scenario 3 – 1&11Mbps Zones; (4) Scenario 4 – 11&5.5&2&1Mbps Zones. The performance of SAMMy was evaluated in comparison with three other multimedia delivery schemes, referred to as: Non-Ad, Loss-Ad, and TFRC.

- Adapt-or-Handover Solution – was analyzed in terms of energy efficiency and compared against the Liu et al. Cost Function. Two scenarios are considered: **(1)** a critical test case scenario in which the battery lifetime of the mobile device is running low, and **(2)** a regular test case scenario that combines the use of PoFANS and SAMMy.

- Reputation-based Network Selection Mechanism using Game Theory – the performance analysis of this solution follows three aspects: **(1)** the mathematical **analysis of**

Equilibrium where it is show that *repeated interaction leads to cooperation*, **(2) impact of different strategies and payoffs**, and **(3) impact of user preferences** on the network reputation factor. The mechanism combines the reputation-based systems and game theory in order to strengthen the cooperation between users and networks. It has been shown that by considering reputation in the network selection mechanism is useful in cases of cooperation and when making decisions.

This chapter demonstrates the efficiency of the proposed combined mechanism and shows the necessity of such mechanism in real world scenarios. Nowadays the network operators consider that if they offer high throughput that is translated into satisfied users. However, as this shows that excellent perceived quality of service does not always result from a high throughput, and a good trade-off between quality-energy is needed in order to keep the user satisfied. Network operators need to integrate adaptive mechanisms in order to cater for the user preferences and enable a good balance between energy and quality will be always needed.

Chapter 8

Conclusions and Future Work

This chapter presents the conclusions drawn from this thesis and indicates several directions for future research work.

8.1. Conclusions

8.1.1. Overview

In the ever-evolving telecommunications industry, smart mobile computing devices have become increasingly affordable and powerful, leading to a significant growth in the number of advanced mobile users and their bandwidth demands. People can now connect to the Internet from anywhere at any time, when on the move or stationary. In order to cater for the overwhelming growth in bandwidth demand from mobile Internet users, network operators have started to deploy different, overlapping radio access network technologies. One important challenge in such a heterogeneous wireless environment is to enable network selection mechanisms in order to keep the mobile users '*Always Best Connected*' anywhere and anytime.

8.1.2. Contributions

In these circumstances this thesis presents the roadmap towards an '*Always Best Connected'* environment by proposing four major mechanisms, performing an energy consumption study for a mobile device, and providing a comprehensive survey on related Game Theory research:

(1) ***Power-Friendly Access Network Selection strategy (PoFANS)*** – a novel network selection mechanism for multimedia content delivery over heterogeneous wireless environments. PoFANS is an application layer solution which selects the best value network for delivering multimedia content. PoFANS consists of a client-side component deployed on the mobile user's device. The network selection decision is based on: user preferences, application requirements, network conditions, and the energy consumption of the mobile device. PoFANS selects the least power consuming network in order to enable the battery lifetime of the mobile device to last longer while running multimedia services and maintaining good user perceived quality levels.

(2) ***Signal Strength-based Adaptive Multimedia Delivery Mechanism (SAMMy)*** – a novel adaptive multimedia mechanism for multimedia content delivery over wireless networks. SAMMy is an application layer solution which offers quality-aware content delivery service to multimedia applications. SAMMy consists of a server-side component and a client-side component. The server-side component is represented by a multimedia streaming server which stores different quality levels of the multimedia content and based on the feedback reports received from the client selects the most suitable quality level for the multimedia content and sends it back to the client. The client-side component is deployed at the media player used by the mobile user's device. The client-side monitors the network conditions and sends feedback reports back to the server. The adaptation decision is based on the received signal strength and packet loss.

(3) ***Adapt-or-Handover*** solution – balances the adaptive multimedia delivery and the network selection in order to improve the energy efficiency at the end-user mobile device, while maintaining good user perceived quality levels. Adapt-or-Handover is a novel application layer solution that combines the proposed PoFANS and SAMMy mechanisms. Consequently, the proposed solution consists of a server-side and a client-side component. The server-side stores the multimedia content encoded at different quality levels. Based on the feedback received from the client the server selects the most suitable multimedia quality level and sends it to the client. The client-side monitors the networks condition and decides whether is better to adapt the multimedia stream or is better to handover to a new network, in order to increase the energy efficiency of the mobile device.

(4) ***Reputation-based Network Selection Mechanism*** **–** a novel network selection mechanism that models the user-network interaction following the principle of the repeated Prisoner Dilemma's from Game Theory. The proposed mechanism is an application layer solution and represents an extension of PoFANS. After the best value network is selected and the user is connected to the new network, the repeated cooperative game starts. The outcome of the game is a network reputation factor, which will be taken into consideration when the next network selection decision takes place.

(5) ***A study on the battery energy usage*** - a study on the mobile device energy consumption for streaming adaptive video to a Google Nexus One Android device over WLAN IEEE802.11g and HSDPA networks. An experimental test-bed was setup to study the impact of the WLAN traffic load and the distance from the access point on the Google Nexus One energy consumption, for streaming a multimedia clip at five different quality levels. This study includes subjective testing to understand the corresponding user-perceived quality values. The impact of different transport protocols on the energy consumption for video streaming was also considered for both UDP and TCP.

(6) ***A survey on the application of Game Theory to the network selection decision problem*** – this comprehensive survey provides a guide to the use of game theory in network selection decision related research work.

8.1.3. Network Selection Score Function

As noticed the major components of the overall proposed solution are network selection and adaptive multimedia. As presented in the 'Technical Background' chapter, the network selection process plays an important role, being part of the handover management as well as the initial call setup procedure. The need to make this choice is becoming more common place as smart phones with a number of wireless interfaces allow today's user a choice of cellular or WLAN communications interface. The decision making mechanism, part of the network selection process, requires essential and relevant information about the available candidate networks. This information is referred to as decision criteria and it is used as input data for a score function. The score function is used to compute a score in order to rank each of the candidate networks. The network with the highest score will be then selected as the target network.

The score function proposed in this thesis uses the multiplicative exponential weighted method (MEW) and is based on three key-parameters: the quality of the multimedia stream, the energy consumption of the mobile device, and the monetary cost of the network. These parameters are weighted and their weights can be set according to the user preferences. In order to be compared, each parameter is scaled with the help of the utility functions and brought into non-dimensional values within the [0,1] interval.

Different utility functions can be used to describe the user utility for each parameter. The choice of shape for the utility function will have an impact on the end score and rank for the networks. For the quality parameter, a zone-based sigmoid utility function is proposed in this thesis work. The sigmoid utility function maps the received bandwidth to user satisfaction. The proposed utility function is justified and matches well to the user-perceived quality measurements taken as part of the test-bed trail. For the energy and the cost parameters, linear increasing utility functions are proposed. The energy utility is based on the estimated energy consumption of the mobile device.

The choice of the MEW-based method for the score function was justified by doing an analysis and comparison of MEW with three other MADM methods: GRA, SAW, and TOPSIS under different conditions. The comparison results show that SAW and TOPSIS present similar results and in both cases an input parameter with a particularly poor value can be overweighed by another parameter with a very good value. Whereas MEW models the network selection problem, by providing a clear difference between the score results of each option and penalizing alternatives with poor parameters values more heavily. In all the comparison cases the MEW algorithm's top ranked candidate was the best choice given the user preferences for the weights.

8.1.4. Device Energy Consumption Study - Experimental Testing

A real experimental test-bed environment was built in order to collect measurements on the energy consumption of a Google Nexus One Android mobile device when running multimedia applications under different network conditions. An in-depth study on the impact of the wireless environment (i.e., link quality, network load, and network technology) on the energy consumption of the mobile device while performing Video on Demand Streaming is presented.

Five different quality levels for a ten-minute multimedia stream were carefully selected from QL5 the lowest quality level to QL1 the highest quality level. Four 20 seconds long test sequences with different spatial and temporal characteristics were extracted from the ten-minute clip at each quality level. These test sequences were used for the purpose of subjective testing. Subjective tests were performed in order to validate the choice of the five quality levels. A number of 16 (Males = 10, Females = 6) non-experts subjects with ages between 22 and 45 years old were asked to rate the overall quality of each test sequence on a 1-5 scale (bad to excellent). The results show that QL1 and QL2 are mapped to 'Excellent', QL3 and QL4 are mapped to 'Good', while QL5 is mapped to 'Fair', according to ITU-T P.910 scale. These results were used to validate the choice of the sigmoid utility function for the quality parameter. It has been shown that if the received quality level, goes below QL5 then the multimedia quality becomes unacceptable and its utility is zero, it worth nothing to the user. On the other hand, if the received quality goes above QL1, it will not add much to the already existing high quality but will increase the energy consumption of the mobile device.

