Innovative Content Delivery Solutions in the Future Network Heterogeneous Environment

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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, and 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.

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To my dearest parents

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List of Publications

1. L. Zou, R. Trestian, G-M. Muntean, "E^{2}DOAS: User Experience Meets Energy Saving for Multi-Device Adaptive Video Delivery", Computer Communications Workshops (INFOCOM WKSHPS), 2015 IEEE Conference on , Hong Kong, April 2015.

2. L. Zou, R. Trestian, G-M. Muntean, "EDOAS: Energy-Aware Device-Oriented Adaptive Multimedia Scheme for Wi-Fi Offload", IEEE Wireless Communications and Networking Conference (WCNC) 2014, Istanbul, Turkey, April 2014.

3. L. Zou, R. Trestian, G-M. Muntean, "DOAS: Device-Oriented Adaptive Multimedia Scheme for 3GPP LTE Systems", Personal, Indoor and Mobile Radio Communications. 24th IEEE International Symposium on (PIMRC) 2013, London, UK, Sep. 2013.

4. L. Zou, R. Trestian, G-M. Muntean, "Device-Oriented Energy-Aware Utility-Based Priority Scheduler for Video Streaming over LTE System", 12th IT&T Conference, Athlone, Ireland (IT&T), Dublin, Ireland, May. 2013. [**Best Paper Award**]

5. L. Zou, R. Trestian, G-M. Muntean, "A Utility-based Priority Scheduling Scheme for Multimedia Delivery over LTE Networks", Broadband Multimedia Systems and Broadcasting (BMSB), 2013 IEEE International Symposium on, June 2013.

6. J. D. Sweeney, L. Zou, G.-M. Muntean, "Optimization of LTE DRX for Performance-aware Applications", IT&T Conference, Dublin, Ireland (IT&T), Nov. 2015. [**Best Student Paper Award**]

7. Y. Shi, L. Zou, and S. Chen, "A Mobility Pattern Aware Clustering Mechanism for Mobile Vehicular Networks", Applied Mechanics and Materials 130 (2012): 317-320.

8. W. Fan, Y. Shi, S. Chen; L. Zou, "A mobility metrics based dynamic clustering algorithm for VANETs", Communication Technology and Application (ICCTA 2011), IET International Conference on, vol., no., pp.752-756, 14-16 Oct. 2011

Contents

List of Acronyms

3GPP 3rd Generation Partnership Project.
3GPP2 3rd Generation Partnership Project 2.

AC Admission Control.
AMC Adaptive Modulation and Coding.
ANDSF Access Network Discovery and Selection Function.
AVC Advance Video Coding.

BET Blind Equal Throughput.
BLER Block Error Rate.

CDMA Code Division Multiple Access.
CQI Channel Quality Indicator.

D2D Device-to-device Communication.
DASH Dynamic Adaptive Streaming over HTTP.
DHS Dynamic Hybrid Scheduler.
DOCSIS Data Over Cable Service Interface Specification.
DRX Discontinuous Reception.
DTX Discontinuous Transmission.

E-UTRAN Evolved UMTS Terrestial Radio Access Network.
EDF Earliest Deadline First.
EDGE Enhanced Data Rates for GSM Evolution.
eNodeB/eNB E-UTRAN Node B or Evolved Node B.
EPC Evolved Packet Core.
EXP Exponential Scheduling.
EXP/PF Exponential/PF.

FDD Frequency Division Duplex.
FDPS Frequency Domain Packet Scheduler.
FIFO First In First Out.

GAN/UMA Generic Access Network/Unlicensed Mobile Access.
GBR Guaranteed Bit Rate.
GOP Group of Picture.
GPF Generalized Proportional Fair.
GSM Global System for Mobile Communication.

HARQ Hybrid Automatic Repeat Request.
HeNB Home eNodeB.
HOL Head of Line.
HSDPA High Speed Downlink Packet Access.
HSPA+ Evolved High-Speed Packet Access.
HSS Home Subscriber Server.

HSUPA High-Speed Uplink Packet Access.
HTTP Hypertext Transfer Protocol.

I-WLAN Interworking Wireless LAN.
IFOM IP Flow Mobility.
IMS IP Multimedia Subsystem.
IoT Internet of Things.
ITS Intelligent Transportation System.

LAN Local Area Network.
LC Load Control.
LIFO Last In First Out.
LIPA Local IP Access.
LLC Logical Link Control.
LOG LOG Scheduling.
LTE Long Term Evolution.
LTE-A LTE Advanced.
LWDF Largest Weighted Delay First.

M-LWDF Modified Largest Weighted Delay First.
MAC Media Access Control.
MAN Metroplitan Area Network.
MCS Modulation and Coding Scheme.
MFS Maxmin Fairness Scheduling.
MIH Media Independent Handover.
MIMO Multi-Input Multi-Output.
MME Mobile Management Entity.
MOS Mean Opinion Score.
MPDU MAC Protocol Data Unit.
MPEG Moving Picture Experts Group.
MPTCP Multi-path TCP.
MSDU MAC Service Data Unit.
MT Maximum Throughput.
MTC Machine-Type-Communication.

NFV Network Functions Virtualization.
NTT Nippon Telegraph and Telephone Public Corporation.

OFDM Orthogonal Frequency-Division Multiplexing.
OFDMA Orthogonal Frequency-Division Multiple Access.
OSI Model Open Systems Interconnection Model.

P-GW Packet Data Network Gateway.
PDCCH Packet Downlink Control Channel.
PDCP Packet Data Convergence Protocol.
PDSCH Packet Downlink Shared Channel.
PF Proportional Fair.
PRB Physical Resource Block.
PS Packet Switch.
PSNR Peak Signal-to-Noise Ratio.
PSS Priority Set Scheduler.

QoE Quality of Experience.
QoS Quality of Service.

RAD Required Activity Detection.
RAN Radio Access Network.
RB Resource Block.
RBGs Resource Block Groups.
RLC Radio Link Control.
RM Resource Management.
RR Round Robin.
RRC Radio Resource Control.
RRM Radio Resource Management.
RTCP RTP Control Protocol.
RTMFP Real-Time Media Flow Protocol.
RTMP Real Time Messaging Protocol.
RTP Real-Time Transport Protocol.
RTSP Real-Time Streaming Protocol.
RTT Round-Trip-Time.

S-GW Serving Gateway.
SAE System Architecture Evolution.
SC-FDMA Single-carrier Frequency-Division Multiple Access.
SDN Software Defined Networks.
SHF Super High Frequency.
SINR Signal-to-Interference-plus-Noise Ratio.
SIP Session Initition Protocol.
SIPTO Selected IP Traffic Offload.
SRTCP Secure RTP Control Protocol.
SRTP Secure Real-Time Transport Protocol.
SVC Scalable Video Coding.

TDD Time Division Duplex.
TDMA Time Division Multiple Access.
TDPS Time Domain Packet Scheduler.
TTA Throughput to Average.
TTI Transmission Time Interval.

UE User Equipment.
UHF Ultra High Frequency.
UWB Ultra Wideband.

VoD Video on Demand.
VoIP Voice over IP.

W-CDMA Wideband Code Division Multiple Access.
WAVE Wireless Access in Vehicular Environments.
WFQ Weighted Fair Queuing.
WiFi Wireless Fidelity.
WiMAX Worldwide Interoperability for Microwave Access.
WLAN Wireless Local Area Network.
WPAN Wireless Personal Area Network.
WRAN Wireless Regional Area Network.

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Abstract

Innovative Content Delivery Solutions in the Future Network Heterogeneous Environment
Longhao Zou

The proliferation of high-end mobile computing devices (e.g., smartphones, tablets, notebooks and more) equipped with high-speed network access, enables the mobile users to watch multimedia content from any source on any screen, at any time, while on the move or stationary. Moreover, nowadays people tend to spend much of their time consuming multimedia content from various devices with heterogeneous characteristics (e.g., TV screen, laptop, tablet, smartphone, etc.). In order to support uninterrupted, continuous, and smooth video streaming with reduced delay, jitter, and packet loss to their customers, network operators must be able to differentiate between their offerings according to device characteristics, including screen resolution. With the mobile networks migrating towards Long Term Evolution (LTE)-Advanced and all-IP networks, people expect to connect to the Internet anytime, anywhere and from any IP-connected device. Therefore, fast surfing speed on Internet, high resolution display screen, advanced multi-core processor and lasting battery support are becoming significant features in the current mobile devices.

In this context, this thesis describes research solutions which help establish an Always Best Experienced heterogeneous environment. The proposed solutions include: (1) a novel Utility-based Priority Scheduling (UPS) algorithm for resource allocation over LTE that considers the mobile device differentiation when providing high quality delivery of multimedia services. The priority scheduling decision is based on the device classification, mobile device energy consumption and multimedia streaming tolerance to packet loss ratio; (2) a Device-Oriented Adaptive Multimedia Scheme (DOAS) for multimedia delivery over LTE networks. DOAS is a cross-layer solution built on top of the downlink scheduler in LTE/LTE-A systems. The adaptation decision in DOAS is based on the end-user device display resolution information and Quality of Service (QoS); (3) an enhanced energy-aware DOAS (eDOAS) to provide an energy efficient interworking solution for LTE -WLAN heterogeneous environments and to prolong the battery lifetime of the mobile devices; and (4) an Evolved Energy-saving QoE-aware Device-Oriented Adaptive Scheme (e^3DOAS) for balancing energy-consumption of mobile devices and perceptual quality of mobile users and fairly adapting trade-off quality level to users by using coalition game theory based mechanism.

A real experimental test-bed for mobile device power measurement was setup to measure the energy consumption of different mobile devices classes while performing Video on Demand (VoD). The impact of the device performance, quality levels of the multimedia stream and the transport protocols on energy consumption is analysed. The performance of the proposed solutions is evaluated using network simulators NS-3, LTE-Sim and Matlab.

Chapter 1

Introduction

The latest digital communication developments have also fuelled important advances in multimedia content delivery solutions. However, there are still open issues and challenges in future communication technologies. This thesis focuses on solution related to the balance between energy consumption and quality for adaptive content delivery in heterogeneous wireless network environments. This chapter presents the motivation and problems for the research discussed in this thesis and lists the contributions and structure of this thesis.

1.1 Research Motivation

According to the latest survey made available by Cisco Visual Networking Index in May 2015 [8], the global total IP-based traffic has increased more than five times in the past 5 years, and will increase three-fold by 2019 (see Figure 1.1). Cisco technical report stated that the mobile IP data traffic increased by over two thirds in 2014 and has reached 2.5EB[1] per month [15]. Therefore, Cisco forecasts the traffic from mobile devices or wireless connection will exceed wired traffic by 2019 [8]. Moreover, the mobile device number grew with a rapid rate in the past twenty years, especially in relation to smartphones. The study made by Kleiner Perkins Caufield & Byers (KPCB) describes a high increase in mobile user population between 1995 and 2014 (see Figure 1.2) [9]. Nowadays over 70% of earth's population uses mobile phones, in comparison with only around 80 million mobile users in 1995. Smartphone shipments are expected to continue

[1] 1 EB = 1 Exabytes = 1×10^{18} bytes

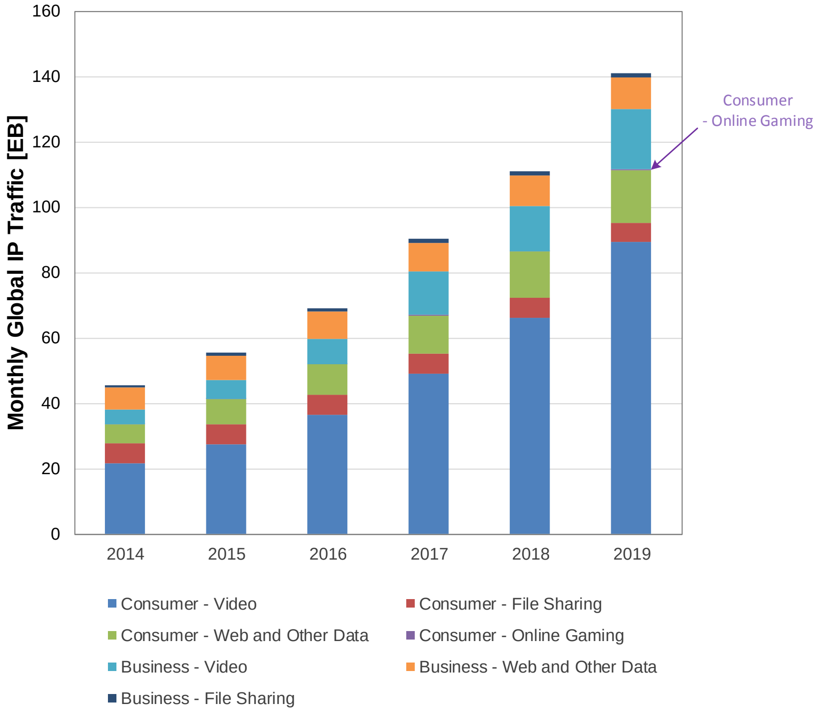


Figure 1.1: Cisco Forecast Report: 2014-2019 (per month) [8]

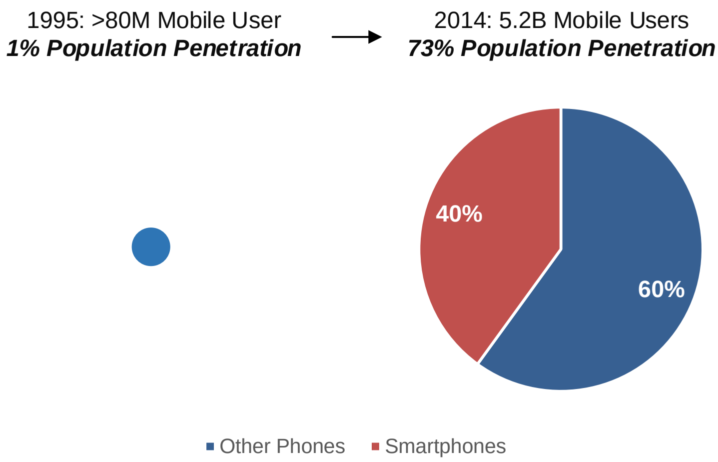


Figure 1.2: Increasing Population of Mobile Users from 1995 to 2014 [9]

to grow at 71.1% CAGR[2] from now to 2017. In this context, it is noteworthy that over half of the mobile IP traffic is due to video transmissions, which grew to 55% of the total traffic by the end of 2014. Additionally, it is notable that video traffic will account for 80% of all IP-based traffic in 2019. Foreseeably, communicating via mobile video will be a widespread service in the future.

[2]CAGR - Compound Average Growth Rate

After four generations, the next set of evolved mobile technologies, namely the fifth generation (5G) will support voice, video and other complex communication services for more than 9 billion users and billions of connected mobile devices [16]. In order to satisfy the requirements of these services by 2020, the estimated technological goals of 5G are: 1000 times the existing mobile data capacity, 10 to 100 times the current number of connected devices, 5 times lower latency, 10 to 100 times the existing data rate and 10 times longer battery life of mobile devices.

1.2 Major Research Challenges

Considering the goals of the future communication technologies it seems that the researchers at both operators and vendors will be faced with great challenges. Some of these challenges are listed next.

- **Bottleneck of Current Network** - Most of the backhaul within the current communication system is deployed using fibres, which provide very high capacity. However, the performance of the air interface inter-connecting base stations and mobile users is still limited in terms of capacity, especially as there is a rapid increasing demand of emerging data traffic services, such as video and web-based interaction. The L1/physical layer peak downlink speed of the current LTE (Category 4) is around 150Mbps, and the latest LTE-A (Category 15) will reach 3.9 Gbps including the overheads of all the layers [11]. Required streaming bitrate of a single 4K video needs at least 12Mbps [17], whereas other results tested by other operators vary from 20 Mbps to 30 Mbps in real service deployment [18]. For instance, due to the limited bandwidth resources, less than 10 users can be served simultaneously with 4K videos in a current LTE single cell network. This is not considering propagation distortions and other latency issues (i.e. ideally 1-3Mbps can be allocated to each user per Resource Block (RB) in every slot in a LTE system). More details can be found in Figure 2.3 of Chapter 2. However, a LTE micro-cell (Category 4) has also to provide voice and data services to 100-200 mobile users at the same time [11]. Furthermore, the 8K video service which would be the mainstream in the near future will need at least 100Mbps bitrate for digital wireless broadcast transmissions. This will be a bandwidth nightmare with respect to the current network capacity. More efficient methods used in network management will be necessary, for instance, employing adaptive encoding and streaming schemes during the transmission. In addition, as 46% of total mobile data traffic was offloaded onto the fixed network through WiFi or femtocell in 2014 [15], it seems that data offloading in the backhaul is a good option before next generation air interface technologies are deployed.

- **Cost of Building and Deploying New Technologies** - Cost efficiency is always one of the first aspects considered by the operators. In Dec 2015, an investigation report by iGR [19] forecasts that 56 billion dollars are required to deliver 5G to US from now until 2025, amount which only includes the cost of Radio Access Network (RAN) upgrades, cell site densification and mobile edge computing without the future operating cost. Therefore, identifying how to evolve to the next generation technologies based on the current architecture and compatibly working with the old but cheaper system are still big challenges for the researchers.

- **Quality of User Experience** - Quality of Experience (QoE) is an emerging hot topic. In the future content delivery services, the conventional end-to-end service assurance and monitoring for network performance are not the only key parameters considered by operators, but also quality of user experience will be equally important. Basically, QoE reflects user perceptual quality measured with Mean Opinion Scores (MOS) following the ITU-T standards [20] or other full/non-reference methods. In this context, the characteristics of mobile devices have become important features which may affect user QoE (see the case study for UK in 2015 shown in Figure 1.3.) Therefore, the generalized future quality of user experience can be defined as the psychological perception of end-users when multimedia services are performing on heterogeneous mobile devices (e.g. different screens, sizes, battery life and other hardware features) in different scenarios (e.g. home, work, transportation and entertainment) in different network conditions (e.g. different packet losses and latencies).

- **Energy Consumption of Mobile Devices** - Saving more energy is not only a topic for environmental friendliness of communication technologies, but also the most concerned feature on mobile devices for users (see Figure 1.3). Generally,

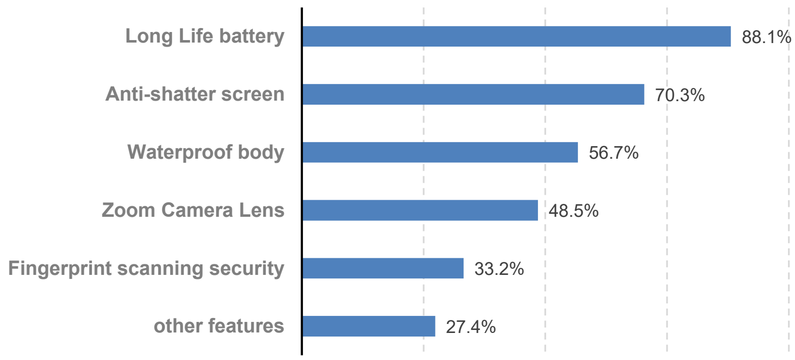


Figure 1.3: The Most Useful Features in A Smartphone (Statista 2015 [10])

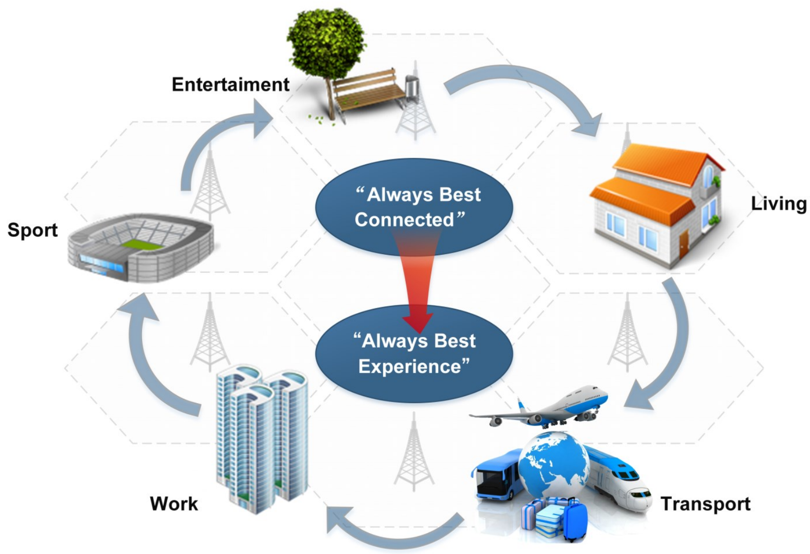


Figure 1.4: Evolved Multimedia Delivery Services

the energy consumption rate of a mobile device is related to its CPU usage, wireless interface power, screen characteristics (e.g. screen resolution, display brightness) and so on [21]. Therefore, higher quality of multimedia streaming services will consume more energy of de/encoding processing on mobile devices. It is noted that it is necessary to find a trade-off to balance the energy consumption and quality of multimedia streaming services before widely using fast charging techniques and innovative battery material for keeping more energy on mobile devices.

- **"Always Best Connected" v.s. "Always Best Experience"** - Always Best Connected (ABC) is the goal of services provided by conventional communication systems [22]. However, the future networks are "Always Best Experience (ABE)". They will focus more on user-centric device-oriented scenario-aware multimedia content delivery services [23], which enable smooth and good perceived quality services for end-users anywhere at any time (see the scenarios illustrated in Figure 1.4). It very challenging that "Always Best Connected" evolved towards "Always Best Experience". This transition involves challenges from advanced network management (e.g. channel condition optimization, data offloading, heterogeneous network handover, etc) to efficient and accurate perceptual quality measurement.

1.3 Thesis Contributions

Facing problems based on the research challenges already described, this thesis proposes a novel architecture and algorithms for multimedia delivery over heterogeneous wireless networks. By balancing user perceptual quality and energy consumption of mobile devices, this system architecture makes the multimedia delivery over wireless networks seamless and smooth and meets the requirements of the "Always Best Experience" paradigm. The main contributions of the work include:

1. Proposal of a **Utility-based Priority Scheduling Scheme (UPS)** for multimedia delivery over LTE network:

- This solution is a MAC layer scheduling scheme developed at the level of the LTE base station (i.e. eNodeB);
- Based on a novel multiplicative exponential weighted utility function, this solution makes use of mobile device characteristics, energy consumption rate and wireless channel conditions to allocate the resources for video streaming;
- UPS was tested via network simulations, and the evaluation results show that UPS outperforms other well-known schedulers for LTE networks in terms of average throughput, packet loss and video quality.

2. Proposal of a **Device-Oriented Adaptive multimedia Scheme (DOAS)** for LTE networks.

- This proposed adaptive multimedia solution is built on the top of current schedulers of LTE eNodeB without any modification on the current LTE scheduler. It is more efficient and flexible;

- By taking the mobile device characteristics and channel conditions into account, DOAS differentiates the adaptive video streaming according to both delivery conditions and mobile devices;
- When enhancing LTE scheduling using DOAS, higher video streaming throughput, lower packet loss and latency, and better video quality, estimated with PSNR are achieved in comparison with when DOAS is not employed.

3. Proposal of an **Energy-aware Device-Oriented Adaptive Scheme** for WiFi offloading (eDOAS).

- eDOAS enhances DOAS by employing traffic offloading techniques and makes the video streaming both smooth and seamless and energy aware;
- eDOAS employs an energy consumption model which helps perform stream-switching such as it increases the battery lifetime of mobile devices and improves the quality of user experience. The energy consumption model is based on the results from real experimental tests involving energy measurements and different mobile device models;
- eDOAS was tested via network simulations against two adaptive schemes: a non-energy-aware device-oriented adaptive scheme and an energy-aware non-device-oriented scheme. The simulation results shows that when using eDOAS longer battery life on mobile device, lower packet loss, and better PSNR are achieved in comparison with when using the other two schemes.

4. Proposal of an **Device-Oriented adaptive streaming scheme over wireless networks by which balances QoE and energy-saving (e^{3}DOAS)**.

- e^{3}DOAS performs adaptation based on the trade-off between QoE and energy-saving;
- e^{3}DOAS employs a novel mathematical model to optimize the video quality levels delivered to different mobile devices based on estimated energy-saving and resulting user QoE;
- Integrates coalition game theory model to adapt fairness to multimedia streaming by considering the network condition;

- Network simulations show that when switching on coalition game theory based fairness control, E^{3}DOAS video streaming achieves better throughput, lower packet loss and higher system fairness in comparison with the case when no fairness adaptation is employed. Additionally, e^{3}DOAS outperforms other adaptive schemes in terms of video streaming throughput and packet loss, received video quality and system fairness.

1.4 Thesis Structure

This thesis is structured in eight chapters as follows:

- **Chapter 1** - Introduces the motivation of the research work and presents an overview of the proposed solutions and thesis contributions.
- **Chapter 2** - Introduces the technical background of the work presented in this thesis.
- **Chapter 3** - Presents a comprehensive survey of the current research on the following topics: downlink packet scheduling, adaptive video streaming and mobile data offloading.
- **Chapter 4** - Presents the system architecture of the solutions proposed in this thesis, and the main algorithms and contributions.
- **Chapter 5** - Presents a real experimental test-bed for energy consumption measurement of the mobile devices, and result analysis.
- **Chapter 6** - Presents a perceptual video quality measurement test-bed, and its associated experimental results and analysis.
- **Chapter 7** - Presents the simulation-based testing of the proposed solutions, and simulation test result analysis.
- **Chapter 8** - Presents the conclusion of this thesis and possible future works.

Chapter 2

Technical Background

This chapter introduces the technical background for the work presented in this thesis. The key wireless network technologies used in this work will be overviewed first. Then the protocols and industry solutions for adaptive multimedia streaming will be described. Furthermore, the current and on-going industry solutions and standards for mobile data offloading techniques within a heterogeneous environment will be presented in detail. The principles of Quality of Service (QoS)/Quality of Experience (QoE) and introduction to Game Theory and utility function will be presented lastly.

2.1 Heterogeneous Wireless Networks

A wireless network is any type of communication technology which provides the connecting nodes with wireless data transmission. In terms of the heterogeneous access technologies, wireless networks include terrestrial microwave networks, inter-satellites communication network, cellular and wireless network, wireless sensor networks, and free-space optical communication networks. This thesis will mainly focus on the cellular and wireless networks. These networks consist of different types of wireless communication technologies which are developed by different organizations depending on the varying transmission distances and various requirements. Moreover, most of the well-known wireless and cellular network technologies are developed by IEEE and 3GPP, respectively. Therefore, the wireless techniques defined in IEEE standards and 3GPP specifications are introduced in the following sections.