The energy measurements were carried out considering six different scenarios, for each of the five quality levels, and for two different transport protocols (i.e., UDP and TCP). A total of 252 tests were carried out, the results for each test were collected and their average values were used for the results analysis and discussions. From the results analysis, several observations can be drawn:

- the real energy measurements show that a great amount of energy can be saved by changing the quality level of the multimedia stream. Considering the ideal case, when a mobile user located near the AP (802.11g), without any background traffic in the network, and is running UDP-based VoD streaming. In this scenario, by decreasing the video quality level from

QL1 (‘Excellent’) to QL2 (‘Excellent’) a 6.7% energy savings can be achieved on the wireless interface only. Whereas if the quality drop is from QL1 (‘Excellent’) to QL3 (‘Good’) or QL5 (‘Fair’) energy savings of 26.7% up to 62.7% can be achieved, respectively.

- the impact of the transport protocol on the energy consumption while performing VoD streaming, is another important observation. Consider the same ideal case, with the user located in an unloaded network, near the AP. If the VoD streaming is performed over TCP, than the measurements show that TCP is more energy efficient than UDP. For example, 13% energy savings can be achieved when transmitting QL1 over TCP rather than UDP. After analyzing the Wireshark trace files, one possible found reason that could lead to this difference in energy consumption is the packet size distribution of the two transport protocols. The packet size distribution for TCP is 1280-2559 bytes whereas for UDP is 640 – 1279 bytes. This means that in the case of UDP there are more packets to be transmitted and processed by the wireless interface of the mobile device, leading to more energy consumption.
- the impact of the link quality (signal strength) on the energy consumption while performing VoD streaming, was also analyzed. The energy measurements were taken when the user was located in two different positions, with different signal strength levels: one with good signal strength (-48dBm to -53dBm) and one with poor signal strength (-78dBm to -82dBm) and no other network load. The results show that the energy can increase as low as 4% for QL4 up to an 11% increase for QL2 and QL5 when streaming over UDP and being located in a poor signal strength area.
- the impact of the network load on the energy consumption while performing VoD streaming was analyzed by comparing the scenario when the user is located near the AP without any traffic load with the scenario in which the user maintains the location but background traffic is added. In this case, the results show that the energy can increase as low as 8% for QL4 up to 30% for QL5, when streaming over UDP in a loaded network.
- the impact of both network load and signal strength on the energy consumption while performing VoD streaming is considered, the user will experience interruptions such as video freezing (re-buffering periods), increasing the playout duration of the multimedia stream, all leading to an increase in energy consumption. QL1 is the most affected, the re-buffering periods representing almost 60% of the playout duration. This leads to a significant decrease in MOS for QL1. Whereas the MOS for QL4 and QL5 are not affected.
- the impact of the network technology on the energy consumption while performing VoD streaming was studied by comparing the case of a mobile user streaming over 802.11g with the case when streaming over UMTS. The results show that by using the UMTS interface, the energy consumption presents an increase as low as 50% for QL3, up to 61% for QL5 in case of UDP-based streaming over UMTS.

The energy measurements obtained from the real experimental test-bed environment, were then used in order to model a mathematical energy consumption pattern for the Google Nexus One Android device. T-tests were performed on the Measured Energy and Computed Energy, assuming equal variance, and it has been shown that there is no statistical difference between the two sets of results. This finding is stated with 95% level of confidence, meaning that the proposed energy equation presents a good approximation of the energy consumption of the Google Nexus One Android device. These results were further used in the testing environment and numerical analysis.

8.1.5. Simulation-based Testing Environment

The performance analysis of the overall proposed solution was performed via simulations. For simulation purposes, Network Simulator 2 (NS-2) and Matlab were used. Simulation models for PoFANS, SAMMy, Adapt-or-Handover, and reputation-based network selection mechanism were developed.

PoFANS was analyzed on two main aspects: (1) energy-quality trade-off; and (2) energy-quality-cost trade-off. The proposed PoFANS solution was compared against another energy-efficient solution proposed by Liu et al. and referred to as the *Cost Function.* The Liu et al. *Cost Function* is based on a simple additive weighting method (SAW) and considers the same main parameters as PoFANS, making them comparable. The results show that PoFANS can find a good trade-off between energy, quality, and cost. By using PoFANS the users could benefit from up to 30% energy savings with insignificant decrease in quality, in comparison with Liu et al. *Cost Function*.

The performance analysis of **SAMMy** was divided in two main categories:

(1) Single-User Environment – where only one user has enabled SAMMy in a wireless environment. Three scenarios are considered: (1) Mobility, No Load; (2) No Mobility, Load; and (3) Mobility, Load.

The performance of SAMMy was compared with three other multimedia delivery schemes: a non-adaptive multimedia delivery solution (Non-Ad), a loss-based adaptive multimedia delivery scheme (Loss-Ad), and a TCP friendly rate control protocol (TFRC). In the first scenario when mobility and no load are considered, SAMMy is the best solution in terms of PSNR and no loss, while Non-Ad has the worst performance with a 3.81% loss rate and the lowest average PSNR. TFRC reacts well achieving a good throughput and 0.54% loss rate while Loss-Ad presents the same throughput as TFRC but 0.94% loss rate. When background traffic is added and no mobility is considered, SAMMy outperforms all the other schemes involved. When located at 100m away from the AP, SAMMy records 93%, 48%, and 84% decrease in loss, 263%, 34%, 100% increase in PSNR, in comparison with Non-Ad, TFRC, and Loss-Ad, respectively. In terms of throughput, SAMMy presents a 52% decrease when compared with Non-Ad, and 75% and 1.5% increase, when compared with TFRC and Loss-Ad. When the user is located near the AP (10m away), SAMMy records 60%, 26%, and 60% decrease in loss, 54%, 23%, 48% increase in PSNR, in comparison with Non-Ad, TFRC, and Loss-Ad, respectively. In terms of throughput, SAMMy presents a 25% decrease when compared with Non-Ad, and 60% and 10% increase, when compared with TFRC and Loss-Ad. In the third scenario, when mobility and load are considered, in comparison with TFRC, SAMMy records a 28.8% decrease in loss and 15.47% increase in throughput, resulting in a 26.6% increase in PSNR. With respect to the Non-Ad and Loss-Ad solutions, SAMMy presents a 85% and 73%, respectively, decrease in loss rate an 64.7% and 47%, respectively, increase in PSNR.

(2) Multi-User Environment – the performance of SAMMy is analyzed in terms of fairness when there are multiple simultaneous video delivery sessions in a wireless multi-user environment. Four scenarios are considered, based on the users' location within the AP's coverage area: (1) Scenario 1 – 11&1Mbps Zones; (2) Scenario 2 – 11&5.5&1Mbps Zones; (3) Scenario 3 – 1&11Mbps Zones; (4) Scenario 4 – 11&5.5&2&1Mbps Zones. The performance of SAMMy was evaluated in comparison with TFRC, which is the best performing alternative solution. In all the considered scenarios, SAMMy reduces the impact of the low rate users on the users located near the AP. The results show that SAMMy maintains a reasonable throughput for all users relative to their proximity to the AP, achieving a significant increase in the overall throughput (up to 18%) of the multi-rate WLAN network, when compared with TFRC. On the other hand, with TFRC the low rate users can achieve more or less the same throughput as the users located near the AP, which is not fair.

The **Adapt-or-Handover** solution was analyzed in terms of energy efficiency and compared against the Liu et al. *Cost Function.* Two scenarios are considered: **(1)** a critical test case scenario in which the battery lifetime of the mobile device is running low, and **(2)** a regular test case scenario that combines the use of PoFANS and SAMMy. The Adapt-or-Handover represented a dual-adaptation solution that makes use of PoFANS and SAMMy, whereas Liu et al. *Cost Function* performs only network selection. The benefit of combining PoFANS and SAMMy into the Adapt-or-Handover solution has been analyzed. The results for the first scenario have shown that the Adapt-or-Handover solution can increase the battery lifetime of the mobile device up to 122% in comparison with Liu et al. *Cost Function*, when considering a critical scenario in which the battery lifetime is at risk. In a regular scenario the Adapt-or-Handover solution could reach up to 31% energy savings in comparison with Liu et al. *Cost Function.*

The *Always Best Connected* vision implies a heterogeneous multi-user multi-provider multi-technology environment, where users can roam in a free manner from one RAT to another or from one service provider to another. In this context, competitive or cooperating behavior among service providers and/or users can be identified. On one side, the service providers seek to maximize their own revenue by attracting more customers, while on the other side, the users want to get the best value services/network for the money they pay. As game theory is often used to study this interaction between rational decision makers, it makes it applicable in the area of network selection strategies.