Table 2.1: Active IEEE Standard Working Groups

Name	Description
IEEE 802.1 [24]	• Local Area Network (LAN)/Metroplitan Area Network (MAN) Architecture Design and Network Management • Internetwork among 802 LANs, MANs and other wide area networks • 802 Link Security • Protocol layers above the MAC and LLC Layers
IEEE 802.3 [25]	Physical Layer and MAC layer design of wired Ethernet
IEEE 802.11 [26]	Physical Layer and MAC layer design of Wireless Local Area Network (WLAN)
IEEE 802.15 [27]	• Physical Layer and MAC layer design of Wireless Personal Area Network (WPAN) • 802.15.1 Bluetooth Certification • 802.15.2 Coexistence of WLAN and WPAN • 802.15.3 High rate WPAN (e.g. Ultra Wideband (UWB)) • 802.15.4 Low rate and low power WPAN (e.g. ZigBee[1]) • 802.15.5 Mesh Networking • 802.15.6 Body Area Network • 802.15.7 Visible Light Communication
IEEE 802.16 [28] [1]	Wireless Broadband Access Technologies, namely Worldwide Interoperability for Microwave Access (WiMAX)
IEEE 802.17 [29]	Resilient Packet Ring designed for data transmission over optical fibre ring networks
IEEE 802.18 [30]	Radio Regulatory Technical Advisory Group for WLAN, WPAN and WiMAX, etc
IEEE 802.19 [31]	Wireless Coexistence Technical Advisory Group for WLAN, WPAN and WiMAX, etc
IEEE 802.21 [32]	Media Independent Handover (MIH) or vertical seamless handover among the same type of networks as well as the different types of networks
IEEE 802.22 [33]	Wireless Regional Area Network (WRAN) using the white spaces in TV frequency spectrum
IEEE 802.23 [34]	Framework for the citizen-to-authority emergency services over IEEE 802 networks
IEEE 802.24 [35]	Vertical Applications (e.g. Smart Grid, Intelligent Transportation System, Smart Homes, Smart Cities and eHealth, etc.) Technical Advisory Group

[1] ZigBee Alliance: `http://www.zigbee.org/`

Table 2.2: Active and Updated IEEE 802.16 Standard Working Groups [1]

Working Groups	**Description**
IEEE 802.16-2012	IEEE Standard for Air Interface for Broadband Wireless Access Systems
IEEE 802.16.1-2012	IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems
IEEE 802.16.1a-2013	IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems–Amendment 2: Higher Reliability Networks
IEEE 802.16.1b-2012	IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems–Amendment 1: Enhancements to Support Machine-to-Machine Applications
IEEE 802.16.2-2004	IEEE Recommended Practice for Local and metropolitan area networks–Coexistence of Fixed Broadband Wireless Access Systems
IEEE 802.16n-2013	IEEE Standard for Air Interface for Broadband Wireless Access Systems–Amendment 2: Higher Reliability Networks
IEEE 802.16p-2012	IEEE Standard for Air Interface for Broadband Wireless Access Systems–Amendment 1: Enhancements to Support Machine-to-Machine Applications
IEEE 802.16g-2015	IEEE Standard for Air Interface for Broadband Wireless Access Systems– Amendment 3: Multi-tier Networks

2.1.1 IEEE Standard Wireless Networks

IEEE 802, one of the protocol families approved and published by IEEE Standards Association Standards Board, is dealing with Local Area Network (LAN) and Metroplitan Area Network (MAN) technologies [36]. The architecture design of IEEE 802 protocols consist to the lower two layers, namely Data Link and Physical Layers of Open Systems Interconnection Model (OSI Model). More specifically, IEEE 802 splits the Data Link layer into two sub-layers, Logical Link Control (LLC) and Media Access Control (MAC) layers. Basically, IEEE 802 family is maintained by IEEE 802 LAN/MAN Standard Committee. The active working groups in IEEE 802 family are listed in Table 2.1. **IEEE 802.1** is an essential specification used for LAN/MAN architecture design and network management [24]. IEEE 802.3 specifies the LLC component for wired Ethernet [25]. Apart from **IEEE 802.1 and 802.3**, most of the 802 technologies are focused on wireless network specification. **IEEE 802.15** Wireless Personal Area Network (WPAN) includes the standards for short-distance and low-power design, such as Bluetooth, Ultra Wideband (UWB), ZigBee and Body Area Networks, etc. Visible Light Communication technique refers to **IEEE 802.15.7** was defined in 2011, will support the future Small Cell Communication [27]. **IEEE 802.22** is a standard for Wireless Regional Area Network (WRAN) which allows sharing of the unused spectrum allocated to television broadcast service based on cognitive radio techniques [33]. **IEEE 802.21** enables the Media Independent Handover (MIH) for the same or different types of networks defined by IEEE standards [32].

IEEE 802.16 (WirelessMAN), commercially named Worldwide Interoperability for Microwave Access (WiMAX), is a series of wireless broadband standards developed by IEEE Standards Board since 1999. Currently, this is the only wireless access solution for mobile broadband network defined by IEEE. In the physical layer, WiMAX supports Time Division Duplex (TDD) and full and half-duplex Frequency Division Duplex (FDD) which is operating scalable Orthogonal Frequency-Division Multiple Access (OFDMA) carrying data in any band from 2 to 66 GHz with the flexible channel bandwidth (e.g. 1.25, 5, 10 and 20MHz) [28], and the sub-carrier frequency space of 10.94kHz. WiMAX also supports the Adaptive Modulation and Coding (AMC) using 64QAM when the signal is good enough or using BPSK when the signal is poor. In the MAC layer, **IEEE 802.16** uses dynamic resource allocation schemes and defines five QoS classes for controlling the video streaming and latency-sensitive voice service based on Data Over Cable Service Interface Specification (DOCSIS). **IEEE 802.16** also supports other mobile access network features, such as Power Management, Handoff, Network Security, Smart Antenna and so on. The latest active and updated working groups in IEEE 802.16 family are listed in Table 2.2.

Additionally, IEEE set up technical advisory groups to monitor and coordinate different working projects. For instance, **IEEE 802.18** makes comments and recommendation policies on the radio regulation for the different wireless standards, such WLAN, WPAN, WiMAX, MIH and WRAN [30]. **IEEE 802.23** provides the framework for the civic emergency services over IEEE wireless networks [34]. The latest standard working group, namely **IEEE 802.24** [35], will support and manage the potential vertical applications (e.g. Smart Grid, Intelligent Transportation System (ITS), Smart Cities, etc.) over future wireless networks.

As most of the research works in this thesis is focused on WiFi, a detailed introduction to IEEE 802.11 is presented in the following sub-section.

Table 2.3: Features of the Well-known IEEE 802.11 Standard Amendments

802.11 Amendments	Release Date	Freq. (GHz)	BW (MHz)	Data Rate (Mbps)	MIMO Streams	Modulation	Coverage (meters)
a	Sep, 1999	5	20	≤ 54	N/A	OFDM	35 to 120
b	Sep, 1999	2.4	22	≤ 11	N/A	DSSS	35 to 115
g	Jun, 2003	2.4	20	≤ 54	N/A	OFDM, DSSS	38 to 140
n	Oct, 2009	2.4, 5	20, 40	≤ 150	4	OFDM	70 to 250
ac	Dec, 2013	5	20, 40, 80, 160	≤ 866.7	8	OFDM	35 to 115
ad	Dec, 2012	60	2, 160	≤ 6912	8, Beamforming	OFDM	60 to 100

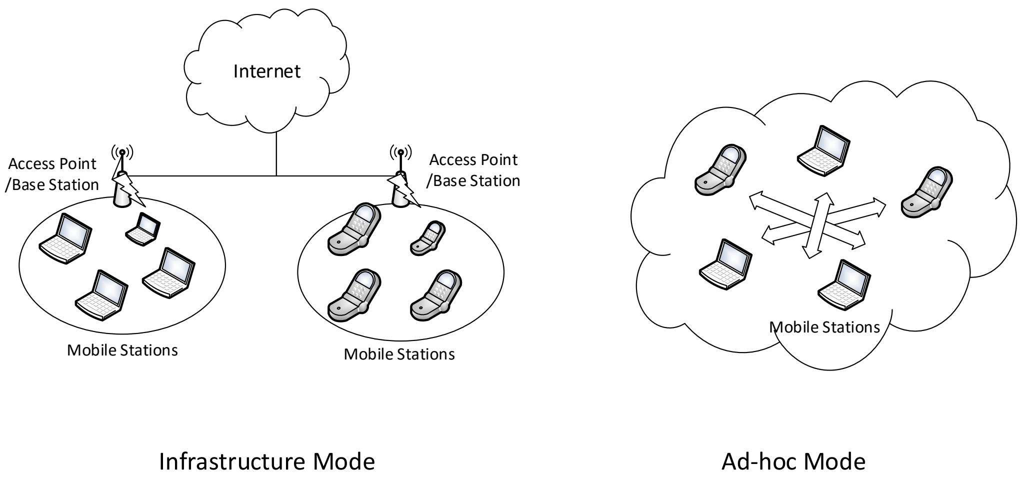


Figure 2.1: Infrastructure Mode and Ad hoc Mode

2.1.1.1 IEEE 802.11 networks

IEEE 802.11 is a set of media access control (MAC) and physical layer (PHY) specifications designed for Wireless Local Area Network (WLAN) created and maintained by the IEEE LAN/MAN Standard Committee (IEEE 802) [26]. IEEE 802.11 networks work in the 2.4, 3.6, 5 and 60 GHz frequency bands, which are simple to deploy and low cost. Generally, the IEEE 802.11 standards provide wireless connectivity in the Ultra High Frequency (UHF) and Super High Frequency (SHF) (e.g. 2.4 and 5GHz), so it is often called **Wireless Fidelity (WiFi)**. Basically, WLAN has two working modes (Figure 2.1): the first is **infrastructure mode** in which the clients are connected through an Access Point (AP); the second one is **Ad hoc mode** in which the clients are directly connected without any AP. **IEEE 802.11a/b/g/n** are widely used and deployed on most of the wireless routers in the current market. **IEEE 802.11ac** is an amendment to 802.11 family, published in December 2013. The latest amendment **IEEE 802.11ad**, namely WiGig can achieve 7Gb/s downlink speed at 60GHz but also causes very serious attenuation and offers short coverage. A list of features of the main IEEE 802.11 technologies are presented in Table 2.3. Compared to other technologies, 802.11a/b/g have lower capacity and short coverage. 802.11n provides very good downlink throughput and coverage on dual-mode frequency. The latest commercialized technology, 802.11ac doubles the downlink speed when compared to 802.11n when it works at 20 or 40 MHz bandwidth with higher Multi-Input Multi-Output (MIMO) streams. In addition, a specific amendment, called **IEEE 802.11p** or Wireless Access in Vehicular Environments (WAVE), provides data exchange and time advertisement service for the Car-to-Car communication within ITS. IEEE 802.11p is operating in 5.9GHz carrier using 10MHz channel bandwidth. In order to reduce the overheads and increase the user-level throughput, the frame aggregation technique combines the MAC Service Data Unit (MSDU) or MAC Protocol Data Unit (MPDU) and averages the overhead over multiple frames, thereby improving the user-level throughput.

2.1.2 Mobile and Cellular Networks

Nowadays mobile and cellular networks are widespread and provide mobile users with convenient and fast connectivity for voice, data and other services via wireless transmissions. However, the mobile and cellular technologies had a spectacular evolution over the years enabling the current speeds. The pre-cellular idea, namely **0G** or mobile radio telephone, was proposed by the predecessors of Bell Labs over 70 years ago [37]. A few years later, the **Mobile Telephone System (MTS)** came to the public commercial service operated by Motorola [38]. The cellular network took around 40 years to upgrade from pre-cellular to **Analog cellular network (i.e 1G)**, which was done by Nippon Telegraph and Telephone Public Corporation (NTT), Japan and Bell Labs, US. The first Analog Cellular network system, **Advanced Mobile Phone System (AMPS)** was widely introduced to North America, Pakistan and Australia, and continued working in Australia and Pakistan until 2000 and 2004, respectively [39].

In Finland in July 1991, **Global System for Mobile Communication (GSM)** the second generation (**i.e. 2G**) digital cellular networks was first deployed, which was

Table 2.4: Releases of 3GPP [2]

Release Version	**Year**	**Brief Descriptions**
Release 96,97,98	1997,1998,1999	GPRS, EDGE
Release 99	2000	UMTS **3G** based on CDMA (i.e. WCDMA)
Release 4	2001	all-IP core network
Release 5	2002	IP Multimedia Subsystem (IMS) and High Speed Downlink Packet Access (HSDPA)
Release 6	2004	Integrated operation with WLAN (e.g. Generic Access Network/Unlicensed Mobile Access (GAN/UMA)), High-Speed Uplink Packet Access (HSUPA), Mb
Release 7	2007	Improvement of VoIP and HSPA+
Release 8	2008	Long Term Evolution (LTE) and Orthogonal Frequency-Division Multiple Access (OFDMA)
Release 9	2009	**4G** LTE HeNB and other enhancement on HSUPA and HSDPA
Release 10	2011	LTE Advanced (LTE-A) introduced
Release 11	2012	Advanced IP interconnection of Services
Release 12	2015	Enhanced small cell, carrier aggregation and other enhancement on LTE-A, MTC, D2D

developed by the European Telecommunications Standards Institute (ETSI). Until now, GSM accounts for over 80% of all 2G subscribers over the world [40]. Meanwhile, the other important 2G technology, Interim Standard 95 (IS-95, **cdmaOne**) was published by Qualcomm in 1995 [41], which is based on Code Division Multiple Access (CDMA) unlike Time Division Multiple Access (TDMA) which is used in GSM. In order to make a globally applicable 3rd generation mobile network based on GSM, an organizational partner project located in ETSI was founded, named 3^{rd} Generation Partnership Project (3GPP) [40]. This organization is in charge of protocol standardizations and collaboration between different telecommunication research institutes and industry partners. Table 2.4 lists the releases of 3GPP from 1996 to present, which contains the 2G, 2.5G, 3G, 3.5G, 3.75G and 4G technologies. In addition, another 3G technology CDMA2000 is standardized by 3^{rd} Generation Partnership Project 2 (3GPP2) mainly used in North America, China, Japan and Korea. As this thesis focuses on the 4G LTE/LTE-A technologies, the detailed description given in the following subsection.

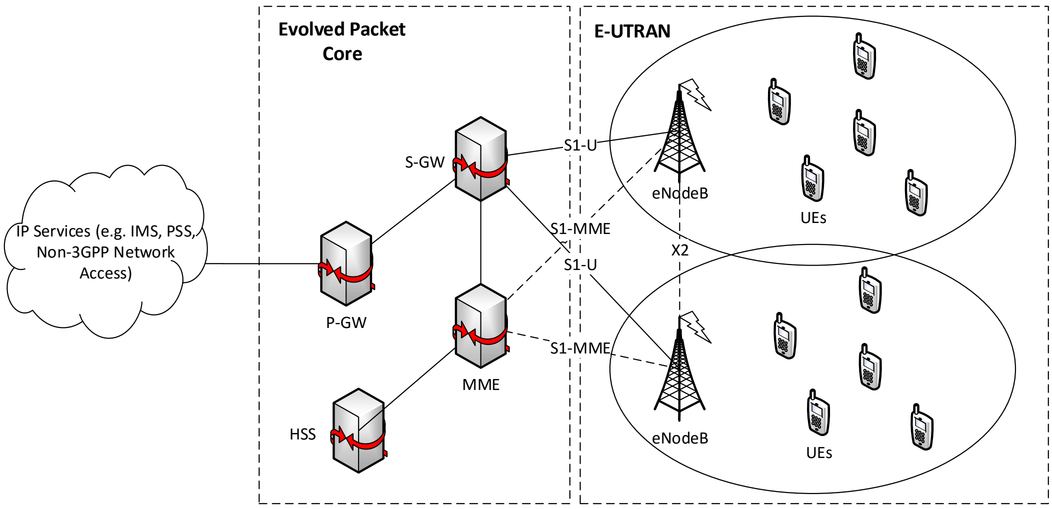


Figure 2.2: LTE SAE Architecture

2.1.2.1 3GPP LTE/LTE-A Networks

The Long Term Evolution (LTE)/LTE Advanced (LTE-A) as defined by the 3rd Generation Partnership Project (3GPP) is a highly flexible radio interface, known as System Architecture Evolution (SAE) based on 3G technologies. LTE/LTE-A simplifies the previous telecommunication system architecture to all-IP networks and consists of two main parts: Evolved Packet Core (EPC) and Evolved UMTS Terrestial Radio Access Network (E-UTRAN) [42], shown in Figure 2.2.

The EPC consists of **Home Subscriber Server (HSS)** that contains information about all the network operator's subscribers, **Mobile Management Entity (MME)** that supports user mobility management and intra-LTE handover, **Serving Gateway (S-GW)** that routes and forwards user data packets to corresponding network nodes, and **Packet Data Network Gateway (P-GW)** that is responsible for connectivity with the external IP networks (e.g. IP Multimedia Subsystem (IMS), packet switch system or WLAN). The E-UTRAN can only host two kinds of network nodes: User Equipment (UE) and E-UTRAN Node B or Evolved Node B (eNodeB/eNB). Basically, **the UE** comprises of three important modules: Mobile Termination (MT) that processes all the communication, Terminal Equipment (TE) that terminates the data streams and Universal Integrated Circuit Card (UICC, i.e. USIM) handling the user registration information [43] [44]. **eNodeB/eNB** is a base station that controls the communication with UEs, which sends and receives radio transmission using the LTE air interface. The connection between the eNodeB/eNB and S-GW is done through the

S1-U interface. Additionally, several eNodeB/eNBs are interconnected through the X2 interface, enabling mobility and handover support for UEs. Whereas the connectivity between the eNodeB/eNB and MME is done through the S1-MME interface.

Generally, the protocol architecture of LTE/LTE-A comprises of Radio Resource Control protocol, Packet Data Convergence Protocol, Radio Link Control, Media Access Control and L1/Physical protocol, from high to low layers defined by OSI Model. The layer upon RRC is IP/Network Layer. The key features of **Radio Resource Control (RRC)** are paging, connectivity among UEs and E-UTRAN, mobility management of UEs, QoS management and UE measurement reporting [45]. **Packet Data Convergence Protocol (PDCP)** is responsible for header de/compression, data transfer of control and user planes and retransmission of PCDP packets [46]. **Radio Link Control (RLC)** is in charge of re/segmentation, transfer, error detection and correction for transmission and reception of data [47]. The **Media Access Control (MAC)** layer consists of the resource block mapping, de/multiplexing of packets and packet scheduling schemes [48]. The lowest layer, **L1/Physical** layer is the air interface which supports physical channel de/modulation and signal transmission [11].

The first release of LTE provides peak rates of 300 Mb/s with MIMO, a radio-network delay of less than 5 ms, a significant increase in spectrum efficiency compared to previous cellular systems, and a new flat radio-network architecture designed to simplify operation and to reduce cost [49]. The LTE specification provides downlink peak rates of at least 100 Mbps, an uplink of at least 50 Mbps and Radio Access Network (RAN) round-trip times of less than 10 ms. LTE enables scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD), as well as a wide range of system bandwidths in order to operate in a large number of different spectrum allocations. The main advantages of LTE/LTE-A are the high throughput, low latency, an improved end-user experience and a simple architecture resulting in low operating costs. LTE/LTE-A also support seamless handover to cell towers with older network technology such as GSM, W-CDMA (UMTS), and CDMA2000.

Most of the features described above are the same between LTE (Release 8, 2000) and LTE-A (Release 12, 2014). However, LTE-A has more enhancement on the LTE air interface, such as using massive MIMO, carrier aggregation and interaction interface with WLAN and so on. This thesis will focus on the main features of LTE.

A. LTE Physical Layer and Orthogonal Frequency-Division Multiple Access (OFDMA)

The flexible spectrum access based on Orthogonal Frequency-Division Multiplexing (OFDM) is used at the LTE physical air interface. In particular, Single-carrier Frequency-Division Multiple Access (SC-FDMA) and Orthogonal Frequency-Division Multiple Access (OFDMA) are adopted for uplink and downlink directions, respectively. SC-FDMA mainly focuses on improvement of UE power efficiency using only adjacent sub-carriers, whereas OFDMA can use the entire spectrum. In this work, the LTE downlink system is considered and used for the packet scheduling solution design. Different from OFDM, OFDMA is capable of higher spectrum scalability, which allocates the sub-carriers to the individual user based on time/frequency domain. This kind of sub-carrier radio resource, is referred to as Resource Block (RB) [11], see Figure 2.3. Moreover, the downlink radio interface can support two types of frame structure [11]: Time Division Duplex (TDD) and Frequency Division Duplex (FDD). For TDD, a frame is divided into two consecutive half-frames, each half-frame is 5 ms. Then each half frame is divided into 5 sub-frames. Each sub-frame is allowed either downlink or uplink traffic. Whereas, FDD is able to transmit data on the same sub-frame for both downlink and uplink. Unlike TDD, FDD frame (i.e. 10ms) consists of 10 sub-frames (i.e. 1 ms), and 1 sub-frame has a pair of time slots (i.e. each slot = 0.05 ms). In terms of frequency domain, each time slot contains a number of RBs. Each RB occupies 180 kHz which consists of 12 subcarriers. LTE supports flexible channel bandwidth with different number of RBs (see table with indicator 5 shown in Figure 2.3). An example on about how to estimate the L1/physical data rate on FDD frame structure for 100 RBs is illustrated in Figure 2.3. The maximum L1 data rate with 4×4 MIMO that can be reached is 300Mbps. This thesis will focus on the FDD frame structure.

B. Radio Resource Management and Downlink Packet Scheduling Procedure

In order to allocate the radio resources efficiently, LTE Radio Resource Management (RRM) makes use of several features, such as Channel Quality Indicator (CQI) reporting, Adaptive Modulation and Coding (AMC) and Hybrid Automatic Repeat Request

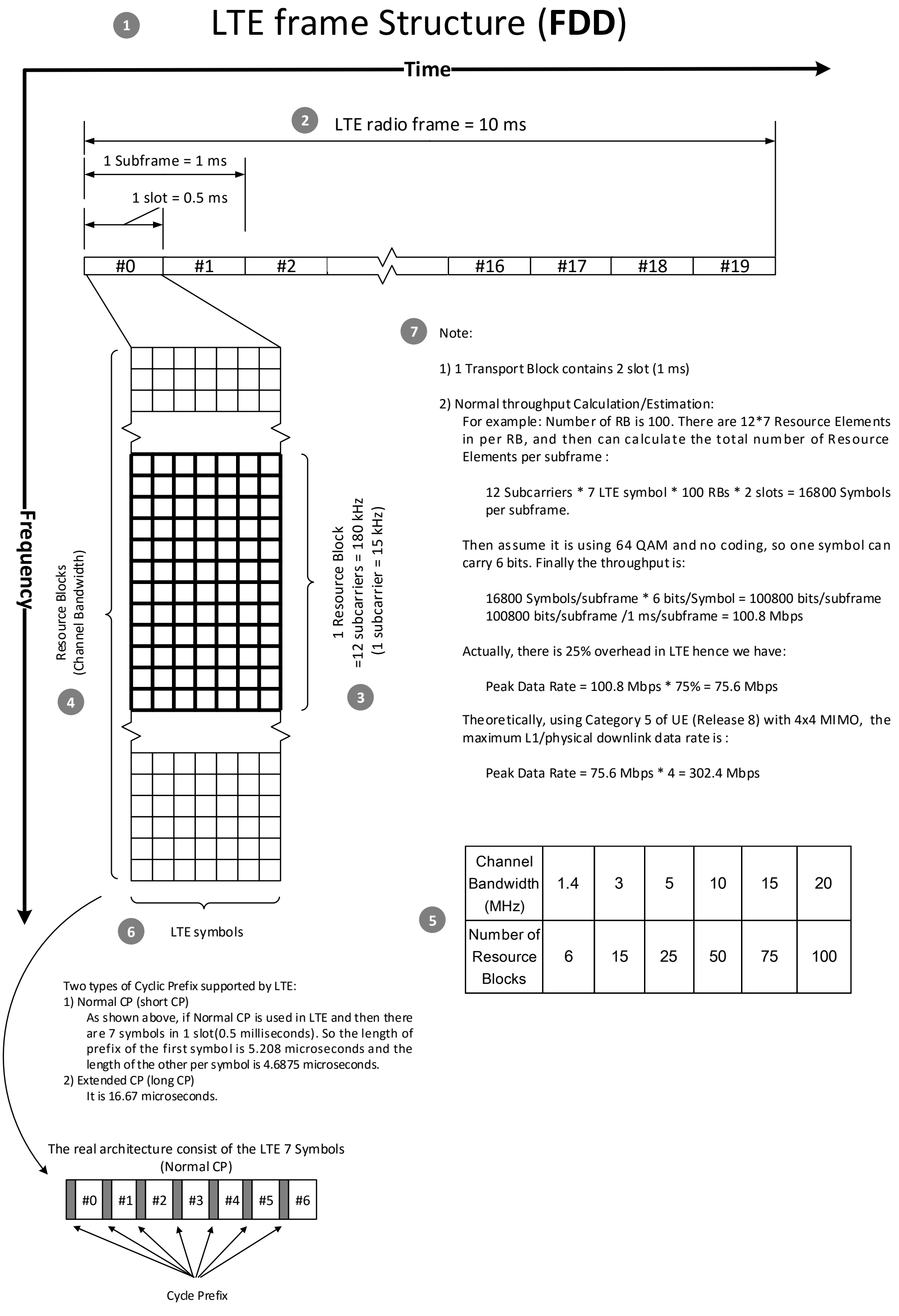


Figure 2.3: LTE FDD Frame Structure and L1/Physical Datarate Estimation [11]

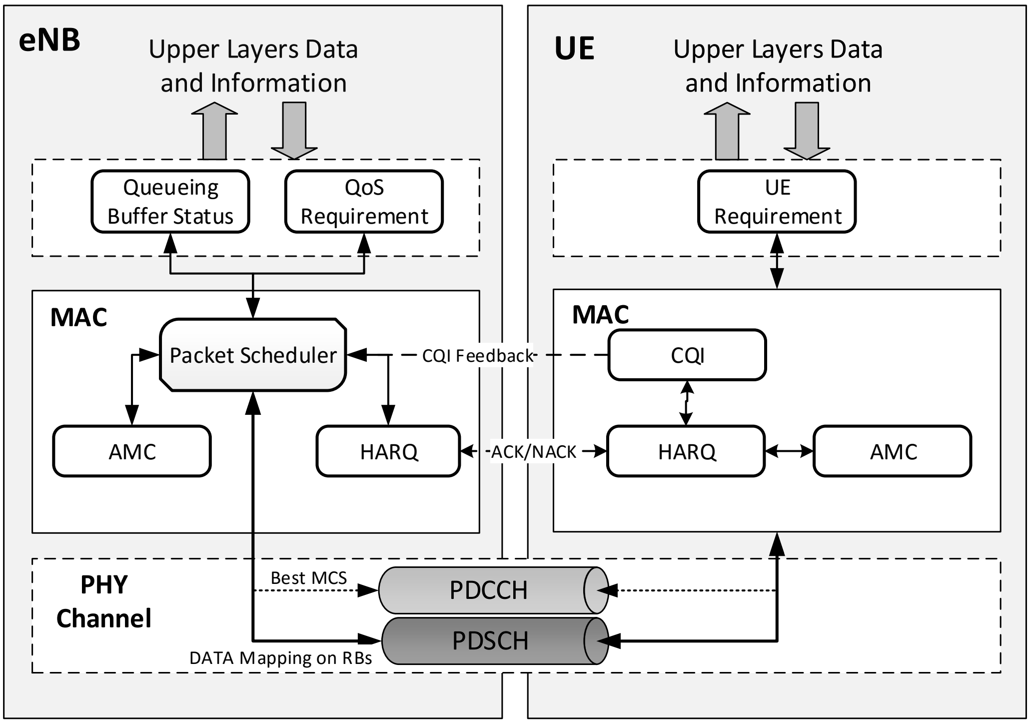


Figure 2.4: LTE Radio Resource Management Architecture [12]

(HARQ). These features are distributed in physical and MAC layer. Figure 2.4 shows the description of LTE RRM architecture [12].