In this thesis the interaction between user and network is studied and a novel **Reputation-based Network Selection mechanism** is proposed. The mechanism combines the reputation-based systems and game theory in order to strengthen the cooperation between users and networks. The interaction between user and network is modeled as a two-player cooperative game using the model of repeated Prisoner's Dilemma game. A network reputation factor is defined based on the output of the repeated game, in order to keep track of network past behavior in the network selection decision. The performance analysis of the proposed mechanism follows three main aspects: (1) the mathematical analysis of Equilibrium, (2) impact of different strategies and payoffs, and (3) impact of user preferences on the network reputation factor.

By defining incentives for cooperation and disincentives against fraudulent behavior, it is shown that *repeated interaction sustains cooperation*. The use of game theory in combination with the network selection mechanism enables the creation of a reputation-based system for the heterogeneous wireless network environment. It has been showed that by considering reputation in the network selection mechanism it is useful in cases of cooperation and when making decisions.

8.1.6. Survey on Game Theory and Network Selection Related Research

In addition to the proposed solutions and the device energy consumption study, this thesis presents a comprehensive survey of the current research on the game theoretic approaches used in the literature to model the network selection problem. The survey provides a useful categorization based on the players' interactions: Users vs. Users, Networks vs. Users, and Networks vs. Networks. Different types of games (e.g., cooperative or non-cooperative) and the different game models adopted (e.g., Auction Game, Bayesian Game, Evolutionary Game, etc.) in order to solve the network selection problem are discussed in details. The major findings from these game models and the main challenges that surround the network selection problem are addressed and summarized in Table 3.2. The survey provides a comparison and analysis of the state-of-the-art game theory solutions on network selection, and outlines the problems faced by the next generation of wireless networks.

Overall, this thesis demonstrates the efficiency of the proposed combined mechanism and shows the necessity of such mechanism in real world scenarios. It has been shown that offering high throughput to mobile users, is not always the best alternative that keeps the user satisfied. A good trade-off between quality, energy, and cost is needed as well, and as it has been shown in this thesis, this can be realized by balancing the network selection and the adaptive mechanisms.

8.2. Publications arising from this work

Edited Books

G-M. Muntean and **R. Trestian**, "Wireless Multi-Access Environments and Quality of Service Provisioning: Solutions and Application", in press, IGI Global, 2011

Journals

R. Trestian, O. Ormond and G-M. Muntean, "Reputation-based Network Selection Mechanism using Game Theory", *Elsevier, Physical Communication*, vol. 4, no. 3, pp. 156-171, 2011.

***R. Trestian**, O. Ormond and G-M. Muntean, "Game Theory-based Network Selection: Solutions and Challenges", *IEEE Communication Survey and Tutorials*, under review 2011.

Conferences

R. Trestian, O. Ormond, and G-M. Muntean, "Energy Consumption Analysis of Video Streaming to Android Mobile Devices", *IEEE/IFIP Network Operations and Management Symposium, (NOMS)*, April, 2012.

R. Trestian, O. Ormond and G-M. Muntean, "Power-Friendly Access Network Selection Strategy for Heterogeneous Wireless Multimedia Networks", *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, March 2010 .

R. Trestian, O. Ormond and G-M. Muntean, "Performance of an Adaptive Multimedia Mechanism in a Wireless Multi-user Environment", *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*, March 2010

R. Trestian, O. Ormond and G-M. Muntean, "Signal Strength-based Adaptive Multimedia Delivery Mechanism", *The 34th IEEE Conference on Local Computer Networks (LCN),* October 2009.

8.3. Future Work

The main focus of the work presented in this thesis is on proposing a complete solution for the Always Best Connected vision. The solution incorporates a reputation-based system for the heterogeneous wireless environment. The roadmap towards this reputation-based system is detailed in this thesis, and includes: PoFANS, SAMMy, Adapt-or-Handover, and Reputation-based Network Selection Mechanism. The aim of the proposed solution is to offer a better multimedia streaming experience to the mobile user, and at the same time to find a good energy-quality-cost trade-off while roaming within the multi-operator multi-technology multi-device multi-application multi-user environment.

The reputation-based system is a valuable tool to make next generation heterogeneous environment work well. Several research directions can be identified for further development of the solution.

The proposed reputation-based network selection mechanism can be further extended by incorporating data from different sources. For example, by considering the ***feedback received from other users,*** which have already interacted with that a specific network operator. The network reputation factor will be then computed based on the user past interaction with the network and the feedback received from other users as well. Of course a credibility factor will have to be considered for the feedback users. Another interesting aspect would be to consider a time constraint on the interactions. As the reputation factors for different networks are computed based on the last n interactions. These interactions could be spread over different periods of time, might be a day for one network or might be a year for another network (which could perhaps have greatly improved in performance in the meantime). By integrating a time constraint this problem can be avoided. Additionally, the time of day, day of year could have an impact on the network performance and reputation – this should also be considered.

Although there are many proposed solutions in the literature in relation to network selection, there are still some open issues that require further investigation. An important open issue is **the impact of computational complexity of the existing solutions**. Because of the wide number of factors (e.g., single or multi-technology, single or multiple operators, centralized or decentralized solution, different number of parameters, different types of utility functions, type of game, etc.) considered by different approaches, it is very difficult to compare them in terms of computational complexity. Thus, further investigation is required to evaluate the impact of the computational complexity for game theoretic-based network selection solutions.

Another open issue is the pricing scheme used by different network operators. The charging and billing models are very simple nowadays, they are: time-based and/or volume-based charging. In this thesis flat rate pricing is considered in order to simplify the analysis. However the next generation of wireless networks requires more complex **pricing and billing** mechanisms. Because of the coexistence of multiple service providers and multiple radio access technologies, new and dynamic pricing models should be implemented so that to be more usage-based, context-based, technology-based, etc.

Another interesting approach would be to consider the **personalization of service classes based on the users' environment and context changes.** For example, when the user enters the house, he/she should have the possibility to transfer the multimedia session from his mobile device on a big screen in his/her living room.

As part of the future work, a study of the **network operators' attitude towards profit gains** could be considered. Here it would help to have some real data provided from the network operators, which usually is difficult to obtain because of the confidentiality issues.

An interesting research direction would be the **group network selection and group handover.** This scenario considers a group of mobile users travelling together (e.g., the users on a bus), and all of them running similar applications, with similar preferences and using a similar network selection solution. The idea here is to find a trade-off between the offered quality of service and the load balancing. Having a group of users handing over at the same time and to the same network could provoke a significant drop in the quality of service provided to all the users in the target network. Consequently, this could trigger the network selection process again and it can cause the group of users to handover again to another or back to the initial network. This process could enter an infinite loop and could be repeated all over again, creating the '*ping-pong*' effect. Of course the probability of such scenario happening is not very high, and by considering a reputation-based system this effect is reduced as different devices will have different reputation values dependent on their preferences and previous experiences with the networks in question.

The observations drawn after analyzing the energy measurements from the real experimental test-bed environment also opened up new possible research directions. Consequently the impact of **the transport protocol (i.e., TCP and UDP) on the energy consumption of the mobile device** while VoD Streaming, could be further investigated in order to determine why TCP is more energy efficient than UDP, and if this is the case for all traffic types or just for video streaming. The impact of the **load distribution on the energy consumption** could be further investigated and understood. The impact of the **network technology on energy consumption** represents another research direction. Measurements could be taken over long periods of time, in order to understand the users usage pattern depending on the time of day (i.e., peak and off peak hours), day of the week (i.e., working days, weekends, bank holidays), weeks in the year (i.e., summer holidays). This could help to create more energy efficient solutions by considering the type of the transport protocol that will be used for communications, the usage pattern, contextual information (e.g., link quality, network load, network technology, transport, adaptive mechanism).

Finally, apart from the Google Nexus One Android device, the energy consumption of **multiple other mobile devices** could be further investigated. The devices could be then classified into classes of energy consumption. An in-depth investigation on how different components (e.g., operating system, CPU, display, etc.) contribute to the overall energy consumption of the mobile device could be carried out.

Bibliography

[1] Cisco Systems, Inc., "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010–2015," 2011. [Online]. Available: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_p aper_c11-520862.html.

[2] P. Nicopolitidis, "*Wireless networks*", John Wiley and Sons, 2003.

[3] M. Sauter, "*Beyond 3G - Bringing Networks, Terminals and the Web Together: LTE, WiMAX, IMS, 4G Devices and the Mobile Web 2.0*", 1st ed. John Wiley and Sons, 2009.

[4] W. Webb, "*The Future Wireless Communications*," John Wiley and Sons, 2007.

[5] *3GPP TS 21.101, "Technical Specifications and Technical Reports for a UTRAN-based 3GPP system".*

[6] *3GPP TS 25.308, "High Speed Downlink Packet Access (HSDPA)".*

[7] *3GPP TS 36.201, "Evolved Universal Terrestrial Radio Access (E-UTRA); Long Term Evolution (LTE) physical layer".*

[8] *C. S.-0. 3GPP2, "Signaling Conformance Specification for Ultra Mobile Broadband Air Interface".*

[9] *ANSI/IEEE Std 802.11, 1999 Edition (R2003), "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications", June 2003.*

[10] *IEEE 802.11a-1999, IEEE Standard for Local and Metropolitan Area Networks Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications High Speed Physical Layer in the 5 GHz Band, 1999.*

[11] Cisco Systems, Capacity, Coverage, and Deployment Considerations for IEEE 802.11g, White Paper, [Online]. Available: http://www.sparcotech.com/Cisco%20Capacity%20and%20Coverage%20with%20G.pdf

[12] *IEEE 802.11b-1999, IEEE Standard for Local and Metropolitan Area Networks Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications High Speed Physical Layer Extension in the 2.4 GHz Band, September 16, 1999.*

[13] *IEEE 802.11g-2003, IEEE Standard for Local and Metropolitan Area Networks Specific Requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band, June 27,2003.*

[14] *IEEE Standard for information technology—Telecommunications and information exchange between systems—Local and metropolitan area networks—Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 5: Enhancements for Higher Throughput, 2009.*

[15] *"IEEE Standard for information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 1: Radio Resource Measurement of Wireless LANs," IEEE Std 802.11k-2008 (Amendment to IEEE Std 802.11-2007), 2008.*

[16] S.D. Hermann, M. Emmelmann, O. Belaifa and A. Wolisz, "Investigation of IEEE 802.11k-based Access Point Coverage Area and Neighbor Discovery," *in 32nd IEEE Conference on Local Computer Networks, (LCN)*, 2007.

[17] B. H. Walke, S. Mangold, and L. Berlemann, "*IEEE 802 Wireless Systems - Protocols, Multi-Hop Mesh/Relaying, Performance and Spectrum Coexistence*", John Wiley and Sons, 2006.

[18] *J. Polk, J. Schnizlein, and M. Linsner, "RFC 3825: Dynamic host configuration protocol option for coordinate-based location configuration information," July 2004.*

[19] J. G. Andrews and A. Ghosh, "*Fundamentals of WIMAX: Understanding Broadband Wireless Networking,*" Prentice Hall PTR, 2007.

[20] *IEEE. 802.20, "Mobile Broadband Wireless Access (MBWA)* http://www.ieee802.org/20/".

[21] E. Gustafsson and A. Jonsson, "Always best connected," i*n IEEE Wireless Communications*, vol.10, no. 1, pp. 49-55, 2003.

[22] *"IEEE Standard for Local and metropolitan area networks- Part 21: Media Independent Handover," IEEE Std 802.21-2008, 2009.*

[23] L. Vollero and F. Cacace, "Managing mobility and adaptation in upcoming 802.21 enabled devices," *in Proceedings of the 4th international workshop on wireless mobile applications and services on WLAN hotspots (collocated with MOBICOM),* 2006.

[24] I. F. Akyildiz, J. McNair, J. S. . Ho, H. Uzunalioglu, and Wenye Wang, "Mobility management in next-generation wireless systems," *Proceedings of the IEEE*, vol. 87, no. 8, pp.1347-1384, Aug. 1999.

[25] Jiang Xie and Shantidev Mohanty, "Mobility Management in Wireless Systems," *in 6.108.Telecommunication Systems and Technologies, edited by Paolo Bellavista, in Encyclopedia of Life Support Systems (EOLSS), developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK, 2007.*

[26] I. F. Akyildiz, Jiang Xie, and S. Mohanty, "A survey of mobility management in next- generation all-IP-based wireless systems," *IEEE Wireless Communications,* vol. 11, no. 4, pp. 16- 28, Aug. 2004.

[27] *IETF Working Group, "Mobility for IPv4 (mip4)," [Online]. Available: http://www.ietf.org/html.charters/mip4-charter.html*

[28] *IETF Working Group, "Mobility for IPv6 (mip6)," [Online]. Available: http://www.ietf.org/html.charters/mip6-charter.html*

[29] *S. Gundavelli, K. Leung, V. Devarapalli, K. Chowdhury, and B. Patil, "Proxy Mobile IPv6," RFC 5213, 2008.*

[30] B. Ciubotaru Petrescu, "*Quality-Oriented Mobility Management for Multimedia Content Delivery to Mobile Users*," PhD thesis, Dublin City University, 2010, [Online]. Available: http://doras.dcu.ie/ 16063/1/Bogdan_Ciubotaru_Thesis_SASHA_Final_Version.pdf

[31] K. Pahlavan et al, "Handoff in Hybrid Mobile Data Networks," *IEEE Personal Communications Magazine*, vol. 7, no. 2, pp. 34-47, 2000.

[32] *3GPP TR 21.905 V6.9.0 (2005-06), Technical Report 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Vocabulary for 3GPP Specifications (R6).*

[33] M. Stemm, and R. H. Katz, "Vertical handoffs in wireless overlay networks", *in Mobile Networks and Applications - Special issue: mobile networking in the Internet*, vol. 3, no. 4, pp 335 – 350, 1998.

[34] C.-H. Yeh, “A Problem-based Selection of Multi-attribute Decision-making Methods,” *International Transactions in Operational Research,* vol. 9, pp. 169-181, 2002.

[35] J. Fülöp, ”Introduction to Decision Making Methods”, *Computer and Automation Institute, Hungarian Academy of Sciences*, Budapest, 2005.

[36] Q. Song and A. Jamalipour, “A network selection mechanism for next generation networks,” *in IEEE International Conference on Communications, (ICC)*, 2005.

[37] R. Machado and S. Tekinay, “A survey of game-theoretic approaches in wireless sensor networks,” *Elsevier Computer Networks*, vol. 52, no. 16, pp. 3047-3061, 2008.

[38] B. Wang, Y. Wu, and K.J. Ray Liu, “Game theory for cognitive radio networks: An overview,” *Elsevier Computer Networks*, vol. 54, no. 14, pp. 2537-2561, 2010.

[39] V. Srivastava et al., “Using game theory to analyze wireless ad hoc networks,” *IEEE Communications Surveys & Tutorials*, vol. 7, no. 4, pp. 46-56, 2005.

[40] T. Alpcan, T. Başar, and S. Dey, “A power control game based on outage probabilities for multicell wireless data networks,” *IEEE Transactions on Wireless Communications* , vol. 5, pp. 890-899, 2006.

[41] S. Sengupta et al., “Dynamic pricing for service provisioning and network selection in heterogeneous networks,” *Elsevier Physical Communication*, vol. 2, no. 1, pp. 138-150, 2009.

[42] D. E. Charilas and A. D. Panagopoulos, “A survey on game theory applications in wireless networks,” *Elsevier Computer Networks*, vol. 54, no. 18, pp. 3421-3430, 2010.

[43] Y. Zhang and M. Guizani, *“Game Theory for Wireless Communications and Networking,”* 1st ed. CRC Press, 2011.

[44] M. J. Osborne, “*An Introduction to Game Theory,”* Oxford University Press, USA, 2003.

[45] M. J. Osborne and A. Rubinstein, “*A Course in Game Theory,”* The MIT Press, 1994.

[46] D. Fudenburg and J. Tirole, “*Game Theory,”* The MIT Press, London, 1991.

[47] J. W. Weibull, “*Evolutionary Game Theory,”* The MIT Press, 1997.

[48] A. MacKenzie, “*Game Theory for Wireless Engineers*”, 1st ed. Morgan & Claypool Publishers, 2006.