- **CQI reporting**: represents the key feature in LTE RRM since it enables to estimate the channel quality based on the Signal-to-Interference-plus-Noise Ratio (SINR) between eNodeB and UEs. The eNB can make a precise allocation by using the CQI reporting [50].

- **AMC**: provides a link adaptation scheme. After getting the CQI report, the eNodeB will select the proper Modulation and Coding Scheme (MCS) to maximize the Transport Block Size (TBS) with the given Block Error Rate (BLER) Target. The larger TBS is, the higher the expected L1 data rate is [12].

- **HARQ**: The procedure of HARQ is based on the stop-and-wait algorithm by sending ACK/NACK messages, which indicates that the packet can be received and decoded successfully or not. Whereas, the eNodeB will retransmit the packet again and wait the ACK message until a successful decoding is advised [12].

The 3GPP technical specification does not introduce a detailed design of the multi-user scheduling scheme at the MAC layer. However, a generic procedure for downlink packet scheduling done every Transmission Time Interval (TTI) (i.e. 14 LTE symbols = 1ms) based on upper layer QoS requirement, CQI reporting, historic resource allocation and the queueing buffer status works as follows [11]:

1. The UE computes the CQI values based on the decoded reference signal, then send it back to the eNodeB;
2. The eNodeB retrieves the CQI values and maps them to the RBs;
3. AMC selects the best MCS that is used for data transmission by the served users based on CQI;
4. Based on upper layers requirements, UE information, the allocated RBs and selected MCS, the scheduling decision is sent to the UEs on the Packet Downlink Control Channel (PDCCH);
5. The served UEs receive the PDCCH information, and access the corresponding scheduled Packet Downlink Shared Channel (PDSCH).

3GPP allows the operators to define their own customized scheduling schemes by changing the MCS selection and priority of RBs allocation according to their own requirements, such as QoS, application types, class of served users.

2.1.3 Overview of Future Mobile and Wireless Networks

After the first release of Long Term Evolution in 2008, researchers expectedly ponder "what's next on the future wireless network?" [51]. The targets for next wireless communication technology have been more and more distinct so far: 1000×LTE-A Capacity/km^2, 100×LTE-A L1 Speed (i.e. 10Gbps), much lower latency (i.e. $\leq$1ms) and 100× energy and link cost reduction [52]. The next mobile and wireless network, called 5G, will consist of a multi-RAT environment, also referred to as Heterogeneous Networks (HetNets) environment. Several key candidate technologies are envisioned for the 5G environment as follows:

- **Small Cells and Densely Distributed Networks** - An extremely effective way to increase the network capacity is through small cells deployment. By using frequency reuse and cooperative interference limited solution, the cell edge data rate of the densely distributed networks will be increased by 50% when the network density is doubled [52].

- **Multi-RAT and Data Offload** - Cognitive radio based cooperative solutions can utilize the different spectrum bands of RATs (e.g. LTE/LTE-A, 3G, WLAN and WiMAX) in the heterogeneous network environment. The other solution is the data IP offloading from cellular network to wireless network, which does not change the current network architecture.

- **Millimeter Wave** - Because of the strict limitations of spectrum resource over microwave, the 5G carrier will extend from several hundred MHz to GHz (e.g. 30-300GHz). Higher frequency results in larger capacity but at the cost of higher power consumption and smaller propagation coverage. This could be beneficial in the Small Cell deployment.

- **Massive MIMO** - MIMO has been widely used in current LTE/LTE-A networks, which makes use of a number of antennas at base station and mobile devices to improve the spectrum efficiency. Moreover, a large scale antenna system, massive MIMO, will lead to higher spectrum efficiency with simpler structure and lower complexity due to the quasi-orthogonal nature of the channel between BS and users.

- **New Air Interface Technology** - The OFDM and OFDMA provide advantages on the current signalling format for high-speed wireless communication, forming the air interface technologies of current WiFi standards and LTE/LTE-A. However, OFDM/OFDMA achieves higher peak-to-average-power and could improve its spectrum efficiency if the strict orthogonality would be released and the cyclic prefixes would be shorter or removed. Therefore, there are some potential air interface technologies that can fit the 5G requirement, such as Filter Bank Multi-Carrier (FBMC) [53], Universal Filtered Multi-Carrier (UFMC) [54], Generalised Frequency Division Multiplexing (GFDM) [55], Filter-OFDM (SCMA) [56] and Vandermonde-subspace Frequency Division Multiplexing (VFDM) [57].

- **Cloud-based Networking** - The future of mobile and wireless networks is represented by software defined and virtualized [52]. Software Defined Networks

(SDN) separate the control and data/user plan in the current network architecture by using the programmable Open Flow protocol, which makes the network deployment more scalable and flexible. Network Functions Virtualization (NFV) allows the traditional telecom hardware running on software applications on a cloud based infrastructure or data center, which makes the network architecture more "open" and cost-efficient. SDN and NFV will be the key enablers for the next generation of core network management.

Apart from the above mentioned features, 5G will integrate vertical applications, such as IoT, Smart Grid, Intelligent Transportation System (ITS) and Smart Cities.

2.2 Mobile Data Offloading

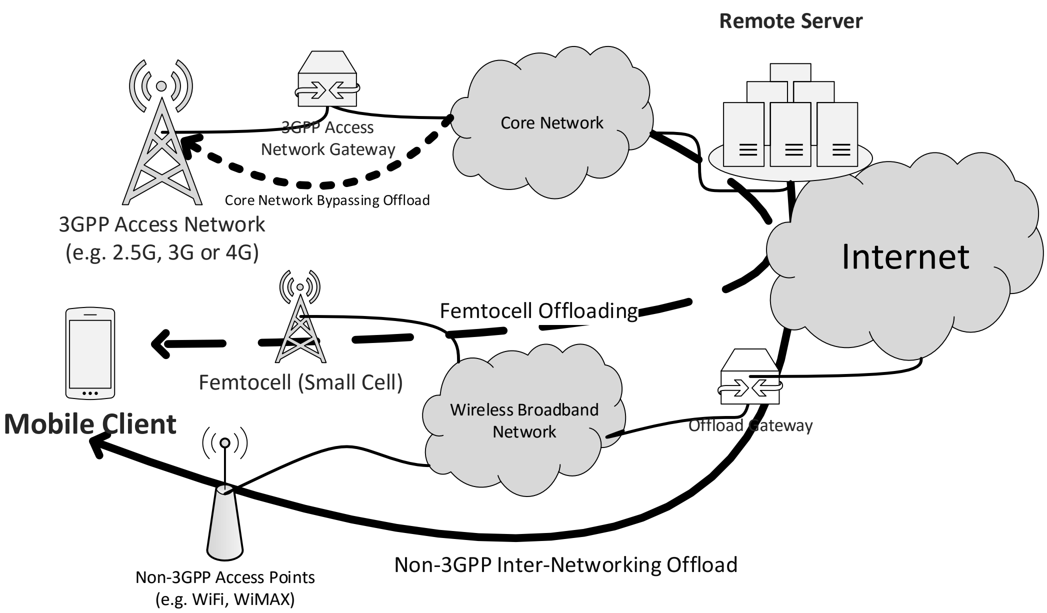


Figure 2.5: Mobile Data Offloading

The 3GPP 4th generation cellular technologies LTE (Release 8) and LTE-Advanced (Release 12) networks have been commercially launched and adopted by many network carriers and vendors. 216 commercial LTE networks were deployed by 2013, and the number of LTE subscriptions reached up to 126.1 million with 350% annual growth [58]. Additionally, the adoption of the femtocell technology for UMTS and WiMAX [59] is aimed at improving the coverage, capacity and reliability of the traditional macrocells. Furthermore, the LTE femtocell technology will be integrated into the LTE-A systems

Table 2.5: 3GPP Data Offloading Working Specification

3GPP TS	Initiative Names	Date of Start	Latest Release	Description
TS 23.234	I-WLAN	2004-03-24	Rel-11	Accessing 3G Services on WiFi Access Networks
TS 43.318	UMA/GAN	2005-01-28	Rel-11	Running GSM/other Cellular Access Network on WiFi unlicensed Spectrum
TS 23.919	Direct Tunnel	2007-06-13	Rel-11	3G SGSN bypass for user-plane traffic between RNC and GGSN
TS 24.312	ANDSF	2008-10-17	Rel-12	The Enhanced Entity of EPC to assist UE to access non-3GPP Networks (i.e. WiFi/WiMAX)
TS 22.220	Femtocell	2008-09-24	Rel-11	Core Network Traffic Offloading to Residential Small Cell within Licensed Spectrum
TS 23.829	LIPA/SIPTO	2009-11-03	Rel-10	Offloading Gateway Solution only working for HeNB
TS 23.261	IFOM	2009-12-11	Rel-11	The UE can maintain the data sessions with the same PDN connection simultaneously over a 3GPP and a WiFi network
TS 36.461-465	LTE Xw	2015-09-01	Rel-13	new LTE and WLAN coexistent working structure design from L1 to Transport Layer

in the foreseeable future. However, with the rapid evolution towards next generation cellular networks, the network operators will face the problem of high infrastructure deployment cost. Therefore, a cost-efficient high-capacity enabler technique, WiFi offloading, has been a key area of study in 3GPP Release-10 [60]. Moreover, there are many other possible inter-networking offloading approaches that have been proposed by 3GPP, as shown in Figure 2.5. The following subsections will introduce the current ongoing offloading projects from research and industry.

2.2.1 3GPP Offload Initiatives

In the 3GPP working projects, there are several studies on data offloading solutions which are defined to work in conjunction with non-3GPP access networks. Recently, a LTE and WLAN coexistent working design was published by 3GPP in Release 13 [61], which provides the design of the new structure from L1 to transport layer. However, this project is still ongoing and has no more details so far. Some examples are listed in the Table 2.5 and described as below.

2.2.1.1 I-WLAN

In early 2004, the 3GPP TS 23.234 [62] showed that the Interworking WLAN (I-WLAN) is defined as the standard for the interworking between 3GPP networks and Wireless LAN, which enables the mobile network operators to offer WiFi with the same security, authentication, experience and services as over their cellular networks. I-WLAN allows the SIM-based User Equipment (UE) to access both trusted cellular base stations and unmanaged/untrusted WiFi hotspots. Moreover, I-WLAN mechanism not only provides a remedy for IP-based services to the operators network congestion, but aims to solve the security, authentication and roaming issues of data offloading from 3GPP systems to WLAN networks. Therefore, I-WLAN provided useful pointers for the SIM-based authentication and charging policy for the subsequent offloading approaches in research area, which is still an important ongoing project in 3GPP working specifications.

2.2.1.2 UMA/GAN

Initially, a novel generic telecommunication system [63], namely Generic Access Network - GAN/UMA (prior to Unlicensed Mobile Access - UMA before April 2005), allowed GSM/GPRS users to access the unlicensed spectrum network (e.g. Bluetooth, WiFi) via the GAN control (i.e. the SIP-based Gateway). The mobile users were able to continue their circuit-switch-based voice and data services on the IP-based network seamlessly. The difference between GAN and I-WLAN is GAN is the telecom system-level implementation for offloading between cellular networks and Wireless LANs, whereas I-WLAN only provides the authentication and roaming policy for seamless handover between 3G and WiFi. In the future, I-WLAN could be an enhanced supplement function implemented in GAN/UMA.

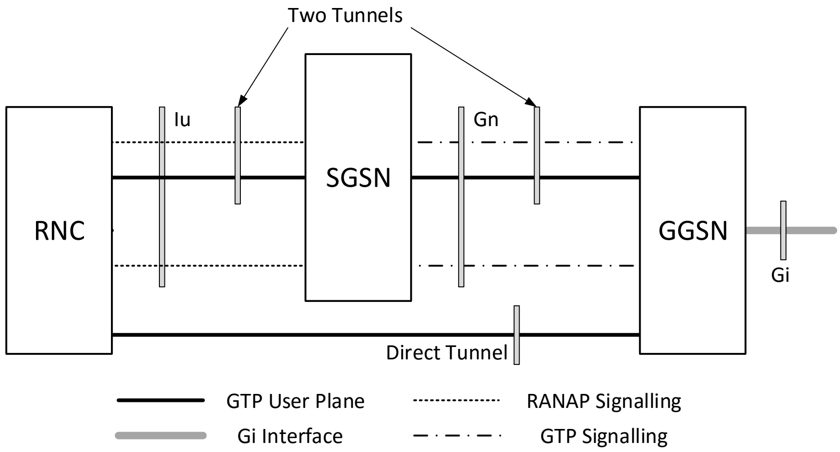


Figure 2.6: Direct Tunnel [13]

2.2.1.3 Direct Tunnel

In evolved packet core network in 3G, Direct Tunnel has been an important feature on the **Iu interface** (the interface between Radio Network Center and Core Network) that allows the SGSN to be bypassed by the direct user plane tunnel between GGSN and RAN within the packet-switched domain [13]. The typical difference between 2G PS domain and the 3G domain is the Iu packet-switched interface implemented between RNC and SGSN in which the control plane and user plane (i.e. control signalling and data traffic) are able to work separately. As shown in Figure 2.6 [13], the original packet core of 3G, both the control plane and the user plane are working on the connection RNC-SGSN-GGSN, namely Two-Tunnel (Dual-GTP Tunnel). However, the Direct Tunnel is established between GGSN and RNC in which only the user plane is working, and the control plane continues to use Two-Tunnel. Therefore, it is convenient and cost-efficient for operators to upgrade from traditional 3G to 4G. So far Direct Tunnel has been an essential offloading approach within 4G packet core network.

2.2.1.4 ANDSF

Access Network Discovery and Selection Function (ANDSF) is a key network element within Evolved Packet Core (EPC) of System Architecture Evolution (SAE) in 3GPP 4G/beyond 4G [64]. ANDSF aims to assist UE to access non-3GPP access networks, such as WiFi, CDMA2000 and WiMAX, which can be used for IP-based services in addition to LTE or HSPA. ANDSF provides discovery, selection and mobility management for accessing non-3GPP networks. Moreover, ANDSF requires Open Mobile

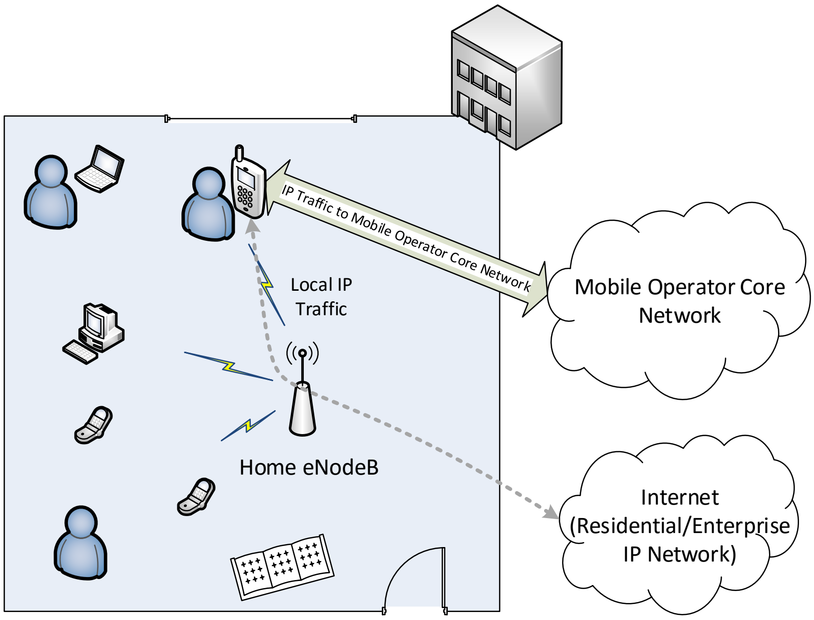


Figure 2.7: Local IP Access in Femtocell

Alliance Device Management (OMA-DM) Management Object (MO) support on mobile devices [65]. OMA-DM is the device management protocol created by Open Mobile Alliance, which configures devices, as well as performs the software synchronization.

2.2.1.5 Femtocell

Femtocell is the small, power efficient access solution in addition to the cellular access network, typically designed for use in small business or residence area. Femtocell belongs to the set of Small Cells [66]. It is connected to the service providers network via broadband, which allows the network operators to extend their cellular coverage indoor or at the cell edge. The concept of Femtocell defined in [67] is applicable to all standards, including GSM, 3G and 4G/LTE. The 3G base station of Femtocell is called Home NodeB (HNB) and Home eNodeB (HeNB) for 4G. The HNB/HeNB with integrated offloading gateway extends the macro cell coverage, reduces the core network traffic load and improves battery lifetime for mobile devices with closer distance. Additionally, the IP capable UE is able to immediately communicate with other IP capable devices which are working in the same Residential/Enterprise IP network via the HNB/HeNB, as illustrated in Figure 2.7 [67].

2.2.1.6 LIPA/SIPTO

Local IP Access (LIPA) and Selected IP Traffic Offload (SIPTO) are handled in the 3GPP TS 23.829 LIPA_SIPTO work item [68]. LIPA is a function entity that enables the UE connected to H(e)NB, enable to transfer the data to a local network connected to the same H(e)NB system immediately, without the traffic traversing the macro cellular network. The scenario of LIPA in residential/Enterprise IP network is illustrated in Figure 2-4. Also, the UE with LIPA is capable to access any external network which is connected to that local network. However, LIPA is only working for H(e)NB access within the Small Cell, not for macro cell access. The offload with LIPA is at the granularity of Access Point Name (APN) and Closed Subscriber Group (CSG) [60]. On the other hand, SIPTO is a method to reduce the load on the core system by offloading the IP traffic from H(e)NB access or cellular network to a local network. The destination network could be a H(e)NB or another cellular gateway that is closer to the communicated UE. SIPTO can be also exploited in the UE mobility scenario. Compared to LIPA, SIPTO is working between Macro Cellular access network and the Small Cell networks (e.g. Femtocell HeNB).

2.2.1.7 IFOM

IP Flow Mobility (IFOM) provides seamless WLAN offload between 3GPP and WLAN based on Dual Stack Mobile IPv6 (DSMIPv6) protocol [69]. Therefore, it can be used for setting up data sessions with the same PDN connection simultaneously over 3GPP and a WiFi network. Additionally, it is able to offload data in both direction 3GPP to non-3GPP access and vice versa. So far, IFOM has been a key function entity interworking with other offloading frameworks (e.g. I-WLAN, ANDSF).

2.2.2 Discussion

I-WLAN and GAN/UMA are telecommunication level frameworks which require significant changes in the current packet core and access systems. However, ANDSF, LIPA/SIPTO and IFOM are flexible and efficiently to interwork with current telecommunication system, such as GPRS, 3G and 4G. Additionally, Direct Tunnel is the low-cost entity deployed for network operators on the upgrade of core system from current 2G/GPRS to 3G, or even 4G. Therefore, ANDSF, LIPA/SIPTO and IFOM will play important roles in the future mobile networks.

2.3 Multimedia Content Delivery

Internet access is becoming a commodity on mobile devices. With the recent popularity of smartphones, smart wearable devices and other mobile devices the Mobile Internet is dramatically expanding. At the same time, mobile users expect high-quality video experience in terms of video quality, latency, lifetime of battery and video content. 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 distortion, wireless channel congestion, 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 outage. The aim of these mechanisms is to maintain high user perceived quality levels and make efficient use of the wireless network resources.

2.3.1 Multimedia Streaming Protocols

Most of the multimedia streaming services are built on the transport and application layer protocols. Some well-known application layer protocols supporting multimedia streaming are summarized in Table 2.6. In this thesis, Real-Time Transport Protocol (RTP), Real-Time Streaming Protocol (RTSP) and Hypertext Transfer Protocol (HTTP) are used in the real experimental test-bed. RTP provides end-to-end real time data delivery based on UDP. However, the multimedia service based on RTP has no QoS guaranteed, transmission control or data protection. Mostly, RTP is working in conjunction with other protocols, such as RTP Control Protocol (RTCP) and RTSP. RTCP enables the transmission monitoring over RTP. RTSP guarantees the QoS and data security. HTTP is widely used for file download and non-real-time multimedia streaming based on TCP. Moreover, HTTP supports reliable streaming functions, for example authentication, higher security and guaranteed transmission. Therefore, many live streaming services are based on HTTP, such as live chat system, online gaming and remote monitor consoles. However, RTSP is fast, and has lower latency than HTTP.

Table 2.6: Well Known Multimedia Streaming Protocols

Protocol Names	Standards	Transport Layer	Ports	Security	Descriptions
RTP, RTCP	IETF RFC 3550, 3605	TCP, UDP	TCP port: 80 or 554, UDP ports: 6970 ∼ 9999	No security and protection, needs alternative solution	RTP provides end-to-end real-time multimedia on-demand delivery and RTCP is used to monitor transmission and control the QoS. While RTP uses even-numbered UDP port, RTCP uses next higher odd-numbered port
SRTP, SRTCP	IETF RFC 3711	TCP, UDP	TCP port: 80 or 554, UDP ports: 6970 ∼9999	Data Encryption	Provides data protection over the transmission based on RTP and RTCP
RTSP	IETF RFC 2326	TCP, UDP	TCP port: 554, UDP ports: 554	Safer than RTP	RTSP establishes Client-Service real time streaming service based on RTP. The protocol can control the media session between the sender and receiver. RSTP also allows the implementation of rate adaptation
RTMP, RTMFP	Adobe	RTMP: TCP; RTMFP: UDP	TCP port: 1935, UDP ports: 1024 ∼ 65535	Data protection but very weak	RTMP and RTMFP provide multimedia streaming service. However, RTMP is used for video broadcast and no QoS guaranteed. RTMFP is able to transmit adaptive stream and supports QoS control and fast retransmission, which is of benefit to P2P live streaming
HTTP/1.1, HTTP/2	IETF RFC 7230, 7540	TCP	80	mostly safe	HTTP provides non-real time multimedia streaming and file download caching.

2.3.2 Adaptive Multimedia Streaming Standards and Industrial Solutions

One of the hot topics in the multimedia networking environment is adaptive streaming, because adaptive streaming solutions are able to cope with the limited wireless resource issues, provide a seamless connection within multimedia content delivery and maintain a good perceived quality of multimedia to mobile users. In this section, the current standards and industry solutions of adaptive streaming are introduced.

In TS 26.234 [70] (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 [71]. The new streaming system consists of storage, transport, and media rate adaptation to available link bit rate. The stream content is divided into media segments that are identical for all users. It is assumed that the HTTP streaming client has access to a Media Presentation Description (MPD) which contains content period, representation and segment description. 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.

The non-profit consortium and standardization organization, **Open IPTV Forum (OIPF)**, proposed an open and free **HTTP Adaptive Streaming (HAS) solution** which is based on the 3GPP AHS specifications [72]. In the case of HAS, the terminal may be able to adapt to the variations in the available bandwidth by seamlessly switching between the encoded segment at higher or lower bitrate. The new HAS method is an extended version of 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** [73]. 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 better support for Content Delivery Network (CDN) - based delivery.

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.

In 2005, **Move Networks** was granted a patent [74], **Apparatus, System, and Method for Adaptive-rate Shifting of Streaming Content**. 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 competitor in the market is **Microsoft Hypertext Transfer Protocol** with its **IIS Smooth Streaming solution**. In August 2011, Microsoft was granted a patent on “Seamless Switching of Scalable Video Bitstreams” [75] . 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 deployed a dynamic streaming service on its own flash media delivery platform [76], 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 up-scaling or down-scaling between the different quality levels, delivering a smooth and seamless service to users. This also aims to provide the best possible user experience their bandwidth and local computer hardware (CPU) can support.

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, as part of QuickTime X and iOS. The video content is segmented into small MPEG-TS files of different duration and bitrate and is adaptively streamed to the client, which also supports live and on-demand content.

One of the online video service providers in US, **Hulu**[1], offers on-demand TV shows, movies, clips, news, etc. Hulu integrated the adaptive bitrate streaming mechanism into their new Hulu player, written in Adobe Flash API (ActionScripts). Three different versions encode video clips with bitrates ranging from 640 kbps up to 1.6 Mbps with resolution from 288p up to 480p, can be adapted by the streaming-switching approach automatically or set by the users manually. Additionally, **upLynk**[2], one of the stream-

[1]Hulu: `http://www.hulu.com/`
[2]UpLynk: `http://www.uplynk.com`

ing players presented by Disney ABC television, can work on multiple platforms, such as iOS, Android, Windows 8, Roku and all PC/Mac/Linux browsers.

Recently, the emerged technology, HTML5 provides the $\langle audio \rangle$ and $\langle video \rangle$ tags which allow JavaScript to control the playing of the multimedia content. However, this is only specified on the application layer and there is no lower layer mentioned, which supports the free implementation according to the specific requirement based on the web API. Similar to HTTP-based streaming, HTML5 streaming will download the content progressively and keeps downloading completely even if the player is paused. So far, **Youtube** [77] and **Netflix** [78] have supported the default HTML5 video streaming.

2.4 Quality of Service and Quality of Experience

2.4.1 Introduction to QoS and QoE

End-to-end Quality of Service (QoS), first introduced by ITU-T E.800 in 1994 [14], represents a set of common key characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service. In the telecommunication system, several components contribute to end-to-end QoS, as illustrated in Figure 2.8. Basically, the contribution to end-to-end QoS depends on the service provider configuration, variability of the performance of the terminal equipment, and the access medium and technology.

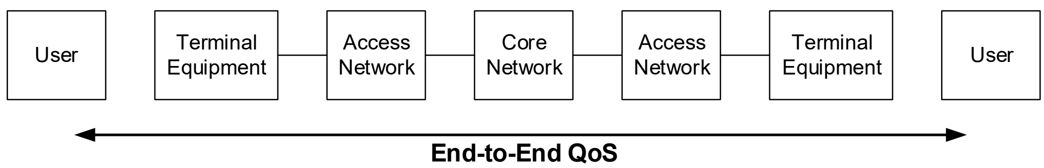


Figure 2.8: Contributions to end-to-end QoS [14]

In particular, QoS comprises both network performance and non-network related performance. For non-network performance, provision time, repair time, range of tariffs and complaints resolution time are considered. Regarding the network performance, a set of common QoS characteristics includes latency, packet jitter, bit error rate and packet loss ratio.