[49] A. Zambelli, “*IIS smooth streaming technical overview*”, Technical Report, Microsoft Corporation, 2009.

[50] L. Korowajczuk, "*LTE, WiMAX and WLAN Network Design, Optimization and Performance Analysis,*" John Wiley and Sons, 2011.

[51] *ITU-T: Recommendation G.1010: "End-user Multimedia QoS Categories", 2001.*

[52] P. Calyam and C.-gun Lee, "Characterizing voice and video traffic behavior over the Internet,"*in Proceedings of the International Symposium on Computer and Information Sciences, (ISCIS), 2005*.

[53] M. Carnec, P. Le Callet, and D. Barba, "Full reference and reduced reference metrics for image quality assessment", *in Proceedings of Seventh International Symposium on Signal Processing and its Applications*, 2003

[54] *ITU-T: Recommendation P.910: "Subjective Video Quality Assessment Methods for Multimedia Applications," Sept. 1999.*

[55] S.-B. Lee, G.-M. Muntean and A. Smeaton, "Performance-aware Replication of Distributed Pre- recorded IPTV Content," *IEEE Transactions on Broadcasting*, vol 55, no. 2, 2009.

[56] Ascom, TEMS, "*Video Streaming Quality Measurement with VSQI*", Technical Paper, 2009, [Online]. Available: http://www.cn.ascom.com/cn/vsqi.pdf

[57] *ITU, "Framework and overall objectives of the future development of IMT-2000 and systems beyond IMT-200," Switzerland, ITU-R M.1645, 2003.*

[58] *Access Network Discovery and Selection Function (ANDFS) Management Object (MO), 3GPP TS24.312 v10.3.0, 2011.*

[59] *Study into Network Selection Requirements for non-3GPP Access, 3GPP TR 22.912 v10.0.0, 2011.*

[60] H.J. Wang, R.H. Katz, and J. Giese, "Policy-enabled handoffs across heterogeneous wireless networks," *in Proceedings of Second IEEE Workshop on Mobile Computing Systems and Applications, (WMCSA),* 1999.

[61] E. Adamopoulou, "Intelligent Access Network Selection in Heterogeneous Networks - Simulation Results," *the 2nd International Symposium on Wireless Communication Systems*, 2005.

[62] Q.-T. Nguyen-Vuong, Y. Ghamri-Doudane, and N. Agoulmine, "On utility models for access network selection in wireless heterogeneous networks," *in IEEE Network Operations and Management Symposium, (NOMS),* 2008.

[63] B. Bakmaz, Z. Bojkovic, and M. Bakmaz, "Network Selection Algorithm for Heterogeneous Wireless Environment," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC),* 2007.

[64] F. Bari and V. Leung, "Application of ELECTRE to Network Selection in A Heterogeneous Wireless Network Environment", in *Proceedings of the IEEE Wireless Communications and Networking Conference, (WCNC),* 2007.

[65] J. D. Martínez-Morales, U. Pineda-Rico, and E. Stevens-Navarro, "Performance comparison between MADM algorithms for vertical handoff in 4G networks," *in the 7th International Conference on Electrical Engineering Computing Science and Automatic Control (CCE),* 2010.

[66] E.H. Watanabe et al., "Modeling Resource Sharing Dynamics of VoIP Users over a WLAN Using a Game-Theoretic Approach," *in the 27th IEEE Conference on Computer Communications, (INFOCOM),* 2008.

[67] K. Mittal, E. M. Belding, and S. Suri, "A game-theoretic analysis of wireless access point selection by mobile users," *Journal of Computer Communication*, vol. 31, no. 10, pp. 2049-2061, 2008.

[68] K. Fahimullah and S. Hassan, "Game-Theory based Wireless Access Point Selection scheme," in *IEEE Silver Jubilee International Multi-topic Symposium (SIMTS),* 2010.

[69] K. Zhu, D. Niyato, and P. Wang, "Network Selection in Heterogeneous Wireless Networks: Evolution with Incomplete Information," *in IEEE Wireless Communications and Networking Conference (WCNC)*, 2010.

[70] F. Fu and M. van der Schaar, "Noncollaborative Resource Management for Wireless Multimedia Applications Using Mechanism Design," *IEEE Transactions on Multimedia*, vol. 9, no. 4, pp. 851-868, 2007.

[71] A. Sahasrabudhe and K. Kar, "Bandwidth allocation games under budget and access constraints," *in the 42nd Annual Conference on Information Sciences and Systems, (CISS),* 2008.

[72] M. Cesana, N. Gatti, and I. Malanchini, "Game theoretic analysis of wireless access network selection: models, inefficiency bounds, and algorithms," *in Proceedings of the 3rd International ICST Conference on Performance Evaluation Methodologies and Tools, (VALUETOOLS),* 2008.

[73] S. Vassaki, A.D. Panagopoulos, and P. Constantinou, "Bandwidth allocation in wireless access networks: Bankruptcy game vs cooperative game," *in International Conference on Ultra Modern Telecommunications & Workshops (ICUMT),* 2009.

[74] M. A. Khan et al., "Game-Theory Based User Centric Network Selection with Media Independent Handover Services and Flow Management," *in Eighth Annual Research Conference on Communication Networks and Services (CNSR)* , 2010.

[75] M.A. Khan et al., "Auction based interface selection with Media Independent Handover services and flow management," *in European Wireless Conference, (EW),* 2010.

[76] M.A. Khan et al., “Auction based interface selection in heterogeneous wireless networks,” *in the 2nd IFIP Wireless Days, (WD),* 2009.

[77] M. Chatterjee, H. Lin, and S. K. Das, “Non-Cooperative Games for Service Differentiation in CDMA Systems,” *Journal of Mobile Networks and Applications,* vol. 10, no. 6, pp. 939-946, 2005.

[78] D. E. Charilas, A. D. Panagopoulos, P. Vlacheas, O. I. Markaki, and P. Constantinou, “Congestion Avoidance Control through Non-cooperative Games between Customers and Service Providers,“ *International Conference* on *Mobile Lightweight Wireless Systems (Mobilight),* 2009.

[79] J. Antoniou et al., “Cooperative user-network interactions in next generation communication networks,” *Elsevier Computer Networks*, vol. 54, no. 13, pp. 2239-2255, 2010.

[80] H. Pervaiz and J. Bigham, “Game Theoretical Formulation of Network Selection in Competing Wireless Networks: An Analytic Hierarchy Process Model*,” in Third International Conference on Next Generation Mobile Applications, Services and Technologies, (NGMAST),* 2009.

[81] H. Pervaiz, “A Multi-Criteria Decision Making (MCDM) network selection model providing enhanced QoS differentiation to customers,” in *International Conference on Multimedia Computing and Information Technology, (MCIT),* 2010.

[82] D. Niyato and E. Hossain, “A Noncooperative Game-Theoretic Framework for Radio Resource Management in 4G Heterogeneous Wireless Access Networks,” *IEEE Transactions on Mobile Computing*, vol. 7, no. 3, pp. 332-345, 2008.

[83] J. Antoniou and A. Pitsillides, “4G Converged Environment: Modeling Network Selection as a Game,” *in the 16th IST Mobile and Wireless Communications Summit*, 2007.

[84] V. Gajić, J. Huang, and B. Rimoldi, “Competition of wireless providers for atomic users: equilibrium and social optimality,” *in the Annual Allerton Conference on Communication, Control, and Computing, (ALLERTON),* 2009.

[85] D. E. Charilas, O. I. Markaki, and P. T. Vlacheas, “Admission Control as a Non-Cooperative Multi-Stage Game between Wireless Networks,” *in the 16th International Conference on Systems, Signals and Image Processing (IWSSIP),* 2009.

[86] M. S. Z. Khan, S. Alam, and M. R. H. Khan, “A Network Selection Mechanism for Fourth Generation Communication Networks,” *Journal of Advances in Information Technology,* vol. 1, no. 4, pp. 189-196, 2010.

[87] D. Niyato and E. Hossain, "A Cooperative Game Framework for Bandwidth Allocation in 4G Heterogeneous Wireless Networks," *in IEEE International Communications Conference (ICC),* 2006.

[88] I. M. Suliman, C. Pomalaza-Raez, I. Oppermann, and J. Lehtomaki, "Radio resource allocation in heterogeneous wireless networks using cooperative games," *Nordic Radio Symposium I Finnish Wireless Communications Workshop, (NRS/FWCW),* 2004.

[89] C-J. Chang, T-L. Tsai, and Y-H. Chen, "Utility and Game-Theory Based Network Selection Scheme in Heterogeneous Wireless Networks," *in IEEE Wireless Communications and Networking Conference (WCNC),* 2009.

[90] J. Antoniou et al., "Access network synthesis game in next generation networks," *Elsevier Computer Networks,* vol. 53, no. 15, pp. 2716-2726, 2009.

[91] M.A. Khan et al., "Cooperative game theoretic approach to integrated bandwidth sharing and allocation," *in International Conference on Game Theory for Networks, (GameNets),* 2009.

[92] S. Buchegger et al., "Reputation systems for self-organized networks*," IEEE Technology and Society Magazine,* vol. 27, no. 1, pp. 41 – 47, 2008.

[93] J-M. Seigneur, and X. Titi, "Reputation-based Telecommunication Network Selection," *in Proceedings of the e-Society International Conference, (IADIS)*, 2010.

[94] N.B. Salem, J.P. Hubaux, and M. Jakobsson, "Reputation-Based Wi-Fi Deployment," *ACM Mobile Computing and Comm. Rev.*, vol. 9, no. 3, pp. 69-81, 2005.

[95] M. Zekri, B. Jouaber, and D. Zeghlache, "On the use of network QoS reputation for vertical handover decision making," *in IEEE GLOBECOM Workshops (GC Wkshps),* 2010.

[96] A.Satsiou, and L.Tassiulas, "Reputation-based Internet Sharing in Wireless Neighborhood Community Networks", *in Proc. of the IEEE International Conference on Communications*, 2010.

[97] O. Ormond, G-M. Muntean, and J. Murphy, "Network Selection Strategy in Heterogeneous Wireless Netorks," *in the Information Technology and Telecommunication Conference, (IT&T),* 2005.

[98] A. Centonza, T. J. Owens, J. Cosmas, and Y.-H. Song, "Differentiated service delivery in cooperative IP-based broadcast and mobile telecommunications networks," *IMA Journal of Management Mathematics,* vol. 18, no. 3, pp. 245 -267, Jul. 2007.

[99] V. Rakocevic, J. Griffiths, G. Cope, “Performance analysis of bandwidth allocation schemes in multiservice IP networks using utility functions,” in *Proceedings of the 17th International Teletraffic Congress, (ITC),* 2001.

[100] J-W. Yoo and K. H. Park, “A Cooperative Clustering Protocol for Energy Saving of Mobile Devices with WLAN and Bluetooth Interfaces,” *IEEE Transactions on Mobile Computing, vol. 10*, no. 4, pp. 491-504, 2011.

[101] Y. Park and T. Park, “A Survey of Security Threats on 4G Networks,” *in IEEE Globecom Workshop on Security and Privacy in 4G Networks,* 2007.

[102] *3GPP TS 26.234: "Transparent end-to-end Packet-switched Streaming Service (PSS); Protocols and codecs".*

[103] *3GPP TS 26.247: "Transparent end-to-end Packet-switched Streaming Service (PSS); Progressive Download and Dynamic Adaptive Streaming over HTTP (3GP-DASH)".*

[104] *OIPF Specification Volume 2a - HTTP Adaptive Streaming V2.1, 2011/06/21.*

[105] *Information technology – MPEG systems technologies – Par6: Dynamic adaptive streaming over HTTP (DASH):ISO/IEC JTC 1/SC 29*

[106] *D. F. Brueck et al., “Apparatus, system, and method for multi-bitrate content streaming”, United States Patent, October, 2010.*

[107] *F. Wu et al., “Seamless switching of scalable video bitstreams”, United States Patent, August, 2011.*

[108] D. Hassoun, “*Dynamic stream switching with Flas Media Server 3*”, Available online: http://www.adobe.com/devnet/flashmediaserver/articles/dynamic_stream_switching.html

[109] J. Padhye, J. Kurose, D. Towsley, and R. Koodli, “A model based TCP friendly rate control protocol,” *in Proc. of Network and Operating System Support for Digital Audio and Video (NOSSDAV),* 1999.

[110] R. Rejaie, M. Handley, and D. Estrin, “RAP: An end-to-end rate-based congestion control mechanism for realtime streams in the Internet,” *in IEEE Conference on Computer Communications, (INFOCOM),* 1999.

[111] D. Sisalem and A. Wolisz, “LDA+ TCP-friendly adaptation: A measurement and comparison study,” *in Proc. of Network and Operating System Support for Digital Audio and Video (NOSSDAV),* 2000.

[112] G. Yang et al., “Smooth and efficient real-time video transport in the presence of wireless errors,” *ACM Trans. Multimedia Comput. Commun. Appl.,* vol.2, no. 2, pp. 109-126, 2006.

[113] S. Cen, P. C. Cosman, and G. M. Voelker, “End-to-end differentiation of congestion and wireless losses,” *IEEE/ACM Trans. Netw.*, vol. 11, no. 5, pp. 703-717, 2003.

[114] M. Chen and A. Zakhor, “Rate control for streaming video over wireless,” *IEEE Wireless Communications,* vol. 12, no. 4, pp. 32-41, 2005.

[115] B.-Y. Choi et al., “Using RTT variability for adaptive cross-layer approach to multimedia delivery in heterogeneous networks,” *IEEE Transactions on Multimedia,* vol. 11, no. 6, pp. 1194-1203, 2009.

[116] L.-A. Larzon, M. Degermark, S. Pink, L.-E. Jonsson, and G. Fairhurst, “The Lightweight User Datagram Protocol (UDP-Lite)”, 2004. [Online]. Available: http://tools.ietf.org/html/rfc3828/.

[117] C. Bouras et al., “Video transmission over TFRC using cross-layer power management,” in *Proceedings of the 17th International Conference on Software, Telecommunications and Computer Networks, (SoftCOM),* 2009.

[118] R. Rejaie, M. Handley, and D. Estrin, “Layered quality adaptation for Internet video streaming,” *IEEE Journal on Selected Areas of Communications (JSAC),* vol. 18, no. 12, pp. 2530–2543, 2000.

[119] J-W. Ding, Z-Y. Chen, W-T. Lee and W-M. Chen, “Adaptive bandwidth allocation for layered video streams over wireless broadcast channels,” *in Fourth International Conference on Communications and Networking, (ChinaCOM),* 2009.

[120] M. Zink, J. Schmitt, and R. Steinmetz, “Layer-encoded video in scalable adaptive streaming,” *IEEE Transactions on Multimedia*, vol. 7, no. 1, pp. 75 – 84, 2005.

[121] M. Qin and R. Zimmermann, “Improving mobile ad-hoc streaming performance through adaptive layer selection with scalable video coding*,” in Proceedings of the 15th international Conference on Multimedia*, 2007.

[122] C.-W. Huang and J.-N. Hwang ; “An Embedded Packet Train and Adaptive FEC Scheme for Effective Video Adaptation over Wireless Broadband Networks” , *in IEEE International Packet Video Workshop*, 2006.

[123] M. van der Schaar, S. Krishnamachari, S. Choi, and X. Xu, “Adaptive Cross-Layer Protection Strategies for Robust Scalable Video Transmission Over 802.11 WLANs,” *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 21, no. 10, pp.1752- 1763, 2003.

[124] E. Piri, T. Sutinen and J. Vehkaper¨a, “Cross-layer Architecture for Adaptive Realtime Multimedia in Heterogeneous Network Environment,” *In European Wireless*, 2009.

[125] C. Krasic, J. Walpole, and W.-chi Feng, “Quality-adaptive media streaming by priority drop,” *Proceedings of the 13th international workshop on Network and operating systems support for digital audio and video, (NOSSDAV),* 2003.

[126] N. Yeadon, F. Garcia, D. Hutchison, and D. Shepherd, “Filters: QoS support mechanisms for multipeer communications,” *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 14, no. 7, pp. 1245–1262, 1996.

[127] M. Prangl, I. Kofler, and H. Hellwagner, “Towards QoS Improvements of TCP-Based Media Delivery,” *in Fourth International Conference on Networking and Services, (ICNS),* 2008.

[128] M. Vijaykumar and S. Rao, “A cross-layer frame work for adaptive video streaming over wireless networks,” *in International Conference on Computer and Communication Technology (ICCCT),* 2010.

[129] M. Hiromoto, H. Tsutsui, H. Ochi, T. Osano, N. Ishikawa, and Y. Nakamura, “Dynamic Rate Control for Media Streaming in High-Speed Mobile Networks,” *in IEEE Wireless Communications and Networking Conference, (WCNC),* 2009.