- **Latency** - Generally, the wireless multimedia communication latency comprises mechanical latency and network latency. The mechanical latency normally depends on the hardware/software performance of end-point terminals (e.g. multimedia server and user equipments) which is applied to time required by the CPU processing, multimedia encoding/decoding. The network latency is defined as the duration between the first bit of a packet sent from the transmitter and the last bit arriving at the receiver [79], which could be divided into several parts: (1) Processing delay - time to process the packet header; (2) Queueing delay - time for packet routing; (3) Transmission delay - time to transmit the bits to the link; (4) Propagation delay - time for the signal transmitted over the medium (e.g. air, fibre, cable and others).

- **Packet Jitter** - is the variation of network delay/latency, namely IP Packet Delay Variation Metric (IPDV) defined in RFC 3933 [80]. Packet Jitter measures the delay difference between two selected packets.

- **Bit Error Rate (BER)** - In digital communication systems, BER is the number of bit errors per unit time which are affected by the channel noise, interference, distortion wireless multipath fading and so on. Generally, BER is a key characteristic of network channel condition.

- **Packet Loss** - is the number of dropped packets occurred during the transmission which is caused by the link congestion, buffer overflow, network connection failure, channel fading and collision occurrence over the medium. It is generally measured as a percentage of the total sent packets.

- **Available Bandwidth** - is another important factor to determine the network performance at the user side. For example, bandwidth estimation scheme in many data transfers will transmit a pilot packet to measure the current channel bandwidth status.

Different application services require various QoS guarantees on delay, jitter and packet loss ratio. Table 2.7 summarizes some QoS related requirements of different application services introduced in ITU-T G.1010 [81], ITU-T Y.1541 [82] and IETF RFC4594 [83], respectively.

In addition, the latest LTE standardization guidelines define the QoS class of Identifier (QCI) for various network application services [3], as illustrated in Table 2.8.

Table 2.7: IP Network Performance Objectives of Multimedia

		Tolerance to		
Network Application and Services	Flow Behaviour	Loss	Delay	Jitter
Network Control, Signalling	Inelastic	Low, < 0.1%	Low, < 100ms	High
VoIP	Inelastic	Very Low, < 0.1%	Very Low, < 50ms	Very Low
Multimedia Conferencing	Inelastic	Low - Medium, < 0.1%	Very Low, < 50ms	Low
Real-time Interactive (e.g. online Gaming)	Inelastic	Low, < 0.1%	Very Low, < 50ms	Low
Multimedia Streaming	Elastic	Low -Medium, < 0.1%	Medium, < 1s	High
Broadcast Video	Inelastic	Very Low, < 0.1%	Medium, < 1s	Low

On the other hand, QoS can be divided into two viewpoints: Service Provider and Customer. From service provider's view, it is similar to the network performance mentioned above. Whereas, it is more complicated to measure QoS from customer's view, namely QoS experienced by the end-user (QoSE) [14]. Currently, this kind of idea can be expressed by **Quality of Experience (QX, QoX, or QoE)**. QoE can be influenced by the delivered QoS network performance and also the psychological factors of end-user perception in different environment with a service (phone call, web browsing, TV and movie streaming, etc). QoE is the key factor to measure the quality of application service, which is focused on understanding the overall human quality requirement based on social psychology, cognitive science, economics, and engineering science.

In the next subsection, the detail about video quality assessment in wireless multimedia streaming will be presented, in terms of QoS and QoE.

2.4.2 Video Quality Assessment in Wireless Multimedia Streaming

Traditionally, video quality assessment makes use of objective QoS parameters, such as throughput, transmission delay and packet loss monitored by the service providers. Currently, subjective QoE experiment [20] become the widely used methodology in video quality assessment in terms of the view expected by the customer. Recently, objective quality models have been developed for video quality assessment in order to

Table 2.8: LTE QCI Characteristics [3]

QCI	Resource Type	Priority Level	Packet Delay Budget	Packet Error Loss	Example Services
1	GBR	2	100ms	10^{-2}	Conversational Voice
2		4	150ms	10^{-3}	Conversational Video (Live Streaming)
3		3	50ms	10^{-3}	Real Time Gaming
4		5	300ms	10^{-6}	Non-Conversational Video (Buffered Streaming)
65		0.7	75ms	10^{-2}	Mission Critical user plane Push To Talk voice (e.g., MCPTT)
66		2	100ms	10^{-2}	Non-Mission-Critical user plane Push To Talk voice
5	Non-GBR	1	100ms	10^{-6}	IMS Signalling
6		6	300ms	10^{-6}	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100ms	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
8		8	300ms	10^{-6}	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
9		9			
69		0.5	60ms	10^{-6}	Mission Critical delay sensitive signalling (e.g., MC-PTT signalling)
70		5.5	200ms	10^{-6}	Mission Critical Data (e.g. example services are the same as QCI 6/8/9)

avoid the high cost of subjective tests. Data-driven video assessment has emerged as a promising way to measure QoE features by considering user viewing time, probability of interruption or return, etc., which is widely used by commercial broadcast television corporations (e.g. FOX, NBC) and on-demand streaming service providers (e.g. Netflex, Hulu, Youtube). The comparison of these video quality assessment methods is illustrated in Table 2.9 [84].

Conventionally, **subjective test methods** directly ask the test participants (assessors) to give their scores for the quality of the video under the experiments. Generally, the subjective experiment can be divided into four steps as illustrated in Table 2.10.

In the first step, the test environment (e.g. home, laboratory) and equipments

Table 2.9: Comparison of Video Quality Assessment Methods

	Direct Measure of QoE	Objective or Subjective	Real-time	Wide application	Cost
QoS Monitoring	No	Objective	Yes	Wide	Not sure
Subjective Test	Yes	Subjective	No	Limited	High
Objective Quality Model	No	Objective	Yes/No	Limited	Low
Data-driven Analysis	Objective	Yes	Yes	Wide	Not Sure

Table 2.10: Steps of Subjective Test

1. Test Preparation	2. Execution	3. Data Processing	4. Results Presentation
• Test Environment and equipment setup • Video source selection and processing • Test Participants Recruitment	• Double-Stimulus Continuous Quality Scale Method • Double-Stimulus Impairment Scale Method • Single-Stimulus Method • Stimulus-Comparison Method	• Check Data completeness • Outlier Detection • Data Screening	• Test configuration • Video information • Participant information • Results and analysis

(e.g. screen size, luminance) are prepared in advance, and then the video (e.g. source, spatial or temporal features) and encoding characteristics (e.g. bitrate, packet loss rate, encoding format and containers) are selected. In addition, at least 15 non-expert participants should be recruited for the test [85]. There are several methods used for subjective test execution. In this thesis, the Single-Stimulus (SS) Scaling method is chosen, which shows each processed video for the participants randomly only one time and then asks the participants to give their Mean Opinion Score (MOS) scores (e.g. 5-grading, 9-grading or 100-grading). A simple procedure is shown in Figure 2.9. Finally, the test results will be processed and presented.

To avoid the cost of subjective testing, the **objective quality models** were developed for QoE prediction. Generally, the objective quality models are classified as Full Reference (FR) Model, Reduced Reference (RR) Model and No-Reference (NR) Model.

- **Full Reference Model** - Requires access to the full original video source by

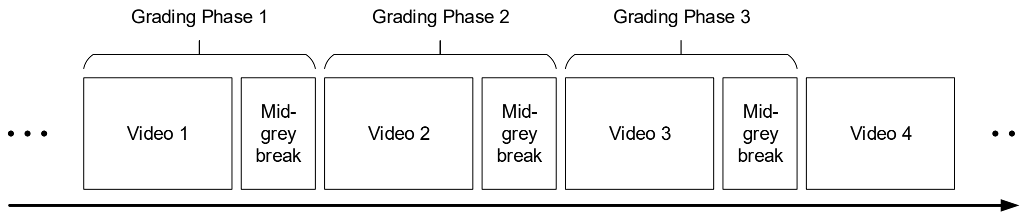


Figure 2.9: Single-Stimulus Video Presentation and Grading

taking into account the metrics of video, such as pixel-based signal, contrast sensitivity, frequency selectivity, spatial and temporal features, blockiness and so on. For instance, Mean Squared Error (MSE), Peak Signal-to-Noise Ratio (PSNR) [86], Moving Picture Quality Metric (MPQM) [87], Perceptual Video Quality Measure (PVQM) [88] and Structure Similarity (SSIM) [89], etc.

- **Reduced Reference Model** - Requires access to the partial information of the original video source. For example, in [90] [91], the packet loss visibility based models indirectly measure the video quality by detecting the visible packet loss. However, it is difficult to classify what kind of packet loss is visible and what kind is invisible.

- **No-Reference Model** - It is convenient to meet the demand of real-time video quality monitoring by using no-reference models which are based on the network-related or application-specific characteristics (e.g. throughput, packet loss, encoding bitrate, frame rate). In [92], the QoE no-reference prediction model uses a logarithmic relationship between source encoding bitrate and received video bitrate. The authors in [93] take into account the UMTS network distortion and predicts the QoE metric by using the transmitted bitrate, block error rate, mean burst length and the content types.

In this thesis, the Peak Signal-to-Noise Ratio (PSNR) is adopted for objective video quality estimation and comparison. The original computation of PSNR is shown below:

$$PSNR = 10 \log_{10} \frac{MAX^2}{MSE} \tag{2.1}$$

with

$$MSE = \frac{1}{|\mathbf{M}||\mathbf{N}|} \sum_{m=1}^{|\mathbf{M}|} \sum_{n=1}^{|\mathbf{N}|} [x(n,m) - y(n,m)]^2 \text{ and } n \in \mathbf{N}, m \in \mathbf{M} \tag{2.2}$$

Where $x(n,m)$ is the sample of the orignal source signal, $y(n,m)$ is the distorted video signal, MAX is the maximum source signal value, and **M** and **N** are the row and column of pixels of video frame, respectively. In order to estimate the video quality over the wireless network transmission more conveniently, [94] simplifies (2.1) - (2.2) to the equation shown below:

$$PSNR = 20 \cdot \log_{10}\left(\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)^2}}\right) \tag{2.3}$$

where $MAX\_Bitrate$ is the average encoded bitrate of the video traffic, EXP_Thr is the average throughput expected to be achieved when delivering the adaptive video traffic and CRT_Thr is the actual measured throughput during the transmission.

2.5 Introduction to Game Theory and Utility Function

Game theory provides a set of mathematical models to study the complex interaction among intelligent rational decision-makers [95] [96], which has found applications in Economics, Engineering, Sociology, Political Science, Philosophy, Psychology, etc. In general, Game Theory can be classified into two branches: non-cooperative and cooperative game theory:

Non-cooperative Game Theory - focuses on the research issues resulting from the interaction among the competing players. The current well-known method to solve this type of problem is Nash Equilibrium [97]. Basically, it enables to model some widely used game theoretic approaches, such as Prisoner's Dilemma, Bargaining Game, Trading Market and Stackelberg competition, etc. A mainstream of studies in the current wireless communication network field makes use of non-cooperative game theory to solve networking problems, with the main focus on resource allocation [98] [99], power control [100] [101], network selection [102] [103], spectrum sharing in cognitive radio [104] and congestion control [105].

Cooperative Game Theory - Different from the competitive scenarios studied in non-cooperative game theory, cooperative game theory focuses on the issues of rational players' behaviour when they cooperate. Generally, it describes a formation of a group of cooperative players as a "**coalition**" [95] also referred to as Coalition Game. Coalition games provide very robust, practical and efficient strategies in resource allocation.

However, there are a few challenges, such as complexity, fairness, especially when developed on a large scale wireless network environment. The well-known approaches modelled by the cooperative game theory are the Talmud's asset allocation and the bankruptcy problem [106].

Utility function is an important tool used in Game theory, to model plays' motivations. Higher utility values mean that the outcome for the player is more preferred [107]. In wireless communication area, the utility function is designed to reflect the application services' elasticity degree or user tolerance with respect to QoS network performance [108] [109]. In general, the forms of utility function can be simply divided into three types, as illustrated in Figure 2.10 [4].

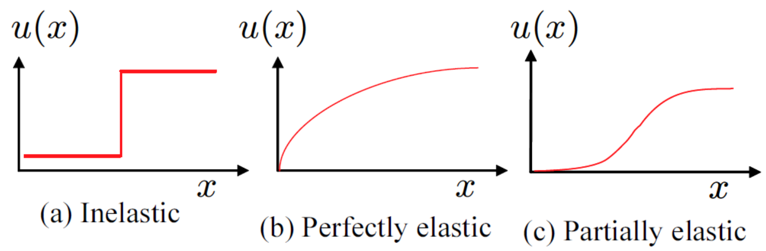


Figure 2.10: Utility Function vs. Application Service's Elastic Degree

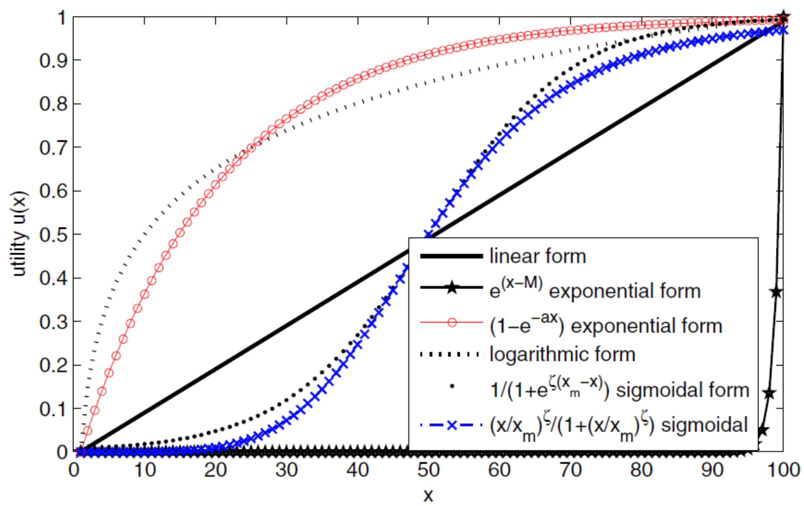


Figure 2.11: Utility Function Forms (Partially Elastic) [4]

- **Inelastic Form** - See Figure 2.10 (a). The real-time voice and video application

Table 2.11: Existing Well-known Utility Function Forms [4]

Utility Forms	Generalized Mathematical Formula	Increasing & Differ-entiability	Concavity	Convexity
Linear piecewise	$u(x) = \begin{cases} 0 & x < x_{min} \\ \frac{x - x_{min}}{x_{max} - x_{min}} & x_{min} \leq x \leq x_{max} \\ 1 & \text{otherwise} \end{cases}$	Yes	No	No
Logarithm	$u(x) = \ln(x)$ or $u(x) = \ln(1 + ax) \quad a > 0$	Yes	Yes	No
Exponential	$u(x) = e^{x-m} \quad x \in [0, m]^*$ or $u(x) = 1 - e^{-ax} \quad a > 0^{**}$	Yes	Yes	*No, **Yes
Sigmoid	$u(x) = \frac{1}{1 + e^{\zeta(x_m - x)}} \quad \zeta, x > 0$ or $u(x) = \frac{(x/x_m)^\zeta}{1 + (x/x_m)^\zeta} \quad x_m > 0, \zeta \geq 2$	Yes	Yes	Yes

(e.g. VoIP, video conferencing) with constant bit rate are inelastic with respect to the requirement of available bandwidth or channel condition [108], as they usually need minimum/maximum bandwidth guarantee. It is generally represented by a step function.

- **Perfectly Elastic Form** - See Figure 2.10 (b). The non-real time applications (i.e. Multimedia streaming mentioned in Table 2.7) usually are perfectly elastic since they are assumed to be tolerant to the QoS performance, such as less delay sensitivity. The form of their utility function is concave.

- **Partially Elastic Form** - See Figure 2.10 (c). Different users set the different values to the applications and related QoS. Accordingly, partially elastic form fits the shape (e.g. "S" shape) of utility function representing the applications or services like real-time adaptive video streaming, non-real time data transfer [109] and network selection or handover. Such types of utility functions meet the most requirements in wireless communication by taking advantage of the characteristics of the prior two forms. In addition, this type of utlity function is suitable to model the behaviour of users [107].

Some well-known partially elastic forms of utility functions are plotted in Figure 2.11, and their characteristics are illustrated in Table 2.11.

2.6 Chapter Summary

This chapter presents the technical background of the research area which is referred by the corresponding proposed architecture design in this thesis. Four main areas of interest are covered:

- **Heterogeneous Wireless Environment** - the commonly used wireless technologies like IEEE WLAN and 3GPP 4G-LTE are introduced in detail. The downlink system framework of LTE is illustrated and its functionality is explained, as this represents the base for the packet scheduling scheme designed in following chapters.

- **Mobile Data Offloading** - The state of the art of data offloading standardizations are listed in this chapter. Mobile data offloading techniques are key features employed in the current and future next generation networks. The integration of mobile data offloading in the proposed "Always Best Experience" architecture is discussed in the following chapters.

- **Multimedia Streaming and its QoS/QoE Measure** - This chapter also presents the current adaptive multimedia streaming solutions and commercial products in the current industry. The QoS and QoE measurement methods are illustrated, which define a set of important characteristics used to evaluate the performance of the proposed architecture in this thesis.

- **Game Theory and Utility Function** - The fundamental information of Game Theory is introduced in the chapter as well as the methodology of utility functions are summarized. This represents an essential theoretical tool used to model the performance evaluation scenarios, aiming at optimizing the user requirement to meet the target of "Always Best Experience" vision.

Chapter 3

Related Works

This chapter introduces some recent related studies from three research areas: 1) Downlink Packet Scheduling Schemes for Radio Resource Management (RRM); 2) Adaptive video streaming solutions; 3) Current mobile data offloading test-beds and solutions. The chapter provides a comprehensive survey of the existing standards, industry solutions, and other approaches from the literature. The main challenges and remaining open issues that need to be addressed for next generation 5G networks are also discussed.

3.1 Downlink Packet Scheduling Research Area

Radio Resource Management (RRM) is the system level controlling mechanism in wireless communication systems, that handles the utilization of the limited radio-frequency spectrum resources by controlling the transmit power, resource allocation parameters, beamforming, throughput, modulation coding schemes or handover criteria. In terms of network based functions [110], RRM methods consist of Admission Control (AC), Load Control (LC), Packet Switch (PS), and Resource Management (RM). The main focus in this thesis is on the downlink packet scheduling mechanisms. The current downlink packet scheduling schemes can be divided into three main categories: channel-unaware, channel-aware and hybrid schemes. The hierarchical relationship of the scheduling schemes is illustrated in Figure 3.1.

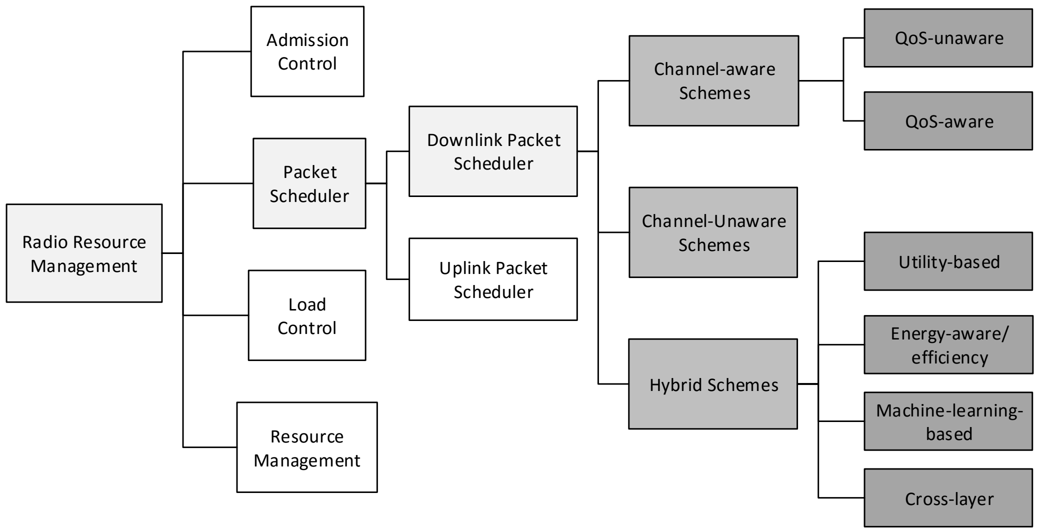


Figure 3.1: Hierarchical relationship of the Radio Resource Management (RRM)

3.1.1 Channel-unaware Scheduling Schemes

Channel-unaware scheduling schemes were first introduced in the general scheduling rules for wired networks [111] [112], being based on the assumption of time-invariant and error-free services. Therefore the standalone channel-unaware scheduling schemes are inapplicable in realistic networks. Typically they are used in combination with channel-aware/QoS-aware scheduling schemes to improve system performance. Hence some basic channel-unaware strategies will be presented in the following paragraphs. Some of the frequently used scheduling parameters are defined in Table 3.1

Table 3.1: Scheduling Metrics

Expression	**Meaning**
$p_{i,m}$	Scheduling priority metric of the i-th user on m-RB
$R_i(t)$	Instantaneous throughput of i-th user at time t
$\hat{R}_i(t)$	Past Long-term/historical average throughput of i-th user at time t
D_i^{HOL}	Delay of head of line of i-th user
$\mathcal{I}$	The set of users
$\mathcal{M}$	The set of RBs

3.1.1.1 FIFO/LIFO

FIFO/LIFO, namely First In First Out/Last In First Out, are the simplest allocation policies according to the order of service requests. They are used to translate the behaviour in LTE scheduling as shown below [113]:

$$p_{i,m}^{FIFO} = t - T_i \tag{3.1}$$

and

$$p_{i,m}^{LIFO} = t + T_i \tag{3.2}$$

where p is the priority metric of i-th user being allocated the m-th resource block; t is the current time and T_i is the time instance when the i-th user issued the service request. Therefore, channel conditions and QoS requirements are not considered by these techniques, which makes them inefficient and unfair.

3.1.1.2 Round Robin

Round Robin (RR) strategy is another one of the simplest early scheduling schemes introduced in [112]. According to the RR implementation in LTE simulator [114], the RR scheduler works by dividing the available resource blocks among the active flows. If the number of RBGs is greater than that of the active flows, all the flows can be allocated in the same subframe. Otherwise, if the number of the active flows is greater than that of RBGs, not all the flows can be scheduled in a given subframe. Then, the exceeding flows will be allocated into a subsequent one within a periodically repeated order. In this case, T_i of FIFO will be the length of one subframe. Thus, RR takes into consideration the fairness of the amount of time in which the channel is occupied by the users. However, in terms of user throughput which depends on the channel conditions, this strategy is unfair. Therefore, the realistic scheduler jointly works with RR by making use of the QoS constraints and channel conditions, to make it more efficient.

3.1.1.3 Weighted Rules

To avoid the possibility of resource starvation caused by simple scheduling schemes (e.g. FIFO/LIFO, RR), the weighted scheduling scheme represents an alternative. In the earlier bandwidth allocation solutions for Wired Network [115] [116], much research has been performed on the Weighted Fair Queuing (WFQ) algorithm. In this case, a specific weight (w_i) is given to the i-th user jointly working with the RR scheme, expressed as:

$$p_{i,m}^{WFQ} = w_i \cdot p_{i,m}^{RR} \tag{3.3}$$

where $p_{i,m}^{RR}$ is the RR specific metric for the i-th user. Moreover in wireless networks, a well-known Weighted Fair Queuing approach jointly combined with FIFO for CDMA-based networks was proposed in [117]. In this case, the largest shared resources are given to the user with the best instantaneous channel conditions. More information about the WFQ approach used in channel-aware or QoS-aware scheduling schemes will be introduced in later sections.

3.1.1.4 Resource Pre-emption Rules

Similar to the weighted rules, the rule based on resource gives the specific 'weights' for the users or the arriving services. But in this case, the resource pre-emption approach groups the queuing users into different classes before serving them. The users will not be served until those users belonging to the highest priority groups in the queue are empty. The resource pre-emption rule is always exploited by the applications (e.g. QoS-sensitive flows) that do not require fairness, which can avoid the starvation of low-priority applications (e.g. non-QoS flows).

3.1.2 Channel-aware Scheduling Schemes

In LTE systems, the scheduler can estimate the channel quality of each UE and predict the maximum achievable throughput by using the Channel Quality Indicator (CQI) which is periodically sent from UEs to the eNodeB/eNB. Here, let $r^i(t)$ and $r_m^i(t)$ be the achievable data-rate expected for the i-th user at the t-th TTI over the entire bandwidth and over the m-th Resource Block (RB), respectively. The value of achievable data-rate can be calculated using the defined Adaptive Modulation and Coding (AMC) model or the Shannon Estimation, as the numerical explanation based on wireless channel capacity shown below:

$$r_m^i(t) = \log\left[1 + SINR_m^i(t)\right] \tag{3.4}$$

Where $SINR^i_m(t)$ is estimated Signal-to-Interference-plus-Noise Ratio (SINR) of m-th RB for the i-th user at t-th TTI. According to the different requirements, the current scheduling strategies making use of the channel-aware characteristic can be further divided into two different types such as QoS-unaware and QoS-aware.

3.1.2.1 QoS-unaware Scheduling Schemes

In general, the QoS-unaware scheduling schemes are implemented in practical network systems widely because they are low-complexity and easy to be conducted. **Maximum Throughput (MT) scheduler** is one of the well-known QoS-unaware strategies in wireless networks, as introduced in [118]. MT aims to serve the users with the largest instantaneous achievable data-rate r^i to maximize the overall throughput in the current TTI. Therefore, the priority metric of MT can be simply expressed as:

$$p^{MT}_{i,m} = r^i_m(t) \tag{3.5}$$

MT is able to maximize the cell throughput, however, it causes an unfairness problem since the users with bad channel condition will only get a low available bandwidth which may lead to scheduling starvation. Hence, some fairness-aware scheduling strategies built based on MT were proposed in the literature. For example, the Proportional Fair (PF) scheme, a well-known and widely used scheduling scheme in wireless networking systems.

Before describing the PF scheduling scheme, it is necessary to introduce a basic important fairness-aware strategy mechanism, namely **Blind Equal Throughput (BET) scheduling scheme** [119]. The priority metric is calculated based on the historical average throughput perceived by the user. The mathematical expression of i-th user over m-th resource block at instantaneous time t can be given by:

$$p^{BET}_{i,m} = \frac{1}{\hat{R}_i(t)} \tag{3.6}$$

where $\hat{R}_i(t)$ is the historical average data-rate of i-th user. In order to guarantee that $\hat{R}_i(t)$ is not equal to zero, the expression of $\hat{R}_i(t)$ using a moving average can be calculated as [120]:

$$\hat{R}_i(t) = \alpha \cdot \hat{R}_i(t-1) + (1-\alpha) \cdot R_i(t) \tag{3.7}$$

where $R_i(t)$ is the instantaneous data rate of i-th user at t-th TTI and $0 \leq \alpha \leq 1$. Because of these properties, R_i will not reach zero and $\hat{R}_i(t)$ will always achieve the next round value even if the user had zero data transmission in the past or in the present. Actually, BET is widely used in most of the state of the art scheduling strategies. In this way, the users that had poor channel conditions or lower average throughput in the past can be allocated with higher priorities, which leads to guaranteed fairness of user throughput distribution at the expense of spectral efficiency.

In order to balance the requirements between fairness and spectral efficiency, the **Proportional Fair (PF) scheduling scheme** is merging the MT and BET. Thus, the priority metric can be expressed as:

$$p_{i,m}^{PF} = p_{i,m}^{MT} \cdot p_{i,m}^{BET} = \frac{r_m^i(t)}{\hat{R}_i(t)} \tag{3.8}$$

The priority metric shows that the historical average throughput can be a weighted factor of the achievable data rate, so that this can be a trade-off between the users with good channel condition and those with worse within a proper fairness time window. This fairness time window is related to the α mentioned in (3.5) and (3.7) and can be expressed as:

$$T_f = \frac{1}{1-\alpha} \tag{3.9}$$

Intuitively, the historical average throughput is equal to the last instantaneous data rate and $T_f = 1$ TTI when $\alpha = 0$. On the contrary, the historical average throughput is only equal to the last historical average throughput and the fairness time window is infinite when $\alpha = 1$ or approaches 1.

In [121], the PF can be broadened to **Generalized Proportional Fair (GPF) scheme** by introducing the weighted factor $\xi \in [0, \infty)$ and $\psi \in [0, \infty)$ as follows:

$$p_{i,m}^{GPF} = \frac{[r_m^i]^{\xi}}{[\hat{R}_i(t)]^{\psi}} \tag{3.10}$$

Therefore, three types of scheduling schemes can be described by changing the values of the weighted factors:

- If $\xi = 1$ and $\psi = 1$, (3.10) can be described as PF scheme;
- If $\xi = 1$ and $\psi = 0$, (3.10) can be denoted as MT scheme;

- If $\xi = 0$ and $\psi = 1$, (3.10) can be indicated as RR scheme;

Additionally, another interesting scheduling scheme, namely **Throughput to Average (TTA)**, represents a trade-off between MT and PF [119]. The priority metric is denoted as:

$$p_{i,m}^{TTA} = \frac{r_m^i(t)}{r^i(t)} \tag{3.11}$$

Intuitively, the instantaneous achievable data rate is normalized by the achievable wideband throughput $r^i(t)$. Since the higher the achievable wideband throughput of the user, the lower the metric will be on the single RB. This means the scheduler not only allocates the best resources to the user with the best channel conditions temporally at the current single TTI, but also considers the fairness of different users over the different RB at different single TTI.

In addition to the queueing scheduling solutions mentioned above, a generic sharing scheme for fair distribution of limited network resources that is widely used in wireless networks is the **Maxmin Fairness Scheduling (MFS) scheme** [122]. The basic idea of MFS is to allocate equal bandwidth to all users served at first. Then the residual resources are distributed among others if a user has not utilized its bandwidth. The total allocated resources strictly satisfies:

$$\sum_i \sum_m r_{i,m} \leq \mathcal{C}, \text{ and } \mathcal{C} \text{ is the total wideband channel capacity} \tag{3.12}$$

For example, consider four mobile users with downloading data rate demands of 2, 2.6, 3.9, and 5Mbps served by a single wireless network where the downlink capacity is 10Mbps. Using MFS, the overall capacity of 10Mbps is divided between the four users with each user getting 2.5Mbps. As this is greater than the first user demand, the residual 0.5Mbps will be distributed among the remaining three users and 0.167Mbps is appended to each user. Now, the 2.667Mbps is larger than the second user requirement, thus 0.0667Mbps is left for the other two users to share, resulting in $2.5 + 0.1667 + 0.0333 = 2.7$Mbps each. Thus, the allocation with fairness would be: 2, 2.6, 2.7 and 2.7. Therefore, MFS guarantees a certain minimum QoS to all the served users and the total user satisfaction is always improved when the bandwidth increases if all the users obtain an equitable QoS, rather than only some users receiving more than others.

In summary, the scheduling strategies mentioned above have an important role in state of the art schedulers. However, they have not considered the QoS according to the requirements of different network services. Next section will introduce some of the well-known QoS-aware packet scheduling schemes.

3.1.2.2 QoS-aware Scheduling Schemes

In general, some practical scheduling schemes have to consider the service differentiation and their minimum specific requirements guarantee, such as multimedia traffic with the minimum requirements for delay, the minimum error and loss, etc. In this section, the well-known QoS-aware scheduling strategies are categorised and discussed .

A basic guaranteed delay scheduling strategy in traditional real-time operating systems, namely **Earliest Deadline First (EDF)** [112] [123], is introduced. Many QoS-aware scheduling scheme over wireless networks were designed on the principle of EDF. EDF aims to schedule the packets with the closest deadline expiration so as to guarantee the transmitted packets to be received in time and avoid the packet drops. The scheduling policy and priority metric calculation of EDF can be expressed as:

$$p_{i,m}^{EDF} = \frac{1}{T_i - D_i^{HOL}} \tag{3.13}$$

where T_i is the delay threshold of the transmitted packets for the i-th user, and D_i^{HOL} is the Head of Line (HOL) delay of i-th user. Additionally, in order to ensure the scheduling of those traffic services, the system should satisfy:

$$\sum_i \frac{D_i^{HOL}}{T_i} \leq 1 \tag{3.14}$$

Similarly, a **Dynamic Hybrid Scheduler (DHS)** proposed in [124] also partly introduces a delay-aware solution for mobile wireless networks. The priority metric is expressed as:

$$p_{i,m}^{DHS} = \frac{D_i^{HOL}}{T_i} \tag{3.15}$$

Intuitively, the increasing head of line delay achieves a more urgent scheduling so that the free Resource Blocks will be allocated to those users with higher priority. The users with the highest HOL delay and the shortest T_i will have the highest priority. At the end of the scheduling process, any free resource will be allocated to the users following the priority order again.

On the other hand, another QoS-aware strategy for wired networks, **Largest Weighted Delay First (LWDF)** jointly working with guaranteed delay and acceptable loss rate requirements, was proposed in [125]. The scheduling metric can be simply described by:

$$p_{i,m}^{LWDF} = \frac{D_i^{HOL}}{\beta_i} \tag{3.16}$$

with

$$\beta_i = -\frac{T_i}{\log \delta_i} \tag{3.17}$$

where β_i is the weight for scheduling and δ_i is the allowed variation probability for the i-th user. In the flow transmission, δ_i can be considered as a metric for the acceptable packet loss ratio for the i-th user. Therefore, the transmitted flows of the user with the satisfied packet loss and packet deadline constraints will be preferable for resource allocation. However, the fairness of LWDF may not be guaranteed and desirable. Additionally, EDF and LWDF were generally designed for wired networks, hence some more solutions designed for wireless network based on them will be presented later on.

In [126] [127], a channel-aware extension of LWDF, **Modified Largest Weighted Delay First (M-LWDF)**, was proposed for the LTE downlink systems. The proposed solution takes into account the balance among spectral efficiency, QoS provisioning and fairness, jointly working with the PF strategy. The scheduling metric can be expressed as:

$$p_{i,m}^{M-LWDF} = p_{i,m}^{LWDF} \cdot p_{i,m}^{PF} = \frac{D_i^{HOL}}{\beta_i} \cdot \frac{r_m^i(t)}{\hat{R}_i(t)} \tag{3.18}$$

According to the analysis in [128], M-LWDF scheduling scheme is throughput optimal depending on both the current channel conditions and the state of the queues (i.e. HOL delay). It only needs to time-stamp the arriving data packets for all users, or to monitor the current queueing length. Moreover, the value of the delay distribution of users can be shaped by controlling the value of parameter β_i. Therefore, M-LWDF can satisfy the QoS requirements for different service types. It is also very easy to implement M-LWDF in other wireless network systems [127].

In [129] [130], the authors took into consideration both M-LWDF scheduling characteristics and the exponential function of the end-to-end delay, and proposed a well-known exponential rule scheduling strategy for a time-division multiplexing system based on M-LWDF and PF, namely **Exponential/PF (EXP/PF)**. Moreover, the authors in [131] implemented EXP/PF on LTE downlink system for real-time streaming services. The scheduling metric of EXP/PF can be calculated as:

$$p_{i,m}^{EXP/PF} = \exp\left[\frac{p_{i,m}^{LWDF} - \overline{p_{i,m}^{LWDF}}}{1 + \sqrt{\overline{p_{i,m}^{LWDF}}}}\right] \tag{3.19}$$

with

$$\overline{p_{i,m}^{LWDF}} = \frac{\sum_i^N p_{i,m}^{LWDF}}{N} \tag{3.20}$$

In this case, when differences of delay between all users are large caused by $p_{i,m}^{EXP/PF}$, then the value of the exponential function will be larger as well. Thereafter, EXP/PF will become more QoS-aware and handle the priority for the real-time services. If the differences of delay are smaller, the value of exponential function is close to 1. In this case, EXP/PF will handle the flows as non-real-time services and it will perform the same as PF.

Another two similar scheduling strategies were presented in [132], namely, **Exponential Scheduling (EXP)** and **LOG Scheduling (LOG)** rules. EXP rule can be considered as an enhanced EXP/PF. Its metric is similar to EXP/PF:

$$p_{i,m}^{EXP} = b_i \cdot \exp\left[\frac{a_i D_i^{HOL}}{c + \left(\frac{\sum_{i=1}^N D_i^{HOL}}{N}\right)^\eta}\right] \cdot \Gamma_{i,k} \tag{3.21}$$

with $0 < \eta < 1$

In addition, the scheduling metric of LOG can be simply expressed as:

$$p_{i,m}^{LOG} = b_i \cdot \log c + a_i \cdot D_i^{HOL} \cdot \Gamma_{i,k} \tag{3.22}$$

where a_i, b_i and c are variables; $\Gamma_{i,k}$ denotes the spectral efficiency for the i-th user on the k-th sub-channel. From the analysis in [132], the authors achieved good scheduling performance when a_i, b_i and c are set as:

For EXP rule (i.e eq.(3.21)):

$$\begin{cases} a_i \in \left[\frac{5}{0.99T_i}, \frac{10}{0.99T_i}\right] \\ b_i = \frac{1}{\mathbb{E}[\Gamma_{i,k}]} \\ c = 1 \\ \eta = \frac{1}{2} \end{cases} \tag{3.23}$$

For LOG rule (i.e. (3.22)):

$$\begin{cases} a_i \in \frac{5}{0.99T_i} \\ b_i = \frac{1}{\mathbb{E}[\Gamma_{i,k}]} \\ c = 1.1 \end{cases} \tag{3.24}$$

Compared to EXP/PF, the EXP rule here takes into account the detailed channel condition values and many tunable parameters. Therefore, EXP appears to be more robust. On the other hand, compared to EXP, the increasing scheduling metric is slowed by the logarithm function of LOG rule with respect to exponential function of EXP.

3.1.3 Hybrid Scheduling Scheme

All of the well-known scheduling strategies introduced in the previous sections only consider the queueing metric within the scheduling procedure (i.e. channel-unaware solutions), or the network channel condition and QoS constraints. Moreover, in the practical cases, many more scheduling solutions based on generic schemes (e.g. RR, PF, MT, TTA, etc) take into account more aspects related to the particular environment and requirements, such as the cross-layer design, energy-efficiency, game theory based analysis, or emerged machine-learning based support. In this section, some hybrid designed scheduling solutions are presented.

3.1.3.1 Cross-layer Scheduling

Cross-layer design is one of key solutions for the hybrid scheduling. Two directions of cross-layer design are illustrated in Figure 3.2. In terms of horizontal view, the cross-layer scheduling scheme can work jointly on both frequency and time domain, reducing

Figure 3.2: Cross-Layer Design

the computational complexity. On the other side, cooperative scheduling among the different OSI Model layers is also widely used. The vertical direction based scheduling solutions often consider the information interaction from upper layers, such as end-to-end latency on the Network Layer or the QoE feedback from the Application Layer, etc.

Pokhariyal et al. in [133] proposed a two-step scheduling technique for resource allocation on both time and frequency domains. First, a set of active users in the current TTI/time slot are selected by **Time Domain Packet Scheduler (TDPS)** based on **Priority Set Scheduler (PSS)**; secondly, the RBs on the frequency domain will be assigned to these prioritized users by PF on Frequency Domain Packet Scheduler (FDPS). The most interesting aspect is that TDPS and FDPS can work with other different basic schedulers mentioned in the previous section. The authors compared the performance of many other jointly working solutions, such as TD-Proportional Fair (TD-PF), TD-Maximum Throughput (TD-MT), TD-Blind Equal Throughput (TD-BET); and FD-PF, FD-TTA. The scheduling decision is based on the outcome of both domain schedulers (See Figure 3.2 (a)). Therefore, the two-tie scheduler can achieve a good trade-off between fairness and spectral efficiency.

In general, the acceptable delay for voice transmission should be around 250ms [134]. Moreover, the delay tolerance of VoIP over LTE systems should be strictly lower than 100ms according to the core network transmission overhead and the RLC and MAC buffering [3]. Monghal et al. in [135] proposed a dynamic scheduling scheme working on time and frequency domain for VoIP traffic. A specific algorithm, referred to as **Required Activity Detection (RAD) with Delay Sensitivity (DS)**, is implemented on TDPS. The time domain scheduling metric is calculated using three factors like the fairness guaranteed RR metric, the VoIP Guaranteed Bit Rate (GBR) requirement and the time constraints for the user with a delay bound, respectively. The PF metric is adopted on the frequency domain.

A MAC layer RB scheduling algorithm for the efficient VoIP service in 3G LTE was presented in [136]. The key idea is the dynamic activation algorithm of a VoIP priority mode for the voice QoS satisfaction sent from UEs over EPS bearer, namely **VoIP priority mode (VPM)**. When VPM is activated, only VoIP flows can be served that satisfies QoS for voice. Moreover, conducting the duration of VPM, the scheduling scheme minimizes the performance degradation induced by its priority mode application.

Based on the E-Model defined in [137], the authors in [138] estimate the QoE metric by using real-time input parameters, such as end-to-end delay and upper layer packet loss ratio measured from UEs through the LTE networks. The scheduling priority of the service for a specific user is decided based on the standard VoIP GBR requirement and dynamic QoE metric.

3.1.3.2 Energy-aware/efficiency Scheduling

Green communication has emerged as a hot topic and many researchers are focused on how to save more energy during the wireless transmission. Generally, the energy saving approaches can be exploited on both sides, eNB and UEs.

On the eNB side, a simple way for reaching this target is to maximize the spectral efficiency. The study in [139] reveals that MT scheduler is more energy efficient than both PF and RR schemes. In [140], the authors present a bandwidth expansion scheduler, referred to as **Bandwidth Expansion Mode (BEM)**, assigning a lower order modulation scheme for each allocated user. In addition, the authors in [141] exploited a **Dynamic Modulation Scaling (DMS)** technique on the system level scheduling framework, enabling a control knob to achieve energy-latency trade-off. This results in significantly lower energy consumption while still bounding the packet delay. They also extend this energy-efficiency technique on Weighted Fair Queuing (WFQ) algorithm, namely **E^2WFQ**. The simulation results reveal that E^2WFQ not only saves more energy consumption with a small, bounded increment in worst case packet latency, but also achieves a good fairness on resource allocation.

On the UE side, the Discontinuous Reception (DRX) and Discontinuous Transmission (DTX) are the popular approaches for energy savings on mobile terminal. When there is no any traffic on the mobile devices, the antennas are switched to a sleep mode or a low power state. In [142], DTX is extended to a cell system, namely Cell DTX. This algorithm is able to switch off the whole cell during a certain idle time, that results in up to 90% energy reduction.

3.1.3.3 Learning-based Scheduling

Normally, different static QoS constraints are exploited for different scheduling scenarios with different requirements. However, that would become inflexible when the QoS requirements are changed. In [143], the authors present a dynamic neural Q-Learning-based scheduling technique that results in an efficient throughput-fairness trade-off. Through the Q-learning training with Neural Network, the algorithm collects as many rewards as possible. The proposed algorithm assigns the different levels of CQIs to the different classes of users. However, this kind of scheduling strategy may cause more complexity and overhead.

3.1.3.4 Utility Theory based Scheduling

Utility theory has been widely exploited in scheduling algorithms for OFDMA networks. These algorithms are simple to implement and fit the different levels of customer requirements. In [144], the authors summarized two basic utility theory based design examples. The first one is **Rate-based Utility optimization Scheduler (RUS)** for best-effort traffic without QoS requirement. The mathematical expression of the scheduling algorithm is given below:

$$p_{i,m}^{RUS}(t) = \arg\max_{i \in \mathcal{I}} U_i(\hat{R}_i(t)) \cdot c_{i,m}(t) \tag{3.25}$$

where $c_{i,m}$ is the QoS constrain of the k-th RB for the i-th user within $\mathcal{I}$. The utility function U_i has to be concave. And the optimized RB will be assigned to the user. In addition, the authors in [145] used the exponential and logarithmic functions to formulate the shape of rate-based utility.

The second basic utility based algorithm introduced in [144] is called **Max-Delay-Utility (MDU)**, which jointly works in channel- and queueing-aware scheduling scheme.

The expression of MDU is given below:

$$p_{i,m}^{MDU}(t) = \arg\max_{i \in \mathcal{I}} \sum \frac{|U_i(\mathbb{W}_i(t)|}{\hat{R}_i(t)} \cdot \min\left(R_i(t), \frac{\mathbb{Q}_i(t)}{T_q}\right) \tag{3.26}$$

where $\mathbb{W}_i$ is the average waiting time of the i-th user, $\mathbb{Q}_i$ is the total bitrate of the whole queue of the i-th user and T_q is the length of the queueing. The $min(x, y)$ is used to avoid the bandwidth wastage when the served bitrate $R_i(t)$ is more than the total queueing size. The utility function of the waiting time/delay is concave, thus the optimized RB will be allocated to the users with longer delay.

3.1.4 Discussion

The main aspects of the scheduling schemes described in the sections above are summarized in Table 3.2. After reviewing state of the art on scheduling solutions, there are four aspects to be discussed for the design of a new proposed scheduling scheme for multimedia delivery over LTE downlink networks:

- **Quality of Service (QoS)**: End-to-end latency, packet loss ratio and instant bitrate of traffic are the key metrics of QoS which affect the users' perceptual quality while using the multimedia service. From the related works of channel-aware and QoS-aware scheduling, the voice service over IP network is more delay-sensitive. In the proposed scheduling algorithm for video transmission, the guarantee of packet loss ratio threshold is more important for non-real time services.

- **Fairness**: In addition to the QoS, the good performance of fairness control will help to avoid the network resource wastage, will increase the system throughput and will provide the acceptable service quality balancing users equality. PF is a basic fairness control algorithm which has been widely exploited in many scheduling solutions. Therefore, PF can be good option for the proposed scheduling scheme.

- **Energy consumption**: Battery lifetime is an essential parameter when analysing the user experience. It has been seen that most of the reviewed solutions focus on the energy-saving on eNB side. In the proposed solutions of this thesis, the energy saving solutions will be integrated with mobile devices.

Table 3.2: Summary of the Scheduling Solutions

Type of Scheduler	**Names**	**Scheduling Target & Aspects**	**Queueing metric**	**Instant Bitrate**	**Historical Bitrate**	**Head of Line Delay**	**PLR**
Channel -unaware	FIFO/LIFO [110]	Priority of queueing	✓				
	RR [111]	Fairness of queueing	✓				
	WFQ [115] [116]	Fairness of queueing	✓				
Channel-aware and QoS-unaware	MT [118]	Target Bitrate		✓			
	BET [119]	Target Bitrate & Fairness			✓		
	PF	Fairness		✓	✓		
	TTA [119]	Target Bitrate; Average Bitrate & Fairness		✓			
	MFS [122]	Target Fairness		✓			
Channel-aware and QoS-aware	EDF [112]	Bounded Delay				✓	
	DHS [124]	Bounded Delay				✓	
	LWDF [125]	Bounded Delay, Packet loss aware & Fairness				✓	✓
	M-LWDF [126] [127]	Bounded Delay, Target Bitrate & Fairness		✓	✓	✓	✓
	EXP/PF [131]	Exponential rule for Bounded Delay & Fairness			✓	✓	✓
	EXP [132]	Exponential rule for Bounded Delay, Spectrum Efficiency & Fairness			✓	✓	✓
	LOG [132]	Log rule for Bounded Delay, Spectrum Efficiency & Fairness			✓	✓	✓
Hybrid	PSS-TDPS [133]	Target Bitrate & Fairness; Joint TDPS and FDPS		✓			
	VPM [136]	VoIP priority; Fairness; Joint TDPS and FDPS			✓		
	[138]	QoE-aware; Delay Bounded; Packet loss aware			✓		✓
	BEM [140]	Energy-aware; target bitrate		✓			
	DMS [141]	Energy-aware; bounded Delay				✓	
	E^2WFQ	Energy-aware; Fairness	✓			✓	
	[143]	Q-Learning-based; Target Bitrate & Fairness		✓			
	RUS [144]	Utility theory based; Target Bitrate & Fairness			✓		
	MDU [144]	Utility theory based; Bounded Delay, Minimun Bitrate		✓	✓	✓	
	RAD-SD [135]	Delay bounded, Guaranteed Bitrate & Fairness; VoIP support; Joint TDPS and FDPS			✓	✓	

- **Utility Theory based Hybrid Design**: It is efficient to trade off different scheduling requirements by using the utility theory. Different scheduling inputs are formulated into the different utility functions and the final scheduling priority is the result of the optimized combination of the utility functions.

Therefore, the proposed scheduling scheme in this thesis makes use of utility theory to find the best value trade-off across QoS guarantee, fairness requirements and energy consumption of the mobile devices. The detailed architecture of the proposed scheme will be presented in the next chapter.

3.2 Adaptive Video Streaming Research Area

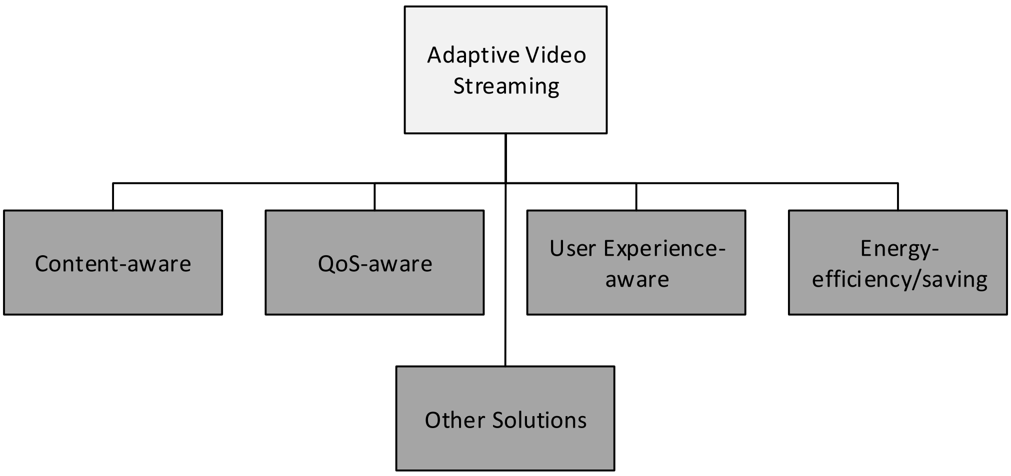


Figure 3.3: Classification of Adaptive Streaming Solutions

Adaptation techniques have been widely exploited in current video streaming mechanisms over the Internet. Moreover, various industry and academic research proposed relevant solutions to address the problems during video streaming while satisfying the different requirements of both transmission environment and users' quality of experience. In terms of the different requirements for video streaming, the proposed adaptation schemes from the literature are divided into five categories (See Figure 3.3): 1) Content-aware adaptive solutions which relate to content-aware encoding and content classification algorithms; 2) Quality-oriented/QoS-aware solutions which consider the transmission channel conditions and QoS requirements; 3) User Experience-aware solutions which mainly consider the users' Quality of Experience when adapting the quality

Figure 3.4: Content Frames Vs. Non-Content Frames

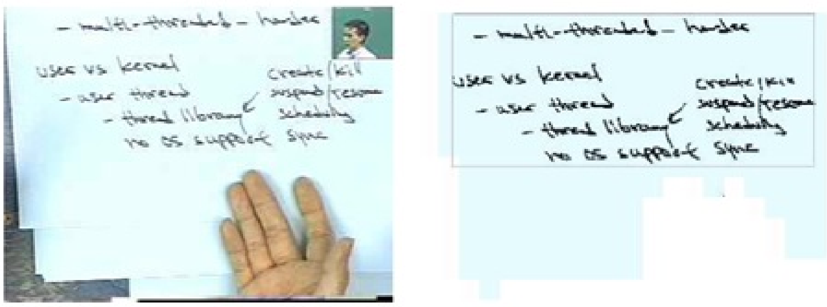


Figure 3.5: Content Adaptive Filtering

levels of the video stream by the client feedback; 4) Energy-efficiency/saving solutions which adopt 'Green' algorithms for saving more power on the server or client side during streaming; 5) Other solutions that perform video adaptation are also considered.

3.2.1 Content-aware Adaptive Solutions

The authors in [146] present a real-time application level solution to the congestion problem during MPEG video streaming over Internet. The proposed solution takes into account network congestion by using the adaptive scaling technique for transmitting video. This adaptive scaling technique with content-awareness consists of three main functionalities: Motion Measurement System, Filtering Mechanism, and Adaptive Content-aware Media System. For instance, if a video scene has a lot of motion, then all the frames with the lowest quality will be scaled and streamed. Thus, the quality is improved. If a video scene has little motion, then some frames will be discarded but the streamed frames are shown with high quality. In the course of their experiments, they only considered either quality or temporal scaling mechanisms so that it would not accurately determine if the video scene with a lot of motion could be strictly filtered into high or low categories. Therefore, the authors mentioned that hybrid adaptive scaling (i.e. combination of temporal and quality scaling) will bring the most benefit to the end-user perceived video quality.

In [147], the authors propose an interesting multicast streaming system for video lectures over wireless networks. The multicast streaming system adapts the processed content (i.e images) with different quality levels to the clients, by using the subjective adjustment feedback and temporal compressing techniques. According to their video content analysis, the video frames can be classified into two types: content frames and non-content frames (see Figure 3.2.1). If the channel condition is bad, the non-content frames would be streamed with low quality level using temporal compression. On the other hand, the content frames would be streamed in a limited size (see Figure 3.2.1), which was resized or 'cropped' by using block-based filter which only detects content (i.e. words) area.

Several video streaming adaptation solutions focus on the video encoding. In [148], the authors present a time stamp-based content-aware retransmission for the streaming encoder. During streaming, the encoder is able to adaptively determine whether to send or discard a packet based on its retransmission deadline which is calculated according to the temporal relationship and the error propagation characteristics within the same Group of Picture (GOP). Briefly, the packets deadline would be extended once the channel condition is worse. Similarly in [149], another adaptive encoding solution is introduced to HTTP streaming. This scheme is able to detect the scene changes and then place I frame on these boundaries to segment the GOP, which performs a better rate distortion than conventional encoding solutions.