[130] T. Takaoka, I. Nagayoshi, T. Hanamura, and H. Tominaga, “Network adaptive rate control for transcoder,” *in Proceedings of the 13th European Signal Processing Conference, (EUSIPCO),* 2005.

[131] X.Y. Wang, Y. Zhang, H.L. Li, and W.L. Zhu. “Adaptive rate control for dynamic bandwidth in video transcoding,” *in Proceedings of IEEE Int. Conference on Communication Systems,* 2008.

[132] M. Medagama, D. Dias, and S. Fernando "Transcoding Based Optimum Quality Video Streaming Under Limited Bandwidth", *4th International Conference on Industrial and Information Systems*, 2009.

[133] D. Chattopadhyay, A. Sinha, T. Chattopadhyay, and A. Pal, “Adaptive rate control for H.264 based video conferencing over a low bandwidth wired and wireless channel,” *in IEEE International Symposium on Broadband Multimedia Systems and Broadcasting,* 2009.

[134] H. Mukhtar, M. Hassan, and T. Landolsi, “A Multi-Level Adaptive Scheme for Multimedia Transmission over Wireless Channels,” *IEEE Consumer Communications and Networking Conference (CCNC),* 2010.

[135] G.-M. Muntean, P. Perry, L. Murphy, “A New Adaptive Multimedia Streaming System for All- IP Multi-Service Networks,” *in IEEE Transaction on Broadcasting,* vol. 50, no. 1, pp. 1-10, 2004.

[136] T. Schierl, T. Wiegand, and M. Kampmann, “3GPP compliant adaptive wireless video streaming using H.264/AVC,” in *IEEE International Conference on Image Processing, (ICIP),* 2005.

[137] X. Qiu, H. Liu, D. Li, S. Zhang, D. Ghosal, and B. Mukherjee, "Optimizing HTTP-based Adaptive Video Streaming for wireless access networks," *in 3rd IEEE International Conference on Broadband Network and Multimedia Technology, (IC-BNMT),* 2010.

[138] T. Kanada, K. Sato, and T. Tsuboi, "An ATM based transport network architecture," presented at *IEEE Int. Workshop on Future Prospects of Burst Packetized Multimedia Commun.*, 1987.

[139] A. Roy and P. Venkataram, "Design of a Link Control Protocol for Multimedia Services in Wireless Local Communication," *Wirel. Pers. Commun.,* vol. 18, no. 3, pp. 247-274, 2001.

[140] *H. Schulzrinne, A. Rao, and R. Lanphier, Real Time Streaming Protocol (RTSP), IETF RFC 2326, 1998.*

[141] *H. Schulzrinne et al, SIP: Session Initiation Protocol, IETF RFC 3261, 2002.*

[142] *H. Schulzrinne et al, RTP: A Transport Protocol for Real-Time Applications, IETF RFC 3550, 2003.*

[143] W.-P. Yiu et al., "Lateral error recovery for media streaming in application-level multicast," *IEEE Transactions on Multimedia,* vol. 8, no. 2, pp. 219- 232, Apr. 2006.

[144] D. Wu, Y. T. Hou, and Y-Q. Zhang, "Scalable Video Coding and transport over broadband wireless Networks," *in Proc. of the IEEE* vol. 89, no. 1, pp. 6 – 20, Jan. 2001.

[145] F. Wu, Shipeng Li, and Y. Zhang, "A framework for efficient progressive fine granularity scalable video coding," *in IEEE Transactions on Circuits and Systems for Video Technology*, pp. 332 -344, 2001.

[146] M. Zink, and A. Mauthe, "P2P Streaming using Multiple Description coded Video*", in Proc. of Euromicro Conference,* 2004.

[147] J.W. Ding, and S.Y. Lan, "Quality-Adaptive Proxy Caching for Peer-to- Peer Video Streaming Using Multiple Description Coding," *Journal of Information Science and Engineering*, vol. 25, no. 3, 2009.

[148] Xiao Su, and W. Web, "Multidescription video streaming with optimized reconstruction-based DCT and neural-network compensations," *IEEE Transactions on Multimedia*, pp.123- 131, 2001.

[149] Z. He, J. Cai, C. Chen, "Joint source channel rate distortion analysis for adaptive mode selection and rate control in wireless video coding," *IEEE Transaction on Circuits and System for Video Technology*, pp. 511-523, 2002.

[150] P. Zhu, W. Zeng, and C. Li, "Joint Design of Source Rate Control and QoS-aware Congestion Control for Video Streaming over the Internet", *IEEE Transaction on Multimedia*, vol. 9, no. 2, pp. 366-376, 2007.

[151] J. Yan, K. Katrinis, M. May, and B. Plattner, "Media- and TCP-friendly Congestion Control for Scalable Video Streams", *IEEE Transaction on Multimedia*, vol. 8, no. 2, , pp. 196-206, April 2006.

[152] M. Chen, and A. Zakhor, "Multiple TFRC Connections-based Rate Control for Wireless Networks", *IEEE Transaction on Multimedia*, vol. 8, no. 10, pp. 1045-1061, 2006.

[153] Z. Fu, X. Meng, and S. Lu, "TCP Friendly Rate Adaptation for Multimedia Streaming in Mobile Ad-hoc Networks", *IEEE International Conference on Management of Multimedia and Mobile Networks and Services, (MMNS),* 2003.

[154] M. van Der Schaar and N. Sai Shanka, "Cross-layer wireless multimedia transmission: Challenges, principles, and new paradigms," *IEEE Wireless Communications*, vol. 12, no. 4, pp. 50–58, 2005.

[155] J. Diaz del Rio, O. del Rio Herrero, and M. Fernandez Veiga, "A Dynamic Cross-Layer Architecture for QoS Provisioning of Multimedia Services on all-IP based Adaptive Satellite Networks," *in Int. Workshop on Satellite and Space Communications, (IWSSC),* 2009.

[156] Z. Li, and J. Zhou, "Adaptive Cross-layer QoS for priority-based video streaming over wireless channel," *in First Int. Conference on Future Information Networks, (ICFIN),* 2009.

[157] X. Li et al., "An Adaptive Cross-Layer Scheduling Algorithm for Multimedia Networks," *in Proceedings of the International Conference on Intelligent Information Hiding and Multimedia Signal Processing (IEEE Computer Society),* 2008.

[158] S. Shakkottai, S. Rappaport, and T.S. Karlsson, "Cross-layer design for wireless Networks," *IEEE Communication Magazine*, vol. 41, no. 10, pp. 74-80, 2003.

[159] S. Choudhury, and J. Gibson, "Joint PHY/MAC Based Link Adaptation for Wireless LANs with Multipath Fading", *IEEE Wireless Communications and Networking Conference*, Vol. 2, pp. 757- 762, 2006.

[160] C. Verikouris, L. Alonso, and T. Giamalis, "Cross-layer optimization for wireless systems: A European research key challenge,“ *Global Communications Newsletter*, 2005.

[161] J. Chen and T. Zheng, "Joint cross-layer design for wireless QoS content delivery," *IEEE International Conference on Communications*, 2004.

[162] J. Zhang et al., "Power-Aware Mobile Multimedia: a Survey (Invited Paper)," *Journal of Communications*, vol.4, no.9, 2009.

[163] Yu Xiao, R. S. Kalyanaraman, and A. Yla-Jaaski, “Energy Consumption of Mobile YouTube: Quantitative Measurement and Analysis,” *in The Second International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST),* 2008.

[164] L.M. Correia et al., “Challenges and enabling technologies for energy aware mobile radio networks,” *IEEE Communications Magazine*, 48, no. 11, pp. 66-72, 2010.

[165] N. Rodriguez, P. Hui, J. Crowcroft, and A. Rice, “Exhausting battery statistics: understanding the energy demands on mobile handsets,” *in Proc. of the 2nd ACM SIGCOMM Workshop on Networking, Systems, and Applications on Mobile Handhelds, (MobiHeld),* 2010.

[166] A. Rahmati and Lin Zhong, “Context-Based Network Estimation for Energy-Efficient Ubiquitous Wireless Connectivity,” *IEEE Transactions on Mobile Computing*, vol. 10, no. 1, pp. 54-66, 2011.

[167] H. Petander, “Energy-aware network selection using traffic estimation,” *in Proc. of the 1st ACM Workshop on Mobile Internet Through Cellular Networks (MICNET)*, 2009.