3.2.2 Quality-oriented/QoS-aware Solutions

Muntean et al. in [150] present a high-level adaptive multimedia delivery system for all-IP networks, namely Quality-oriented Adaptive Scheme (QOAS), which aims to provide a good perceptual quality of the multimedia stream to end-users. This proposed system consists of a server side and a client side. The quality-oriented grading functionality of the server conducts and delivers the adaptation of different quality levels of multimedia streams depending on the feedback on the perceived quality assessment scheme located at the clients. The quality assessment scheme takes into consideration **Packet Loss Ratio, Delay** and **Jitter** of the current multimedia transmission. The grading scheme combines these parameters and generates a score for the final delivery.

An adaptive multimedia scheme for IEEE 802.11e network was proposed in [151]. The proposed approach is an application-aware scheduling method which adapts the multimedia service depending on the traffic classification and instantaneous MAC layer buffer condition functionality in IEEE 802.11e, namely Hybrid Coordination Function (HCF). Therefore, this algorithm is able to provide QoS guarantees with low packet loss, end-to-end latency and jitter, and maximize the channel utilization. Additionally, this scheme not only considers the downlink delivery systems but also coordinates the uplink streams according to the traffic directions.

In [152], the authors propose a Quality-Aware Bandwidth Allocation scheme (QABA), for on-demand streaming over wireless networks. In order to maximize the bandwidth utilization and accommodate high bandwidth variation of wireless networks, the proposed scheme makes use of the Fine-granular-scalability (FGS) encoding, one of the layered coding techniques. With FGS encoding, a video stream can be compressed into one low bitrate Base-layer (BL) stream and only one full high bitrate Enhancement-layer (EL) stream. Thus, FGS reduces the coding bitrate further rather than the conventional layered coding techniques. Considering the variation problems of the wireless networks, QABA takes advantage of the rate-distortion characteristics of videos to maximize the overall quality perceived by all the users in the system.

A low-layer Adaptive Modulation and Coding (AMC) scheme for video streaming over LTE networks is introduced in [153]. The AMC makes use of the no-reference metrics (i.e. Blocking and Blurring metrics) for link-adaptation of video streaming, instead of using Channel Quality Indicator (CQI). Therefore, the AMC provides a trade-off between user perceived video quality and transmission delay with variations in modulation and coding rates over different channel conditions. Evaluation results show that different code rates have similar performance when the channel condition is good. However, for poor channel conditions, it is best to use low modulation and coding rates. Additionally, the authors also consider the Multi-Input Multi-Output (MIMO) which supports more efficient modulation and coding schemes.

De Vleeschauwer et. al in [154] propose a HTTP-based Adaptive Streaming (HAS) scheme built on top of the PF scheduler at LTE eNodeB, referred as Adaptive Guaranteed Bitrate Scheduler (AGBR). AGBR makes use of the utilities of different traffic types (i.e. video and data traffic) to prioritize the served traffic. Therefore, a utility maximization problem is considered and the highest utility for video traffic is aimed at being achieved. The performance evaluation shows that the proposed scheme guarantees the utility maximization for the video traffic and the target bitrate for the data traffic.

In [6], the authors present an intelligent Prioritized Adaptive Scheme (iPAS) over IEEE 802.11 networks. iPAS differentiates the multimedia streams and provides proportional allocation of the wireless channel bandwidth, not only based on the QoS-related parameters (i.e. delay, jitter and packet loss rate) but also making use of video content characteristic (i.e. video resolutions). A stereotype solution is used to combine the QoS-related parameters and the video content characteristic for priority classification (i.e. Five Levels) in bandwidth. The multimedia streams are prioritized to share the channel resources accordingly. The network simulation results show that iPAS guarantees a lower latency and packet loss ratio for QoS sensitive streams, but differentiates the best-effort background traffic with high delays.

Recently, the authors in [155] propose an HTTP-based adaptive streaming scheme considering the quality-fairness problems, referred to as Quality-fair Adaptive Scheme (QFAS). The framework of QFAS consists of an HTTP Adaptive Scheme (HAS) Server, Media-aware network elements (MANE), eNB and HAS clients. HAS server stores video sequences, and generates Media Presentation Descriptors (MPD) which contain video segmentations and manifest files requested by HAS clients. The MANE located close to eNB, is in charge of intercepting and processing the MPD requests in order to collect channel state information (CSI) from eNB and update the adaptive bitrate of video segmentations (i.e. called Chunks). The fairness of video quality among multiple HAS clients are considered by controlling the rate on MANE. The proposed scheme was evaluated in NS-2 and compared to the Best-effort scheme and AGBR scheme in [154].

3.2.3 User Experience-aware Solutions

In [156], the authors present a user-perceived quality aware adaptive scheme for MPEG-4 delivery over best-effort IP networks. The proposed adaptive scheme is using an optimum adaptation trajectory (OTA) where 120 subjective tests were set up to ask users to select their preferred clips. A fitting curve is then built to model the relationship between resolutions and frame rate. The OTA curve is used to adjust the quality level of the streamed videos in the adaptive server, which maximizes the perceived video quality by the end-users. However, the adaptive scheme has not been implemented in a real streaming server and validated in second-round subjective tests after video streams were received at the client side.

A QoE-aware DASH system (QDASH) is proposed in [157] which consists of QDASH-abw and QDASH-qoe functionalities. QDASH-abw is an available channel bandwidth measurement system detecting the highest quality level of video that the current network conditions can support. QDASH-abw makes use of a probing methodology to send and collect the probing packets via a measurement proxy. It is an accurate method to determine the sending rate and available bandwidth via the probing packets samples during Round-Trip-Time (RTT). On the other hand, QDASH-qoe adapts the streaming rate depending on the buffering information feedback via the DASH standard and the available bandwidth estimated by QDASH-abw.

Essaili et al. in [158] propose a Quality of Experience (QoE) driven algorithm for multi-user over Dynamic Adaptive Streaming over HTTP (DASH) in LTE networks. In order to enhance QoE awareness to the end-user, the proposed scheme makes user of an QoE estimation model which calculate the Mean Opinion Score based on the video stream data rate variation. Jointly considering the estimated MOS of each video and channel conditions and for each end-user the optimal streaming rate is adjusted. This QoE driven scheme also implements a QoE-based proxy server which is redirecting the video requests from the end-users and proactively adapts the streaming rate while the channel condition is bad. The proposed solution was evaluated and was implemented for two standard adaptive HTTP clients: Microsoft Smooth Streaming and DASH-enabled VLC.

NOVA (Network Optimization for Video Adaptation), a simple asymptotically optimal online algorithm for QoE-driven DASH-based video delivery, is proposed in [159].

NOVA is a joint optimization system between network resource allocation scheme and video quality adaptation scheme. In order to maximize the perceptual video quality of the end-user with a trade-off among the mean quality, temporal variability in quality and fairness. Distributing the resource allocation to network controllers and adaptation tasks to end-users, NOVA is asynchronous and more flexible, which is suited for current network and normal DASH system.

Many QoE-aware adaptive schemes focus on how to adapt a proper stream to the end-users switching between the stream bitrates. However, the frequent switching of the bitrate from high to low or low to high would cause higher streaming overhead and worsen the user experience. Moreover in [160], the authors present a QoE friendly algorithm to solve this. It makes use of a fixed-interval buffer to maintain the unchanged bitrate and to keep a smooth switching-up or switching-down. Additionally, once the buffer is going to overflow, then a quick boot algorithm is exploited to get the proper bitrate to fitting a current bandwidth.

A QoE-driven adaptive streaming algorithm formulated from real subjective experiments results is presented in [161]. In order to maximize the QoE to the end-users, the proposed algorithm investigates the problem of how to cache and manage a set of media files with optimal streaming rates. Then, the authors formulate this problem as a convex optimization problem which is going to be solved with Lagrange multiplier method. Through three alternative search algorithms (i.e. exhaustive search, dichotomous-based search and variable step-size search), the authors find the optimal number of cached media files for high expected QoE and low complexity. However, this algorithm of adaptive streaming cache management is only evaluated in a single content scenario. Whereas multiple distinctive contents stored on a cloud-based server would be considered as part of the future work.

A cross-layer Video-QoE adaptive scheduling scheme jointly working with DASH is presented in [162]. The proposed scheme based on the Gradient Algorithm makes use of the periodic buffer level feedback (i.e. standardized in DASH standard) of user-clients to prioritize the streamed user at each time instant. Also the scheme considers the CQI feedback on the scheduling process. The performance evaluation shows that the scheme is able to provide the continuous adaptive streaming rate for user-clients with a good perceptual video quality (i.e. computed by the difference between the mean and standard deviation of PSNR) compared to the other three scheduler: conventional PF scheduler, PF with barrier for frames (PFBF) scheduler [163] and Gradient with Min rate (GMR) scheduler [164]. Additionally, the scheme could be flexibly exploited in non-video streaming service by choosing custom optimization criterion (i.e. changing buffer level feedback to delay or loss tolerance).

3.2.4 Energy-efficiency/saving Solutions

Schurgers et al. early in [165] present a dynamic power management solution over wireless data transmissions for portable mobile devices. The proposed solution makes use of a modulation scaling scheme which is similar to the voltage scaling solution in conventional digital circuits (e.g. power saving in CPU running). The modulation scaling takes into considerations the trade-offs of delay and energy consumption. Considering the optimization solution based on the relationship among delay, transmitted bits and energy consumption, lower delay per bit reduces energy consumption per bit. The energy saving solution was integrated in the EDF scheduler, achieving energy savings of data transmission of up to 50% compared against that without EDF.

Another physical-layer-level energy saving solution for data streaming is proposed in [166]. Taking into consideration the transmission energy and the circuit energy consumption, the proposed solution makes use of Multilevel Quadrature Amplitude Modulation (MQAM) and Minimum Frequency-shift Keying (MFSK) in Additive White Gaussian Noise (AWGN) to optimize the transmission time and modulation so that up to 80% energy savings are achieved with respect to nonoptimized system. Moreover, the trellis-coded narrowband MQAM system is able to increase energy efficiency with increasing of the transmission distance. On the other hand, uncoded MFSK outperforms coded in reducing energy consumption of short-range application with the Forward Error-correction Codes (ECCs).

A cooperative scheme between the base station and the mobile terminals for energy savings is presented in [167]. A Rate-Based Bulk Scheduling service model is implemented on the base station side, which is a proxy monitoring the streamed data and sending mobile terminals feedback of when the stream buffer could start or stop. According to the buffered information (e.g. channel conditions, delay of transition), the mobile terminals decide how to save energy optimizing the sleep interval of wireless network interfaces. However, this solution was only evaluated in Enhanced Data Rates for GSM Evolution (EDGE) which is an old wireless data transmission standard. Additionally, the solution outperforms the other rate-based fair queuing algorithms used for Audio-on-Demand.

The solution in [168] provide two-tie methods for energy saving in H.263 video wireless streaming. First, a power saving mode on IEEE 802.11e access point is considered, referred to as Power Saving Quality-of-Service enabled Access Point (PSQAP). The PSQAP optimizes the APs awakening/sleeping pattern in a manner using a Network Allocation Map (NAM), which guarantees delay and packet loss requirements for multiple real-time traffic. Secondly, an energy efficient H.263 streaming over PSQAP is proposed. Using a discrete auto-regressive prediction model (DAR), the required aggregate video bandwidth is dynamically estimated, in order to achieve AP/client power saving.

In [169], authors present an interesting application-based energy saving approach for video streaming, called Battery and Stream-Aware Adaptive Multimedia Delivery for Wireless Devices (BaSe-AMy). BaSe-AMy makes use of the remaining battery level of mobile devices, remaining stream duration and packet loss ratio of transmission to decide how to switch the video streaming data rate or not, while also maintaining good perceived quality of video to the users. As BaSe-AMy is an application-level scheme, it is very convenient to be developed on current smartphone platforms (e.g. Windows Phone, Android and iOS).

Power Saving Mode throttling (PSM-throttling) is a client-centric energy efficient server for bulk data transmission over TCP in WLANs [170]. PSM-throttling quickly detects the current TCP flow throughput with a low cost. When the transmission data rate of the streaming flow is much lower than the current bandwidth, then the stream will be reshaped into periodic bursts with the same average bitrate as the original stream. The new data bursts of the stream will be allocated to the unused network bandwidth. Thereafter, PSM-throttling will switch the wireless network interfaces (WNIs) to idle mode or sleeping mode. Thus, the WNIs will be turned on while bursts of packets arrive at the right time. This application solution is suitable for the transmission of uplink session and device-to-device communication environment.

3.2.5 Other Solutions

In the research area, not only the adaptive solutions mentioned above are considered, but also other interesting adaptive video streaming solutions are introduced depending on the different requirements and streaming environment. Most of them are cross-layer designed and based on advanced scalable storage environment.

iDASH, a well-known improved DASH scheme with Scalable Video Coding (SVC) is presented in [171]. Coping with the congestion during multiple user adaptation, SVC provides features to represent different representations of the same video content within the same bit stream (i.e. a base layer) by selecting a valid sub-stream (i.e. one or more enhancement layers). iDASH with SVC is able to avoid network congestion and guarantees the perceived quality of video with different equipment capabilities requirements when compared to Advance Video Coding (AVC).

Cloud-based computing, a new highly scalable storage system, is not only able to handle amounts of data to a very large number of nodes, but also provides data streaming techniques. Many cloud-based adaptive streaming systems have been proposed recently, such as AMVSC [172], Stormy [173], cloud-based transcoding mechanism [174], AMES-Cloud [175] and Cloud-assisted adaptive streaming system for social-aware video [176]. All these cloud-based adaptive streaming systems transcode the video and store the video segments on a private server which delivers the streams to the users depending on the link condition feedback. Different from the traditional streaming server, the cloud-based streaming server is more scalable, adaptable, consistent and supporting multi-tenancy. Nowadays, the cloud-based streaming system is much smarter, and delivers the relevant videos to some specific areas in advance depending on users' watching history in those areas. Cloud is seen as being the way of adaptive streaming storage in the future.

The authors in [177] present an interesting multimedia adaptive scheme, referred to as COMEDY. It is short for Cost-oriented adaptive Multimedia Delivery (COMEDY) which makes use of a price model to trade off video quality and users willingness to pay. COMEDY differentiates the video streams with different quality levels depending on how much the users are willing to pay. For example, COMEDY adapts a lower quality video to the users who cannot afford too much, but a higher quality video to the users who can pay more. COMEDY also takes into consideration the quality of user experience in terms of the different resolutions of mobile devices. In the evaluation, COMEDY shows a money saving comparison among the different network operators (i.e. Vodafone Ireland, O2 Ireland and T-Mobile). Therefore, cost-oriented adaptive solutions will be beneficial for the network operators to think about balancing the users needs and the limited bandwidth.

In [178], authors present a cloud-based SVC adaptive streaming solution which takes the device parameters into account. Similar to the other SVC-based adaptive schemes, this solution provides different format coding for the video stream. Moreover, a Bayesian network environment and a multi-variable linear regression model are considered before the SVC coding decision. The Bayesian model is able to predict whether the streamed videos would conform to user requirements and to consider whether the overall battery power of mobile device could support a complete video playback, which is depending on the device characteristic feedback, such as screen resolution, CPU, battery, start and end time of video decoding, video coding bitrate and available bandwidth. Thereafter, the appropriate SVC streams will be delivered to the corresponding users so that good video perceived quality for users will be achieved.

The authors in [179] propose a hybrid adaptive streaming solution, namely E^2DOAS , which considers both QoE and energy-saving. The QoE and energy-saving factors proposed in this scheme are quantized and modelled based on the perceptual video quality of mobile users and the energy measurement results of real mobile device models, respectively. A utility function based on both normalized QoE and energy-saving factors is computed by a multiplication exponential weighted method. By solving this concave utility function, a set of video quality trade-offs are adapted, which balances QoE and energy-saving requirements of mobile users. For example, when a user prefers to watching high quality video streams on the mobile device, but ignoring higher power of mobile device might be consumed, then E^2DOAS will adapt high quality level to the transmission. However, when a user wants to play a good quality video but also save energy of mobile device, then E^2DOAS will adapt down the quality levels of video and select the best one to fit this specific requirement. For the users who only care about the energy consumption rates, the appropriate low quality level will be adapted which also maintains an acceptable quality for user experience.

3.2.6 Discussion

Inspired by the previously summarized related works on the adaptive streaming area, five key aspects of the design for the proposed adaptive solutions over future networks in this thesis are considered as follows:

- **Quality of Service (QoS)**: The basic requirement of adaptive streaming solutions is that of maintaining a good or at least acceptable quality of service for end-users. The adaptive solutions referred to in Section 3.2.2 can be categorized into three types: a) Network Protocol-based solutions: they are the most reliable for quality of service but have the most complicated modifications on the current architecture due to the strict standardization procedure (e.g. [151], [153]): b) Codec/Transcoding-based solutions: are developed efficiently on the application layer, however they would cause more computational complexity that is related to the hardware support of the mobile device (e.g. [152], [178]); c) Bitrate switching-based solutions: are the simplest and most efficient adaptive techniques built on top of the current network architecture (e.g. over HTTP) and widely used in the practical world (e.g. [150], [154], [6], [155]).

- **Energy-saving**: Real-time multimedia streaming is QoS-sensitive and bandwidth-intense making it the most energy consuming application. According to the study mentioned above, the ways to reduce the energy consumption over the mobile multimedia delivery systems are by maximizing the spectrum efficiency and reducing the network congestion. Adaptive streaming solution is able to decrease the probability of network congestion by using the quality level/bitrate scaling.

- **Quality of Experience (QoE)**: QoS and battery lifetime bring essential impact on the quality of end-user experience. Most of the existing QoE-aware solutions integrate the predicted QoE model and balance the bitrate level of video and perceptual quality. QoE is the key aspect in the proposed adaptive streaming solution in this thesis.

- **Heterogeneity of Mobile Device**: Nowadays mobile devices can be categorized into different levels depending on the different prices and requirements for end-users. The heterogeneity of mobile devices is also expressed as the devices with different CPU/GPU processing performance, screen sizes, resolutions and battery capacity. Hence the proposed adaptive scheme in this thesis will integrate the heterogeneity factors of mobile devices and differentiate the multimedia service to the end-users novelly.

- **Trade-offs and Optimization**: Game-theory based trade-off method enables optimizing the performance of the proposed adaptive solutions by combining different requirements of QoS, QoE, energy-saving and heterogeneity of mobile devices.

The detailed architectures and algorithms design will be presented in the next chapter.

3.3 Mobile Data Offloading Solutions

Mobile data offloading from cellular network has emerged as an important solution for the current wireless networks environment and network operators. However, it is difficult to classify the offloading solutions as they don't work independently and they are designed on the system-level architecture. Therefore, some recent well-known offloading applications or experimental platforms will be introduced below.

Ra et al. in [180] proposed a wireless link selection algorithm for video uploading applications over the WiFi and 3G/EDGE environment. The proposed novel link selection algorithm achieves appropriate trade-off between mobile device power consumption and video transmission delay by taking advantage of a non-negative, scalar function, namely Lyapunov optimization function. In this Lyapunov theoretical model, higher instantaneous delay would cause higher transmission power and vice versa. Therefore, the proposed optimization algorithm defined that the delay-tolerance applications would prefer to maximize energy savings and defer the transmission till selecting a good link connection. With respect to low delay tolerant applications, the algorithm would choose a link connection with lower delay and higher bandwidth in the same energy usage condition. To conclude, the proposed algorithm makes the optimal uploading transmission decision by taking several factors into account: size of the uploading queuing buffer, power consumption of the different wireless interfaces (i.e. 3G/EDGE, WiFi) and the channel quality (i.e. received signal strength, video transmission delay and channel bandwidth). The proposed solution was compared against a WiFi-only, minimum-delay (i.e. the best channel quality among 3G or WiFi), 3G static-delay, WiFi static-delay, and a KNOW-WiFi algorithm [68]. The evaluation scenarios include a campus, a shopping centre and an airport with different load, respectively. Additionally, the authors also mentioned that the Lyapunov optimization framework can be used for downloading applications in mobile devices.

In [181], Ristanovic et al. introduced two energy efficiency offloading schemes for 3G Networks, namely HotZones and MixZones. The HotZones Algorithm allowed the delay-tolerance applications on mobile devices to download the content over the WiFi connection when the mobile devices are close to the WiFi access point coverage, assisted by predictions made by the network operator. The connection and deployment information is sent and stored at the mobile subscribers. However, the difference for MixZones scheme is that the WiFi access points information are only operated and stored by the network operator. For example, the User A wants to get the delay-tolerant content from the User B, and then User A will get a timer with the timeout equal to the delay set by the corresponding application. If User A can enter the cell range of User B before the timeout, the operator allows User A to get the data from User B over the current WiFi connection immediately. If not, User A would download the data over the 3G connection. Therefore, MixZones is an opportunistic transfer scheme based on ad hoc networks. Both of the offloading schemes enabled to trade delay for energy and reduce 50% of the battery consumption coming from 3G transfers of delay-tolerant data, and have the lowest delay during the peak hours. Moreover, the performance evaluation shows that a WiFi coverage of 3 to 4 times more cells is needed for the real-time offloading from 3G.

The authors in [182] presented an optimal scheduling algorithm for mobile data offloading to WiFi network to minimize the cost of cellular data for multiple smartphone applications. The algorithm is formulated for the WiFi offloading framework based on the varying streaming data size and application delay tolerance, dynamic network coverage (i.e. cellular and WiFi) and bandwidth. Through the optimization based on Mixed Integer Linear Programming (MILP) solution, the author found a appropriate data size (i.e. 512-byte MTU) and the coverage and bandwidth of WiFi, which achieved the traffic offloading trade-off between Cellular and WiFi, and greatly minimized the cost of mobile data. The decreasing cost of using cellular data may cause the decreasing energy consumption on mobile phone. Also, the trade-off between the Cellular data usage and the application delay tolerance was analysed. The longer the delay tolerance is, the applications data stream deadline is shifted further waiting for the WiFi connection. When the delay tolerance is larger than 256 seconds, the application would only use the WiFi offloading completely.

In [183], Ding et al. introduced a real collaborative mobile data offloading architecture, namely Metropolitan Advance Delivery Network (MADNet), saving more energy consumption for smartphones. There are two important components in the offloading system: Proxy-Cellular AP and Proxy-WiFi AP. The Proxy-Cellular AP is responsible for handling the data transmission and offloading control messages. Whereas, the Proxy-WiFi AP is used for the offloading data transmission and the capacity prediction of each connection over WiFi. The authors evaluated the system over the real environment and deployed several components mentioned above along a road. When the user walked/drove along the road, the MADNet will predict the motion of the smartphone by the GPS based on the KNT mobility predication algorithm. If the user entered the coverage of Proxy-WiFi, then the MADNet next calculated whether the accessed WiFi AP could provide enough bandwidth and speed for offloading data requirements. If the connection with WiFi AP is in good condition, that AP will start to cache the data for the streaming application within their delay tolerance. The evaluation results show that the MADNet saves up to 80% energy consumption when compared to the transmission over 3G only.

The authors in [184] presented an efficient WLAN access points deployment scheme for the Cellular Network offloading scenarios. The scheme makes use of the density of user requests frequency to optimize the locations of the operator-deployed WLAN APs. Through the optimization, the cellular coverage area is divided into S×S grid, and the resulting grid is further divided into N×N sub-grid. The deployed WLAN AP must be centred in each sub-grid. A greedy heuristic approach was used to find the efficient location of WLAN APs in which they have the maximum data requests frequency (i.e. the highest offloading ratio). The authors illustrate how to achieve the optimum solution using the Integer Linear Programming approach (ILP) based on the solution of IBM ILOG CPLEX software. Regarding the benchmarks, the simulation results of the proposed scheme was compared to the ILP optimal, sequential scheme (i.e. APs were deployed one by one) and the HotZone scheme. Moreover, the proposed algorithm improved the offloading ratio compared to the sequential scheme and HotZone scheme. For further division of the sub-grid (i.e. n is increasing, e.g. n = 2, 3, 4, 5, 6), the greedy approach results were closer to those of the ILP optimal.

3.3.1 Discussion

After reviewing the sate of the art mobile data offloading test-beds, some advantages and disadvantages are summarized below:

Advantages

- **Cheaper Billing**: Using data offload from cellular networks to non-cellular networks, end-users could save more money on the real-time multimedia streaming. Basically, non-cellular networks (e.g. WiFi) have very low connectivity billing or are free.

- **Link Backup**: Data offloading is able to set up a back up link connection apart from the main backhaul. For instance, data offload provides seamless handover making the data transfer safer and more stable.

- **Resource Aggregation**: Data offload provides a possible way to aggregate more data traffic transmission at the same time. Using Multi-path TCP (MPTCP), the mobile devices receive the data from multiple access interfaces concurrently, and the network capacity will be increased.

- **Energy saving**: Basically, the connectivity of cellular networks (i.e. 3G, 4G-LTE) has higher power consumption than using the non-cellular networks (i.e. WiFi). For example, switching the traffic from LTE to WiFi will save more energy on the end-user's mobile device. Energy measurement tests will be introduced in Chapter 5.

Disadvantages

- **Network Management issues**: Generally, due to the fact that cellular and non-cellular networks are designed and standardized by different organizations, they are working on different network architectures. Therefore, data offloading solutions need a lot of modification on the current network protocols, which would result in higher complexity and intense competition among the different operators.

In addition, interference management for the heterogeneous networks is also a complicated issue.

- **Cost of Infrastructure**: A large number of non-cellular network APs are deployed which solves the 'Last mile' coverage issue. However, it may lead to an issue on how to balance the cost of infrastructure deployment and the operator's revenue. More discussions on the cost trade-off are presented in [185]

To conclude, the proposed adaptive solution using data offloading in this thesis is mainly focused on how to save more energy on the mobile devices side. The detailed description is provided in the next chapter.

3.4 Chapter Summary

This chapter presents the state of the art from three research areas:

- **Downlink Packet Schedulers**: This chapter presents a comprehensive survey of the current downlink packet schedulers for LTE networks which were categorized into: channel-unaware, channel-aware and hybrid scheduling schemes. The analysis and discussion of these three solutions are included.

- **Adaptive Video Streaming Solutions**: In terms of adaptive video streaming solutions this chapter classifies the current adaptive techniques presented in the literature into five main approaches: 1) Content-aware - based on content encoding and classification algorithm; 2) QoS-aware - related to network constraints; 3) QoE-aware - based on the user perceptual quality; 4) Energy-aware - considers energy consumption and power saving during multimedia transmission; 5) Hybrid solution - adapts streaming by making use of different aspects (e.g. QoS, QoE and energy-saving factors).

- **Mobile Data Offloading Test-beds**: The current academic level experimental solutions for mobile data offloading were introduced in this chapter. Their advantages and disadvantages were discussed at the end of this chapter.

The related research works are included in this chapter, which motivates the design of the proposed "Always Best Experience" architecture presented in the next chapter.

Chapter 4

Proposed System Architecture and Algorithms

This chapter presents the proposed system architecture and introduces the algorithms of four thesis contributions: 1) Utility-based Priority Scheduling (UPS) Scheme - a cross layer resource allocation mechanism for LTE networks to support multimedia service differentiation; 2) Device-Oriented Adaptive Multimedia Scheme (DOAS) for LTE networks - an adaptive mechanism for multimedia streaming that takes into consideration mobile device class characteristics; 3) Energy-Aware Device Oriented Adaptive Multimedia Scheme (eDOAS) for WiFi offload - an enhanced version of DOAS that considers the energy of the mobile devices in the adaptation process and offloads the mobile data traffic between LTE networks and WLAN networks. 4) Evolved QoE-aware Energy-saving Adaptive scheme for wireless networks (e^3DOAS) for wireless network - makes use of the Coalition Game theory and adapts the multimedia streams to the end-users in a fair manner while maintaining acceptable quality levels of experience.

4.1 Multimedia Delivery over Mobile Wireless Networks: Adaptation and Continuity

The growing popularity of high-end mobile computing devices, such as smartphones (e.g. iPhones, Android Phones), tablets (e.g. iPads, Galaxy Notes, Nexus, Surface), netbooks or laptops, smart-home devices (e.g. Apple TV, Mi TV) and wearable devices (e.g. apple watch, Moto 360) equipped with advanced wireless network access, enables

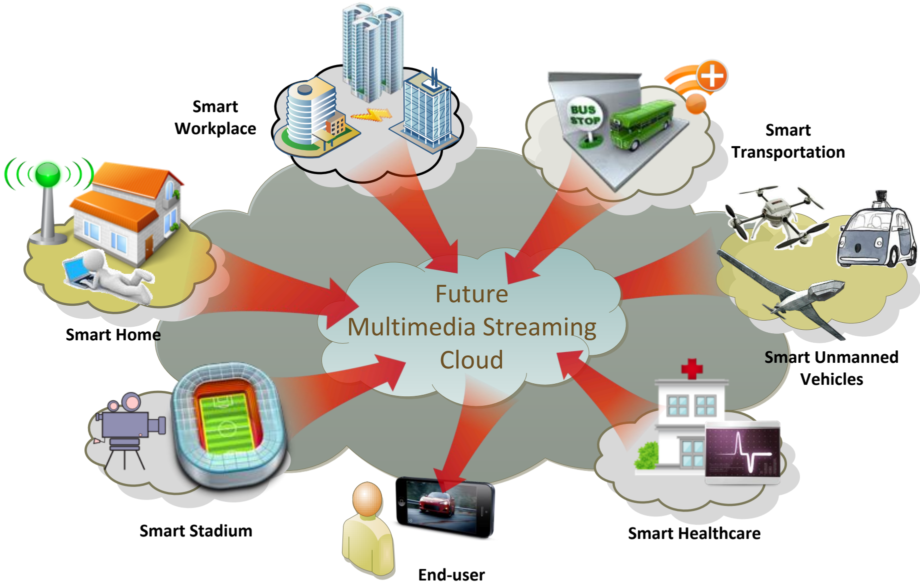


Figure 4.1: Heterogeneous Wireless Networks Scenario and Proposed System Architecture

mobile users to retrieve multimedia content (e.g. YouTube, Netflix, Facebook and Spotify) from any source and display it on any screen, at any moment, while on the move or stationary.

According to Cisco [8] [15], the current environment is facing a rapidly increasing mobile broadband data traffic, estimating a 10-fold increase by 2019 over that of 2014. This creates challenges for network providers that will have to cope with this boom in mobile broadband data traffic. Even though the 4G LTE-Advanced and the next 5G network technologies promise to bring 100× and 1000× improvement in terms of frequency efficiency, the network operators will still have to face some essential issues including: increasing demands for higher quality levels for multimedia delivery (i.e. higher bitrate, frame rate, resolution, etc.), limitation of the channel bandwidth, provide seamless user experience over different device characteristics and resolutions.

In this context, a possible solution is the use of adaptive multimedia delivery mechanisms together with LTE scheduling schemes in order to maintain acceptable user QoE and QoS given the limited 4G-LTE network resources. Another solution is the use of a traffic offloading technique which moves a part of the mobile broadband data traffic from cellular networks to WiFi networks at peak times. In this way the network operators could cope with the increase in the data traffic while enabling "Always Best Experience" for their mobile users. Mobile users want to be able to access multimedia content from any screen, at any place and at any time without any energy concerns, as envisioned in Figure 4.1.

In this context, this thesis proposes an integrated solution that will enable the "Always Best Experienced" mobile users to seamlessly roam within a heterogeneous wireless environment while performing multimedia streaming. An example of a usage scenario in this heterogeneous wireless environment is illustrated in Figure 4.2. The proposed solution is distributed and consists of a server side integrating an adaptive multimedia server and a client side roaming through the heterogeneous environment. The environment deploys two different access network technologies: LTE cellular and IEEE 802.11 WLAN. Figure 4.2 also presents a potential journey of a user in this heterogeneous wireless environment.

In order to improve the performance of multimedia delivery over the cellular (i.e. LTE) and the WLAN (i.e. IEEE 802.11) networks, and maintain an acceptable quality level of user experience while travelling through the heterogeneous environment, the main contributions of this thesis are identified and discussed in the journey of this user. This journey includes the points A to D and involves LTE and WLAN networks:

- **Point A** – a novel **Utility-based Priority Scheduling (UPS)** algorithm for resource allocation over LTE that considers mobile device differences when providing high quality delivery of multimedia services. The priority scheduling decision is based on the device classification, mobile device energy consumption and multimedia streaming tolerance to packet loss. The proposed scheduling scheme is deployed at the level of the LTE eNodeB downlink resource allocation system referred to as UPS-eNodeB.

- **Point B** – Apart from the UPS algorithm integrated in the eNodeB, an easy-deployable and low-cost adaptive streaming scheme, referred to as **Device-Oriented Adaptive Multimedia Scheme (DOAS)** is proposed for multimedia delivery over LTE networks. DOAS is a cross-layer solution built on top of the downlink scheduler in LTE/LTE-A systems. The adaptation decision in DOAS is based on the end-user device display resolution information and QoS levels.

- **Point C** – Due to the growing popularity of WLAN spots, mobile users can select the cheapest and fastest ways to access the Internet content. Most of the

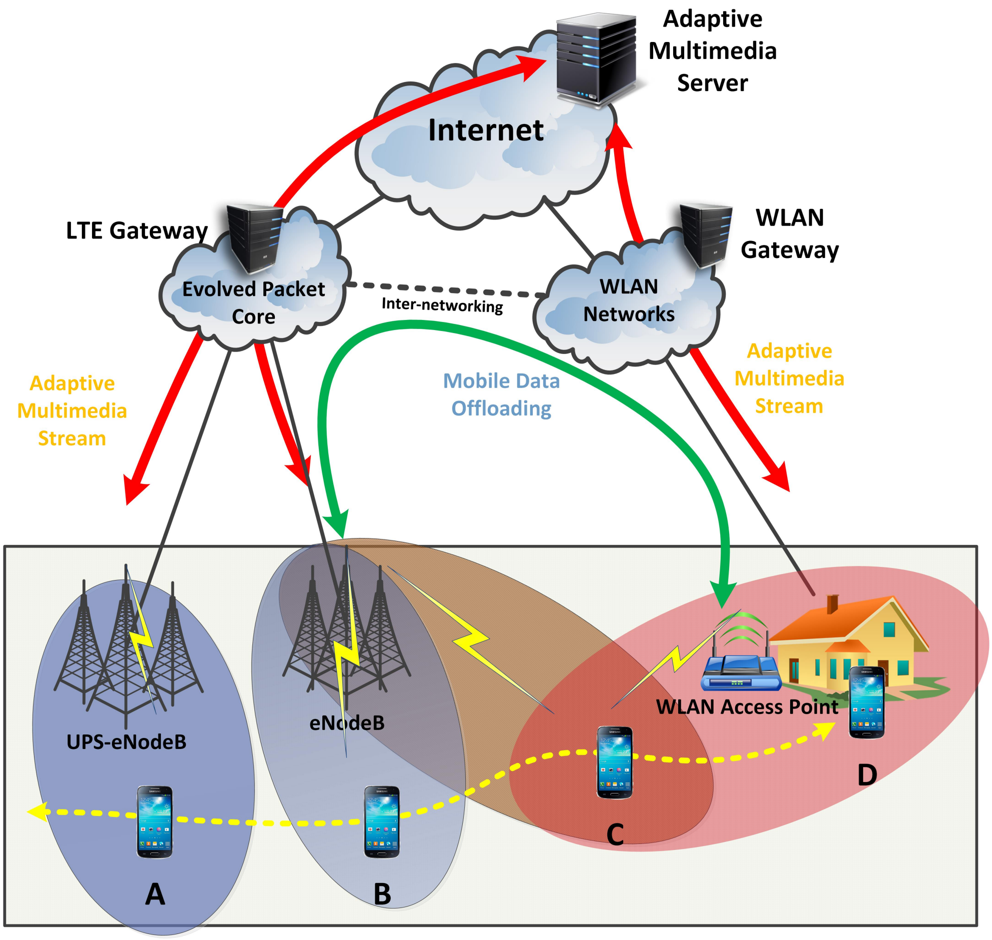


Figure 4.2: Heterogeneous Wireless Networks Scenario

network operators have realized that they have to find a way which is economically beneficial for both themselves and their mobile users. Accordingly, many researches have indicated that WLAN offloading technologies have been the key solutions in this context [185]. The **enhanced energy-aware DOAS (eDOAS)** is proposed to provide an energy efficient solution for WiFi offloading scenario.

- **Point D** – Currently, improving both video perceived quality and mobile device battery lifetime is challenging for researchers. In this thesis, an **Evolved QoE-aware Energy-Saving DOAS (e^{3}DOAS)** is proposed to balance the QoE level and energy consumption and consider the fairness of the service allocation for mobile users within the OFDMA-based Small Cell and fits the "Always Best Experience" requirement.

The detailed architecture and algorithms for each proposed solution are presented in the following sections.

4.2 Utility-based Priority Scheduling Scheme (UPS)

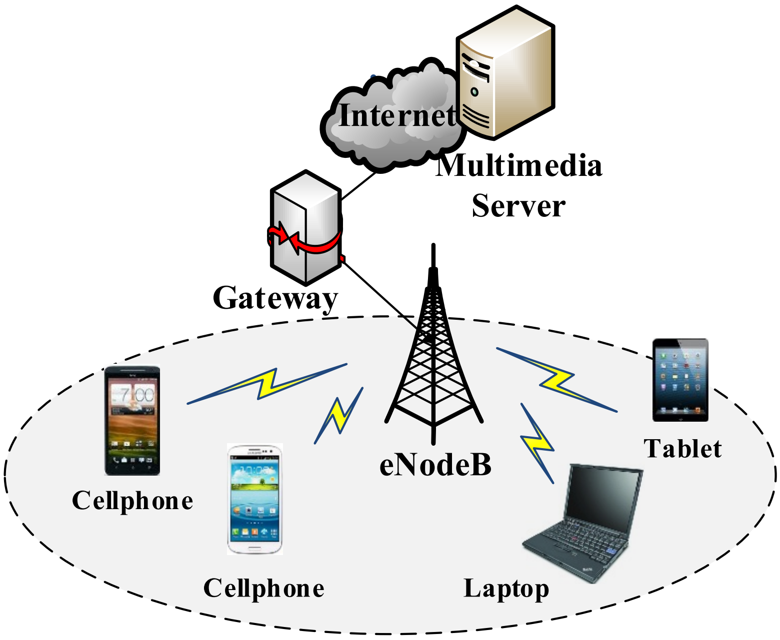


Figure 4.3: Multi-screen Diversity Scenario in LTE Network

With the advances in technologies, mobile computing devices such as smartphones, PDAs, small netbooks, etc. have become both more affordable and powerful, while mobile users expect everywhere seamless connectivity, and high quality level services. A study reported by Google says that 90% of all media interactions of users on a daily basis are screen based [186], meaning that a person spends on average 4.4 hours of leisure time per day, in front of screens (e.g., smartphone, laptop/PC, tablet, television, etc.). In this context the main challenge that the mobile network operators are facing is the ability to differentiate between multi-screen offerings in order to provide seamless multimedia experience with minimal delay, jitter, and packet loss, to their customers. An example of a multiscreen diversity scenario within a simple LTE network is illustrated in Figure 4.3, which simply describes that four different mobile devices are served with multimedia streaming server via a wireless connected link consists of a LTE eNodeB/eNB and a LTE Gateway.

Due to the popularity of the high-performance mobile devices, the scheduling schemes for resource allocation should take into account, apart from the conventional constraints, the mobile device characteristics, such as: screen display resolution and battery lifetime.

This section introduces a novel **U**tility-based **P**riority **S**cheduling (**UPS**) algorithm for multimedia streaming over LTE networks. The proposed UPS mechanism takes into account the QoS constraints of the multimedia application, the information about device screen resolution and the energy consumption of mobile devices in order to prioritize the resource allocation and ensure the best multimedia experience to the mobile users.

4.2.1 LTE Downlink Architecture Overview

According to Figure 2.2 presented in Chapter 2, the LTE network architecture includes two parts: Evolved UMTS Terrestial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC). The E-UTRAN provides downlink/uplink interface for User Equipment (UE), such as smartphones, laptops or tablets. The EPC structure consists of Evolved Node B (eNodeB), gateways (e.g. Serving GW/PDN GW) and core network (e.g. Internet) which is based on an all-IP architecture. For the downlink transmission the Orthogonal Frequency-Division Multiple Access (OFDMA) is employed. The unit of OFDMA is the Resource Block (RB) which contains 12 consecutive subcarriers of 180 kHz bandwidth in the frequency domain, and in the time domain this accounts for a 0.5 millisecond time slot [11]. Two consecutive RBs (referred to as Physical Resource Block (PRB) in this work) are assigned to a user for a Transmission Time Interval (1 millisecond). Moreover, a brief description of the downlink resource allocation strategy over OFDMA is illustrated in Figure 4.4. Resource allocation is usually based on the value of a priority metric, and each RB is allocated to a content streaming UE whose priority according to this metric is the highest. In general, the priority metric is based on some specified conditions, such as channel status, QoS requirements or fairness conditions. For instance, the channel status can be estimated by the CQI report based on Signal-to-Interference-plus-Noise Ratio (SINR) between UE and eNodeB.

4.2.2 Framework of the Proposed Scheduling Mechanism

The proposed UPS framework is illustrated in Figure 4.5. UPS is distributed and consists of server-side, eNodeB-side and mobile client-side components.

At the **Mobile Client-side**, the UEs are represented by LTE compatible devices

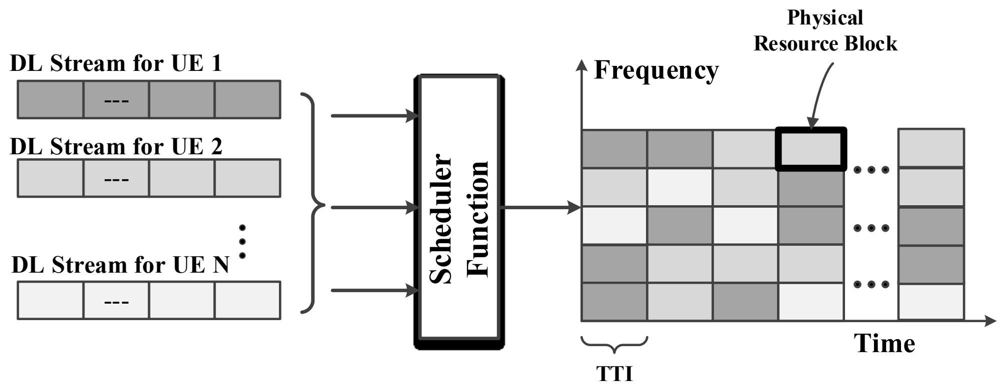


Figure 4.4: A Simple LTE Downlink Resource Allocation Model

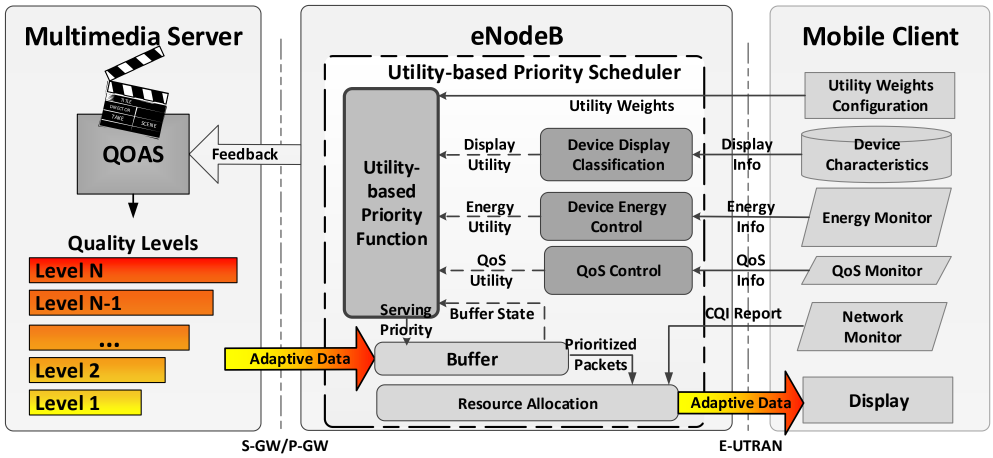


Figure 4.5: Utility-based Priority Scheduling Mechanism - Framework

and they are attached to eNodeB. The UEs integrate the following several functional blocks, such as:

- **Utility Weights Configuration block**, which allows the user to set his/her preferences towards energy savings or required video quality level, and sends the utility weights to the eNodeB;
- **Device Characteristics block** which provides information about the device resolution;
- **Energy Monitor block** which provides information about the energy consumption of the mobile device;
- **QoS Monitor** which provides information about the packet loss rate;

- **Network Monitor** which provides the Channel Quality Indicator (CQI) Reports.

According to the LTE standard [12], the CQI reports could contain aperiodic or periodic CQI by using the subband or wideband approaches, respectively. The proposed mechanism makes use of subband aperiodic CQI report. Consequently, each UE collects CQI information on each physical resource block and sends this as part of a CQI Report to eNodeB together with display information, energy information and QoS information. As described in the LTE standard, a CQI report is sent periodically, at every Transmission Time Interval (1 TTI = 1 millisecond). A report containing display information, energy information and QoS information is sent to eNodeB every 10 TTIs via the LTE EPC/EPS bearer which provides a dedicated secure virtual connection for exchanging user requirement information [42]. This report over EPS bearer has the following format: device ID, UE IP address, display resolution, parameters of energy consumption model, and guaranteed packet losses and will be discussed in details later on in this chapter. Any UE access in an LTE system is always authenticated, so no bogus UEs are allowed access to resources. Additionally, no malfunctioning or false reporting UEs are considered. In this thesis, the energy consumption of the downlink streaming is considered, and the energy consumed by the control message exchange (uplink) is ignored as its size is small in comparison with the video data. For instance, for a 10 min MPEG-4 4Mbps-encoded video streaming via TCP over WLAN, there are 308.04 MB of video data to be transferred in comparison with approximately 1.4 MB of control messages.

The **Server-side** integrates the **Quality-oriented Adaptation Scheme (QOAS)** which adaptively transmits the multimedia streams [187]. The server either stores different quality levels (e.g., N levels) of the pre-recorded multimedia streams, from lowest (e.g., level 1) to highest (e.g., level N) or is able to transcode existing multimedia content into any of the N quality levels. Based on the feedback received from eNodeB, QOAS adjusts the data rate dynamically.

The core of the proposed mechanism Utility-based Priority Scheduler (UPS) is deployed at the **eNodeB-side** between the OSI Media Access Control (MAC) and physical (PHY) layers. UPS can be divided into two main conceptual phases: utility-based prioritization and resource allocation, illustrated in Figure 4.5.

The **Utility-based Prioritization phase** consists of several functional blocks as illustrated in Figure 4.5:

- The **Device Display Classification block** makes use of the device resolution information in order to compute the *Display Utility*;
- The **Device Energy Control block** which makes use of the device energy consumption information in order to compute the *Energy Utility*;
- The **QoS Control block** which makes use of the device QoS information in order to compute the *QoS Utility*;
- The **Utility-based Priority Function block** makes use of a multiplicative utility function in order to compute the priorities of the service requests based on the *Display Utility*, *Energy Utility*, *QoS Utility*, and the information about the buffer state. This information is then used in order to perform priority-based dynamic scheduling.

The **Resource Allocation phase** is in charge with a process which is triggered once the utilities for all UEs are calculated. Accordingly, a UE with the highest utility value will be prioritized as well as allocated with the highest bandwidth share. Therefore, the PRBs with the highest bit rate located in the buffer will be mapped to the highest priority user in each TTI. In the contrary, a UE with lower utility value will be allocated the lower bandwidth resources.

4.2.3 UPS Message Flow Exchange

In order to illustrate how the proposed UPS mechanism works, a sequence diagram of the message flow exchange between a UE and a server via LTE network is presented in Figure 4.6. Initially, the UE sends a *Session Setup Request* to the eNodeB after its user requests video playing on the mobile device. This initiates a video streaming session involving the requesting UE and the LTE system. Once the *Session Setup Request* is accepted, the UE sends information about the display and the energy consumption of the mobile device to the eNodeB. The scheduler located at the eNodeB makes use of this information in order to classify the UE devices and assign priorities. The resource allocation is then done based on the computed priorities, such as the devices with higher priority will get more resources and so on. Additionally, the UE will start sending CQI

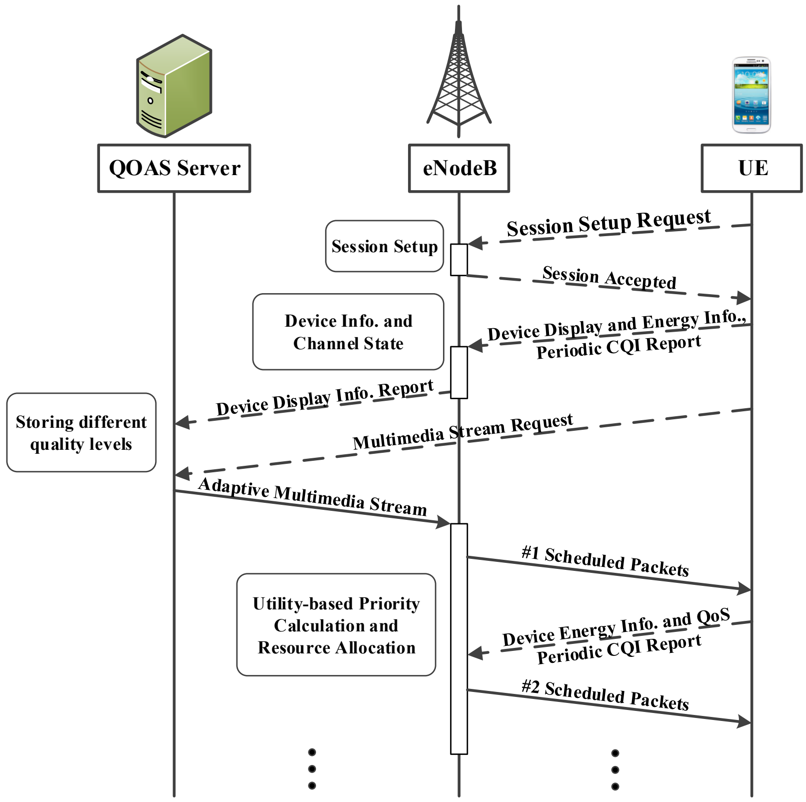


Figure 4.6: UPS Control Message Exchange Flow

reports to eNodeB as well. The Multimedia server deploys the QOAS mechanism which based on the received feedback adapts the multimedia stream dynamically. In the eNodeB, the scheduler assigns the prioritized PRBs to the physical channel and transmits them to UEs. Afterwards, the QoS reporting per TTI for transmission starts.

4.2.4 UPS Utility Function

Previous studies in [188] have shown that utility theory enables the mapping between received throughput of multimedia streaming and user satisfaction. According to the principle of the proposed scheduling mechanism UPS, the scheduler makes use of the following attributes: device screen characteristic (i.e. display resolution), energy consumption rate and QoS of the multimedia stream transmission to prioritize the resource allocation. However, these three criteria are based on different range of values and have diverse units of measurement, and therefore they need to be normalized through the use of utility functions. This thesis proposes an overall utility function based on the multiplicative exponential weighted (MEW) [189] method as given in eq.(4.1):

$$U^{i,j}(t) = \left[u_r^{i,j}(t)\right]^{w_r} \cdot \left[u_e^{i,j}(t)\right]^{w_e} \cdot \left[u_{plr}^{i,j}(t)\right]^{w_{plr}} \tag{4.1}$$

Where $U^{i,j}(t)$ is the overall utility for stream j of UE i at current scheduling instant t. $u_r^{i,j}$, $u_e^{i,j}$ and $u_{plr}^{i,j}$ are the utility functions for resolution of device display, energy consumption and packet loss rate (i.e. percentage) for UE i, stream j at instant t, respectively. In addition, w_r, w_e and w_{plr} are the weights for those three criteria, and their sum is 1. The values for the weights can be defined by the user in the **Utility Weights Configuration** block as illustrated in Figure 4.5. The overall utility is calculated for each UE and mapped to the priority in a decreasing order so that the UE with the highest utility score will have assigned the highest priority and the UE with the lowest score will have assigned the lowest priority.

4.2.4.1 Display Utility

In order to ensure good quality of experience to the mobile user, the multimedia stream should be played out on a display with an adequate resolution. Additionally, there are other factors that may impact the quality of the video, such as the available bandwidth, performance of the receiver, etc. As various devices have different characteristics and hence different multimedia stream requirements, the device resolution was taken into account when deciding on the device priority. For example, if the device resolution is high, in general there is a need of high required quality of content and therefore the scheduler will assign a higher priority to this device and the multimedia server will select a high quality level for the multimedia stream. For lower resolution devices, normally they have lower capability and are unable to handle high quality levels multimedia streams. Accordingly, lower priority and quality levels will be allocated to the devices with lower resolutions, which also results in saving more channel bandwidth and enables more smooth video playing on those devices. In order to do this classification in [6] is employed and the display utility $u_r^{i,j}$ is defined based on the different range of resolutions as indicated in Table 4.1. In general, the display resolution of a mobile device is fixed while playing videos. Therefore, the utility of display resolution is not varying over time.