[168] I. Joe, W.-T. Kim, and S. Hong, “A Network Selection Algorithm considering Power Consumption in Hybrid Wireless Networks,” *in Proc. of 16th International Conference on Computer Communications and Networks, (ICCCN),* 2007.

[169] I. Smaoui, F. Zarai, R. Bouallegue, and L. Kamoun, “Multi-criteria dynamic access selection in heterogeneous wireless networks,” *in 6th International Symposium on Wireless Communication Systems, (ISWCS),* 2009.

[170] Huaiyu Liu, C. Maciocco, V. Kesavan, and A. L. . Low, “Energy efficient network selection and seamless handovers in Mixed Networks,” *in IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks & Workshops, (WoWMoM),* 2009.

[171] R.Y. Kim and S. Mohanty, “Advanced power management techniques in next-generation wireless networks,” *IEEE Communications Magazine*, 48, no. 5, pp. 94-102, 2010.

[172] S. Lee, J. Koo, and K. Chung, “Content-aware rate control scheme to improve the energy efficiency for mobile IPTV,” *in Digest of Technical Papers International Conference on Consumer Electronics, (ICCE),* 2010.

[173] G.Perrucci, F.Fitzek, G.Sasso, and M.Katz, “Energy Saving Strategies for Mobile Devices using Wake-up Signals“, *Proc. ACM Press*, 2008.

[174] V. Namboodiri and Lixin Gao, “Energy-Efficient VoIP over Wireless LANs,” *IEEE Transactions on Mobile Computing,* vol. 9, no. 4, pp. 566-581, Apr. 2010.

[175] Z. Li, F. Zhai, and A. Katsaggelos, “Joint video summarization and transmission adaptation for energy-efficient wireless video streaming,” *Journal on Advances in Signal Processing (EURASIP),* 2008.

[176] M. Kennedy et al., “Battery and Stream-Aware Adaptive Multimedia Delivery for Wireless Devices”, *IEEE Intl Workshop on Performance and Management of Wireless and Mobile Networks (P2MNET),* 2010.

[177] M. A. Baker, V. Parameswaran, K. S. Chatha, and B. Li, “Power reduction via macroblock prioritization for power aware H.264 video applications,” *in Proc. of the IEEE/ACM/IFIP International Conference on Hardware/Software Co-design and System*, 2008.

[178] H. Van Antwerpen et al., “Energy-aware system design for wireless multimedia,” *in Proc. of Design, Automation and Test in Europe Conference and Exhibition*, 2004.

[179] S. Pasricha, S. Mohapatra, M. Luthra, N. Dutt, and N. Venkatasubramanian, “Reducing Backlight Power Consumption for Streaming Video Applications on Mobile Handheld Devices,” *in Proc. Embedded Systems for Real-Time Multimedia Workshop,* 2003.

[180] P.-C. Hsiu, C.-H. Lin, and C.-K. Hsieh, “Dynamic backlight scaling optimization for mobile streaming applications,” *in International Symposium on Low Power Electronics and Design, (ISLPED),* 2011.

[181] K. Mahmud, M. Inoue, H. Murakami, M. Hasegawa and H. Morikawa, “Measurement and usage of power consumption parameters of wireless interfaces in energy-aware multi-service mobile terminals,” *in IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, (PIMRC),* 2004.

[182] I.A. Getting, “Perspective/navigation-The Global Positioning System,” IEEE Spectrum, vol. 30, no. 12, pp.36-38, 43-47, 1993.

[183] A. Gunther and C. Hoene, “Measuring round trip times to determine the distance between WLAN nodes” *Proceedings of Networking,* 2005.

[184] B. H. Walke, S. Mangold, and L. Berlemann, "*IEEE 802 Wireless Systems - Protocols, Multi-Hop Mesh/Relaying, Performance and Spectrum Coexistence*", John Wiley and Sons, 2006.

[185] S.D. Hermann, M. Emmelmann, O. Belaifa and A. Wolisz, “Investigation of IEEE 802.11k-based Access Point Coverage Area and Neighbor Discovery,” *in 32nd IEEE Conference on Local Computer Networks, (LCN),* 2007.

[186] P. Calyam and C-G. Lee, “Characterizing voice and video traffic behavior over the Internet” *in Proceedings of the International Symposium on Computer and Information Sciences, (ISCIS*), 2005.

[187] A. S. Tanenbaum. Computer Networks. Pearson Education International, fourth edition, 2003.

[188] S. B. Moon, J. Kurose, P. Skelly, and D. Towsley, "*Correlation of packet delay and loss in the internet*," Technical report, Amherst, MA, USA, 1998.

[189] D. Aguayo, J. Bicket, S. Biswas, G. Judd and R. Morris, "Link-level measurements from an 802.11b mesh network," *in Proceedings of ACM SIGCOMM*, 2004.

[190] G. Holland, N. Vaidya, and P. Bahl, "A rate-adaptive MAC protocol for multi-Hop wireless networks," *in Proceedings of the 7th annual international conference on Mobile computing and networking,* 2001.

[191] A. Kamerman and L. Monteban, "WaveLAN(C)-II: a high-performance wireless LAN for the unlicensed band," *Bell Labs Technical Journal*, vol. 2, no. 3, pp. 133, 118, 1997.

[192] R. V. V. S. V. Prasad, V. Srinivas, V. V. Kumari and K. V. S. V. N. Raju, "Credibility Based Reputation Calculation in P2P Networks ", in *Distributed Computing and Internet Technology*, vol. 5375, pp.188-195, 2009.

[193] Q. Song, A. Jamalipour, Network selection in an integrated wireless LAN and UMTS environment using mathematical modeling and computing techniques, *IEEE Wireless Communications Magazine,* 2005.

[194] ITU-T, P.910: Subjective video quality assessment methods for multimedia applications. Geneva, Switzerland: International Telecommunication Union, 2008.

[195] Millennial Media's Mobile Mix™, Report June 2011. [Online]. Available: http://www.millennialmedia.com/wp-content/images/mobilemix/MM-MobileMix-June2011.pdf

[196] X. Tan et al., "Perceived Video Streaming Quality under Initial Buffering and Rebuffering Degradations", *MESAQIN*, 2006.

[197] The Network Simulator 2, [Online] Available: http://isi.edu/nsnam/ns/

[198] No Ad-Hoc Routing Agent (NOAH), [Online] Available: http://icapeople.epfl.ch/widmer/uwb/ns2/noah/

[199] M. Fiore, realistic patch for NS-2, [Online] Available: http://perso.citi.insalyon.fr/mfiore/research.html

[200] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: a practical approach," *in Proceedings ACM MSWiM*, 2004.

[201] J. P. Pavon and Sunghyun Choi, "Link adaptation strategy for IEEE 802.11 WLAN via received signal strength measurement," *in IEEE International Conference on Communications, (ICC),* 2003.

[202]M. H. Manshaei, T. Turletti, and T. Guionnet, "An Evaluation of Media-Oriented Rate Selection Algorithm for Multimedia Transmission in MANETs," *EURASIP Journal on Wireless Communications and Networking,* vol. 2005, pp. 757-773, 2005.

[203] Cisco Aironet 802.11a/b/g Wireless Card, [Online] Available: http://www.cisco.com/en/US/prod/collateral/wireless/ps6442/ps4555/ps5818/product_datasheet09186a00801ebc29.html

[204] Enhanced UMTS Radio Access Network Extensions for ns-2, [Online] Available: http://eurane.ti-wmc.nl/eurane/

[205] M. Heusse, F. Rousseau, G. Berger-Sabbatel and A. Duda, "Performance anomaly of 802.11b," *in Proceedings of IEEE Conference on Computer and Communications Societies (INFOCOM),* vol. 2, pp. 836-843, 2003.

[206] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "On the Throughput Allocation for Proportional Fairness in Multirate IEEE 802.11 DCF," *in IEEE Consumer Communications and Networking Conference (CCNC),* pp. 1-5, 2009.

[207] S-D. Lee et al., "Improving TCP Throughput and Fairness over Multi-rate IEEE 802.11 Wireless LANs," *in Computational Science and Its Applications (ICCSA),* pp. 720-729, 2006.

[208] L. Zhang, Y. Shu, and O.W.W. Yang, "Throughput and fairness improvement in 802.11b multi-rate WLANs*," IEEE Personal, Indoor and Mobile Radio Communications (PIMRC),* vol. 3, pp. 1946-1950, 2005.