Table 4.1: Utilities of Display Resolutions

	Class 1	Class 2	Class 3	Class 4	Class 5
Resolutions	$\geq 1024 \times 768$	$(1024 \times 768, 768 \times 480]$	$(768 \times 480, 480 \times 360]$	$(480 \times 360, 320 \times 240]$	$< 320 \times 240$
$u_r^{i,j}$	1	0.75	0.5	0.25	0

4.2.4.2 Energy Utility

Depending on the device type and characteristics, as well as the network conditions and the type of application, the estimated energy consumption rate per unit time for UE i can be described as in eq.(4.2)([190]).

$$e_{i,j} = \frac{r_d \cdot D_{i,j} + r_t \cdot \mu + c}{E_c} \tag{4.2}$$

where $D_{i,j}$ is amount of data in stream j of UE i required to be transmitted ($Mbit$), r_d is the energy consumption rate for the transmitted data ($mJoule/Mbit$), r_t is the energy consumption rate while the UE device is on standby per unit of time (mW), μ is the duration of the multimedia stream (i.e. the length of a video clip is acquired after the user requests it from the sever-side, then it will be sent to the eNodeB together with the energy information later), c is tunable constant that is for background energy consumption, and E_c is the residual energy capacity of the UE device ($mJoule$) before video playout. These energy consumption parameters (i.e. r_d, r_t, E_c and c) are reported to the scheduler periodically. Generally, smaller energy consumption rates are more preferable. Therefore, the energy consumption utility is defined as in eq.(4.3):

$$u_e^{i,j} = \begin{cases} 1 & , e_{i,j} \leq e_{min}, \\ \dfrac{e_{max} - e_{i,j}}{e_{max} - e_{min}} & , e_{min} < e_{i,j} < e_{max}, \\ 0 & , \text{otherwise} \end{cases} \tag{4.3}$$

Where e_{max} is the maximum energy consumption rate and e_{min} is the minimum energy consumption rate among all the UEs served for resource allocation. The UEs with lower energy consumption rates have higher scheduling priority, and vice versa.

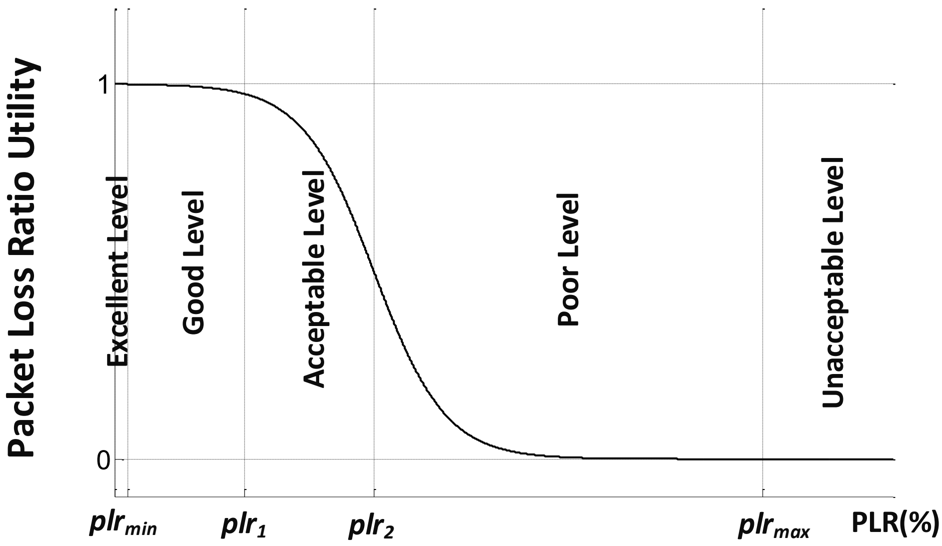


Figure 4.7: Packet Loss Ratio Utility

4.2.4.3 QoS Utility

The studies presented in [191] and [192] indicate that the quality of the received videos (encoded with H.264 and MPEG 2) over IP networks have an acceptable user perceived quality if the packet loss rate is lower than 2%. Based on the utility function study in [193], the QoS utility is represented by a negative Sigmoid function which describes the tolerance of the multimedia streams to the packet loss rate (i.e. percentage).

Based on this, and making use of the packet loss rate classification from [6], the QoS Utility considered is illustrated in Figure 4.7. Five levels for the impact of packet loss rate on the quality of the multimedia stream quality are defined: *Excellent*, *Good*, *Acceptable*, *Poor* and *Unacceptable*. According to the real experiments discussed in [194], it is noted is that plr_{min}(e.g. 0.1% [81]) is the packet loss rate tolerance for multimedia stream with *Excellent* quality. If the packet loss rate goes above plr_{max} (e.g. 5%), the quality of the multimedia stream becomes *Unacceptable*. In addition, *Good* level and *Acceptable* level of the multimedia quality are defined by plr_1 (e.g. 1%) and plr_2 (e.g. 2%), respectively.

Since low packet loss is associated with better quality for the multimedia stream, the shape of the QoS utility is considered to be concave as the packet loss rate increases. Therefore, the equation of the s-shape curve for stream j of UE i at instant t is given as in eq.(4.4):

$$u_{plr}^{i,j} = \begin{cases} 1 & , plr_{i,j} \leq plr_{min}, \\ 1 - \dfrac{1}{1 + \exp\left(-\alpha \cdot plr_{i,j} - \beta\right)} & , plr_{min} < plr_{i,j} < plr_{max}, \\ 0 & , plr_{i,j} \geq plr_{max} \end{cases} \tag{4.4}$$

$$plr_{i,j}(t) = \frac{\sum_{t-t_w}^{t} LossPkts_{i,j}}{\sum_{t-t_w}^{t} TransmittedPkts_{i,j}} \tag{4.5}$$

where $\alpha > 0$ and $\beta > 0$ are parameters which determine the slope and the location of the concave point (i.e. plr_2) of the function, respectively. The utility uses $plr_{i,j}$ which is computed as in eq.(4.5), $plr_{i,j}(t)$ represents the packet loss rate of stream j of UE i measured during the same transmission window t_w, $LossPkts_{i,j}$ is the packet loss (*bytes*) of stream j measured at UE i during the transmission window and $TransmittedPkts_{i,j}$ is the amount of data (*bytes*) of stream j transmitted to UE i during t_w.

Based on the definition of the utility function, lower real-time packet loss ratio achieved by streaming to a UE means that the network channel with respect to that UE is better. As the video transfer to that UE achieves higher utility value, it has a higher scheduled priority. An alternative approach would be if UPS prioritizes UE video streaming with higher packet loss, but then the services to the UEs which have better channel quality would be negatively affected, which was not desired and therefore this avenue was not taken.

4.2.5 Utility-based Priority Scheduling Procedure

Using eq.(4.1), the overall utility for all the UEs served with any number of multimedia streams each in the scheduling buffer is calculated. Next by using the UPS function defined in eq.(4.6), the priorities of the streams with respect to all UEs are computed.

$$P^{i,j}(t) = \overline{Th^{i,j}}(t) \cdot U^{i,j}(t) \tag{4.6}$$

where $P^{i,j}(t)$ is the priority of the multimedia stream j for UE i at scheduling instant t, and $\overline{Th^{i,j}}(t)$ (see eq.(4.7)) is the average instantaneous data rate of the multimedia stream j of UE i over all the unallocated physical resource blocks.

$$\overline{Th^{i,j}}(t) = \frac{\sum_{m \in M_{URB}(m,t)} C^{i,j}(m,t)}{|M_{URB}(m,t)|} \tag{4.7}$$

In eq.(4.7), $M_{URB}(m,t)$ is the set of the unallocated physical resource blocks at scheduling instant t in the buffer, $|M_{URB}(m,t)|$ is its cardinality, and $C^{i,j}(m,t)$ is the instantaneous rate of stream j of UE i with physical resource block m at instant t.

Algorithm 4.1 Utility-based Priority Downlink Scheduling Scheme

Input: Pre-defined $\mathcal{I}$, the set of served UEs; $\mathcal{J}$ the set of the requested corresponding multimedia streams of UEs; t, the scheduling instant; TTI, the scheduling unit; w, time windown for packet loss computation; M_{URB}, the set of current unallocated physical blocks; the values of r_d and r_t of all the served UEs.

Output: i^*, the scheduled UE with the highest priority; m^*, the resource block of UE i^* to be allocated

Initialization $t = 0$
while $\mathcal{I} \neq \emptyset$ **do**
  for *each* $i \in \mathcal{I}$ **do**
    for *each* $j \in \mathcal{J}$ **do**
      Obtain $u_r^{i,j}(t) \leftarrow$ Table 4.1
      Compute $u_e^{i,j}(t) \leftarrow$ eq.(4.3) & eq.(4.2)
      Compute $plr_{i,j}(t) \leftarrow$ eq.(4.5)
      Compute $u_{plr}^{i,j}(t) \leftarrow$ eq.(4.4)
      while $|M_{URB}(m,t)| > 0$ **do**
        Compute $\overline{TH^{i,j}}(t) \leftarrow$ eq.(4.7)
        Compute $U^{i,j}(t) \leftarrow$ eq.(4.1)
        Computer $P^{i,j}(t) \leftarrow$ eq.(4.6)
      end
    end
  end
  Obtain $i^* \leftarrow \arg\max_{i \in \mathcal{I}} P^{i,j}(t)$
  Obtain $m^* \leftarrow \arg\max C^{i^*,j}(m,t), \forall m \in M_{URB}(m,t)$
  The physical resource block m^* will be allocated.
  $t \leftarrow t + TTI$
end

According to the priority function described above, the highest priority is given to the stream j of the UE i which has both the highest priority and the highest average instantaneous rate. The rest UEs will be assigned after next priority calculation until all the UEs are served. The UEs with overall zero utility will be associated the lowest priority to access the resources. The UEs with equal overall utility (including 0) will be allocated resources in no particular order, if there are still resources available to be allocated. A pseudo-code of the proposed utility-based priority scheduling scheme is shown in Algorithm 4.1. Note that from Step 2 to 10, the utility values and priority metrics for all the served UEs and their corresponding streams are calculated in the same scheduling duration (i.e. 1 TTI). In Step 11 the UE with the highest priority is scheduled, and the resource block with the highest instantaneous rate (i.e. the best channel condition) will be assigned to that UE. The complexity of this algorithm is $O(n^2)$ since the process from Step 3 to 10 is linear. In the simulation, A linear mathematical expression is used in Step 11 to 12. Therefore, the total complexity from Step 3 to 12 is $O(n^2) + 2 \cdot O(n) = O(\max(n^2, n)) = O(n^2)$.

4.3 Device-Oriented Multimedia Adaptive Scheme (DOAS)

This section introduces a novel **D**evice-**O**riented **A**daptive Multimedia **S**cheme (DO AS) that works in conjunction with any scheduling algorithm (e.g. PF, M-LWDF) in order to make efficient use of network resources and provide higher perceived video quality to multi-screen end-users. DOAS proposes a mobile device classification based on screen resolution and a quality grading and delivery scheme for LTE-A systems.

4.3.1 DOAS Framework

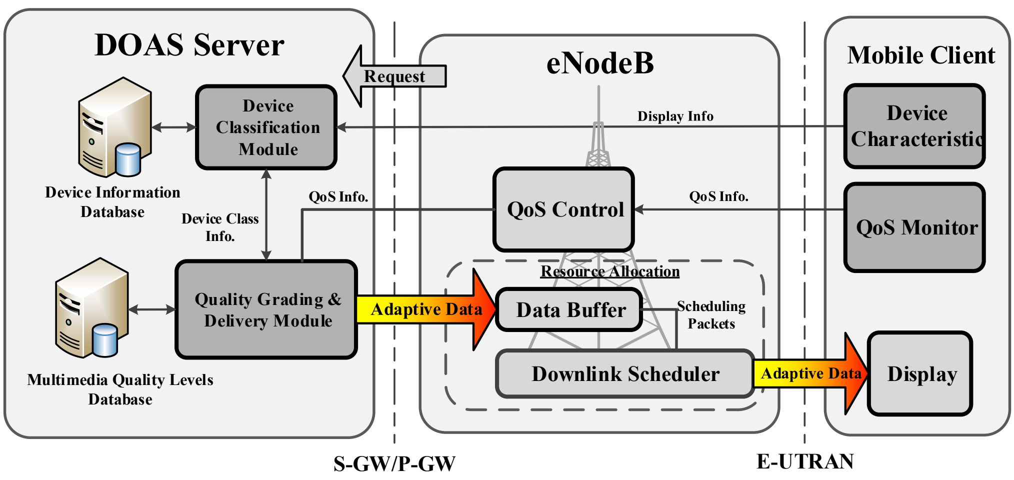


Figure 4.8: Device-Oriented Multimedia Adaptive Scheme - Framework

The framework of the proposed scheme is illustrated in Figure 4.8. DOAS is distributed and relies on three components: the LTE UE side, the LTE eNodeB side and the server side.

The **LTE UE side** is represented by the mobile client as illustrated in Figure 4.8 and represents an important component of the DOAS architecture. It consists of several functional blocks as follows:

- The **Device Characteristic block** which registers the device information (e.g. screen resolution, operation system information, battery lifetime) with the DOAS Server after it is attached to the eNodeB. The device information will be delivered to DOAS Server over the **Session Initiation Protocol (SIP)** which establishes a dedicated connection across the network after the mobile client initiates the request for a video stream.

- The **QoS Monitor block** which periodically provides average throughput, packet loss rate and other transmission quality information of traffic via the Evolved Packet System bearers [3];

- The **Display block** which is the entity installed in the mobile device that presents the multimedia content to the mobile user.

The **LTE eNodeB** side consists of:

- The **QoS Control block** which is in charge for processing the QoS feedback received from the LTE UE side and for providing the QoS control messages to the server side;

- The **Resource Allocation block** mainly includes the data flow buffer and downlink scheduling mechanisms. The resources, for the adaptive data stream received from the server side, are re-allocated efficiently to the UE sides by the Resource Allocation block.

The core of the proposed adaptive multimedia scheme is the server side referred to as the DOAS server. Similar to the DASH server adaptation presented in [73], the DOAS server adapts the streaming depending on the specific network condition. Additionally, DOAS server also adjusts the delivery based on device characteristics. Therefore, the **DOAS server** can be divided into two functional modules: the **Device Classification Module** and the **Quality Grading and Delivery Module**. The **Device Classification Module** makes use of the ***Mobile Device Classification Scheme (MDCS)*** and the device information database in order to classify the devices

Table 4.2: Statistics of Browser Display [5]

Year	Higher	1024 × 768	800 × 600	640 × 480	other
2015	93.7%	4%	0.3%	<2%	<0.5%
2014	93%	6%	0.6%	<0.5%	<0.5%
2013	90%	9%	0.5%	<0.5%	<0.5%
2010	76%	20%	1%	0%	3%
2007	26%	54%	14%	0%	6%
2004	10%	47%	37%	1%	5%

Table 4.3: Statistics of Cellphone Screen Resolution (2012) [5]

No. of Cell-phone brands	No. of Cell-phone models	$\geq 1024 \times 768$	$(1024 \times 768, 768 \times 480]$	$(768 \times 480, 480 \times 360]$	$(480 \times 360, 320 \times 240]$	$< 320 \times 240$
227	4914	11	322	93	2099	2389

based on their resolutions. The device information (i.e. user IDs, device models and corresponding screen resolutions) provided from UE side is processed and classified by MDCS, then stored into the *Device Information Database* integrated in the server. The **Quality Grading and Delivery Module** takes into account the current channel conditions and the device classification in order to grade the quality levels using ***Video Quality Grading & Delivery Scheme (VQGDS)***. Finally adaptive traffic with respect to appropriate quality level (i.e. video frame rates, bitrates and resolutions) is selected from the *Multimedia Quality Levels Database* in the server, and delivered to the eNodeB and then to the UE. The details of MDCS and VQGDS are presented in the following sections.

4.3.2 Mobile Device Classification Scheme (MDCS)

Mobile device screen resolution has become a significant factor which impacts the mobile user experience. For example, generally the multimedia server delivers high quality video content with high data rate to a mobile device having a low resolution. But the device cannot give a good experience level to the user rather it wastes the network bandwidth resources and could cause traffic congestion. Ideally each device would receive content at parameters according to its display and graphic processing capability. In this context, the MDCS provides a classification of the mobile devices based on their screen resolution. The variety of resolutions on mobile devices was investigated and

Table 4.4: Classification of Mobile Device Based on Screen Resolutions [6]

Device Classes	Class 1	Class 2	Class 3	Class 4	Class 5
Resolutions	$\geq 1024 \times 768$	$(1024 \times 768, 768 \times 480]$	$(768 \times 480, 480 \times 360]$	$(480 \times 360, 320 \times 240]$	$< 320 \times 240$

illustrated in Table 4.2 [5]. Table 4.3 indicates the variety of screen resolutions and the trend of the most common screen resolutions used for accessing the Internet [5]. The provided information reveals just few devices with high resolution, where most of the devices are desktops, laptops and netbooks. However, it is difficult to classify the mobile devices which include laptops, netbooks, tablets and cellphones. Hence, the cellphones and tablets present on the current market were also investigated. The information is illustrated in Table 4.3 and includes 227 device brands and 4914 device models.

According to the data listed in Table 4.2 and Table 4.3, the mobile devices were divided into five classes based on their screen size resolution. The highest resolution class ($\geq$1024$\times$768) includes most of the cellphones with high resolution and nearly all the laptops and netbooks. The classification of mobile devices based on screen resolution is indicated in Table 4.4 [6]. Once a new mobile device attaches to eNodeB and intends to request video services, the MDCS will classify this device and VQGDS will deliver the adaptive data stream according to the device classification.

4.3.3 Video Quality Grading & Delivery Scheme (VQGDS)

Video Quality Grading & Delivery Scheme (VQGDS) consists of the *Video Quality Grading mechanism* and the *Video Delivery Control mechanism.* VQGDS assumes the video sources have been either pre-encoded into a set of video clips with different quality levels (from high to low) and stored in the Multimedia Quality Levels Database, or via on-the-fly transcoding mechanism which converts the original high quality stream into lower bitrate versions at the desired quality level. Depending on the MDCS, the *Video Quality Grading mechanism* allocates an adequate set of video clips with different quality to the corresponding device class, shown in eq. (4.8).

$$\text{Class } m \longleftarrow \{QL^{(m)}\ m, \cdots, QL^{(m)}\ N\} \tag{4.8}$$

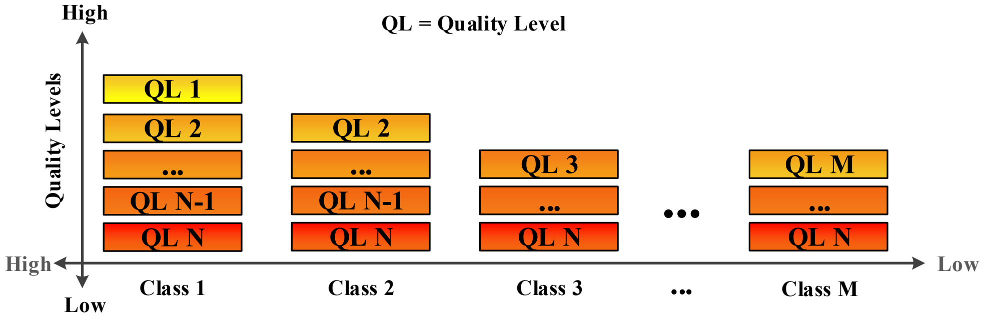


Figure 4.9: Video Quality Levels Allocation vs. Different Classes

For example, a video source has been pre-encoded into N video clips with the same content but different bitrates (e.g. 1920kbps, 960kbps, 480kbps, 240kbps, 120kbps and so on). Then the video clips from Quality Level 1(i.e. $QL^{(1)}$ 1) to $QL^{(1)}$ N representing the highest to lowest quality level, are assigned to the devices in Class 1. Similarly, the video clips from $QL^{(2)}$ 2 to $QL^{(2)}$ N are assigned to the devices in Class 2. Figure 4.9 indicates the relationship between different quality levels of the video clips and the different classes of devices.

The other component of **VQGDS** is the *Video Delivery Control mechanism* which adapts the delivery of the adequate video stream quality level to the mobile device depending on the QoS conditions of the current channel. In this work, the Video Delivery Control mechanism makes use of estimated system bandwidth to control the video stream delivery. Initially, the *Video Delivery Control mechanism* assigns the best quality video stream for mobile devices of each class. For example, $QL^{(1)}$ 1 video will be allocated for the devices in Class 1 and similarly $QL^{(2)}$ 2 video will be delivered to the devices in Class 2. If the available system bandwidth is high enough, the Video Delivery Control mechanism will deliver the highest quality level video streams to all these devices. If the available system bandwidth is low (i.e. due to increased number of users or severe background traffic), then the *Video Delivery Control mechanism* is triggered and the video stream delivery will be adapted to the appropriate quality level considering the correct channel conditions. The actual video quality level QL_m^* can be

Algorithm 4.2 Video Quality Grading & Delivery Scheme (VQGDS)

Input: M, the number of classes of UEs, $m \in \mathcal{M} = \{1, 2, 3, \cdots, M\}$; $\mathcal{K} = K_1 \cup K_2 \cup \cdots \cup K_m \cdots \cup K_M$, the set of all the UEs from all the classes, K_m is the set of UEs in classe m; $\Phi(t)$, the available system bandwidth at time instant t; TTI, scheduling unit.

Output: QL^*, the desired qulity level video stream to be allocated.

Initialization $t = 0$
Number of Classes, M;
Number of UEs of each class, K_m;
Let k_m be the index of UEs in class m, and $k_m \in K_m$;
Set the best bitrate of each class as R_k^m.
while *Streaming Service not Stop* **do**
    while $\mathcal{K} \neq \emptyset$ **do**
        for *each* $m \in \mathcal{M}$ **do**
            for *each* $k_m \in K_m$ **do**
                Compute $R_{m,k} \leftarrow$ eq.(4.10);
                Select $QL^* \leftarrow$ eq.(4.9)
            end
        end
    end
    $t \leftarrow t + TTI$
    Compute $\Phi_{Avail}(t) \leftarrow$ Network Conditions
end

selected by using eq.(4.9).

$$QL_m^* = \begin{cases} QL_m^{(m)} & , R_{m,k} \in [R_m^m, +\infty), \\ QL_{n+1}^{(m)} & , R_{m,k} \in \left[R_m^{n+1}, R_m^n\right), \\ QL_N^{(m)} & , R_{m,k} \in \left(0, +R_m^N\right) \end{cases} \tag{4.9}$$

where $QL_m^{(m)}$ is the best quality level for the devices in Class m, for example, the best quality level of the devices in Class 3 is $QL_3^{(3)}$ namely QL 3, as listed in Figure 4.9; similarly, $QL_N^{(m)}$ is the lowest quality level for the devices in any of the Class; n is the index of quality level and it is assumed that $m \leq n < n+1 \leq N$; $R_{m,k}$ is the available video bitrate of the k-th mobile device in Class m, which is computed in eq. (4.10).

$$R_{m,k}(t) = \Phi_{Avail}(t) \cdot \frac{R_k^m}{\sum\sum R_{m,k_m}^n} \tag{4.10}$$

where is the available system bandwidth (*kbps*) at time instant t; m is the index of the Class and $m \in \{1, 2, 3, , M\}$; k_m is the index of devices in the device class and $k \in K_m$. In addition, the available system bandwidth Φ_{Avail} can be predicted by using either the well-known bandwidth estimation tools studied in [195] or the CQI reports [12] from LTE system.

The detailed procedure of **Video Quality Grading & Delivery Scheme (VQGDS)** is described in Algorithm 4.2. For example, assume that UE **A** belongs to Class 1, then streaming to UE **A** can be adapted involving 5 adaptation levels or 5 QLs (i.e. 1920 kbps, 960 kbps, 480 kbps, 240 kbps, and 120 kbps). According to the available bandwidth estimated by the CQI report received by eNodeB (i.e. UEs CQI reports are delivered to eNodeB in advance), the available adaptive bitrate for UE **A** is calculated based on eq. (4.10). If the available bitrate is greater than 1920 kbps, then the highest QL with 1920 kbps will be assigned to it. If its available bitrate is less than 1920kbps, then a lower QL with 960kbps will be served and so on. Streaming to UE **B** of Class 2 can be adapted with 4 adaptation levels or 4 QL (i.e. 960 kbps, 480 kbps, 240 kbps, and 120 kbps). Similarly, the highest QL with 960 kbps will be allocated to UE **B** if the available bitrate calculated by the CQI report is greater than 960 kbps. If its available bitrate is lower than 960 kbps, then the lower QL with 480 kbps will be adapted to UE **B** and so on. A similar adaptation is performed for users of other classes. Since the procedure from Step 3 to 11 is linear, the algorithm complexity is $O(n^2)$.

4.4 Energy-aware DOAS for WiFi Offloading (eDOAS)

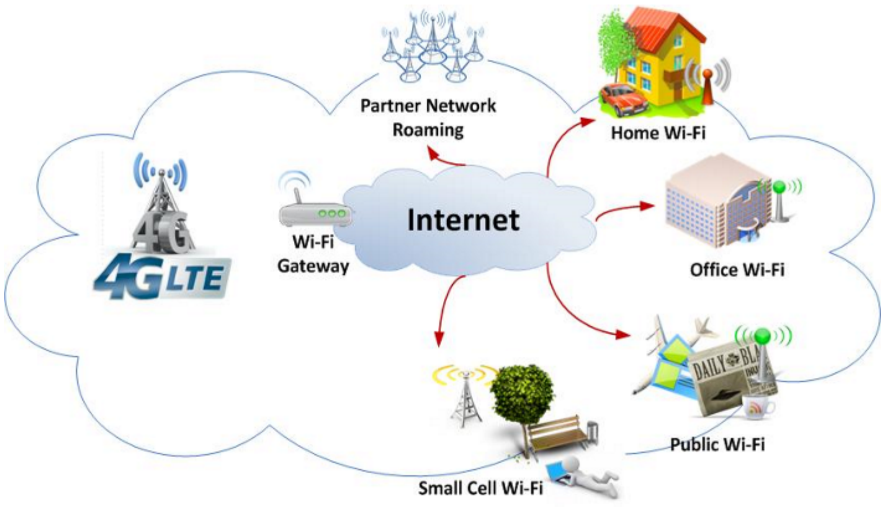


Figure 4.10: WiFi Offload - Example Scenario

The worldwide developing and rapid evolution towards next generation cellular networks make the network operators to face the problem of high infrastructure deployment cost. Therefore, a cost-efficient high-capacity enabler technique, mobile data offloading, has been key effects worldwide, included in 3GPP Release-13 [62]. Because of the all-IP network architecture and technical similarity between LTE femtocell and WiFi networks, it is easier to integrate data offloading from LTE networks to WLAN networks (e.g. IEEE 802.11 series protocols), compared with previous situations involving other 3GPP networks (e.g. GSM, UMTS). To this end, many network operators are starting to integrate WiFi as a new radio access interface with 3GPP cellular backhual, as shown in Figure 4.10.

This solution enables the transfer of some traffic from the core cellular network to WiFi at peak times at key locations (e.g., home, Office=, Public HotSpot, etc). The WiFi offloading solution is already adopted by many service providers. For example, O2 in United Kingdom offers the TU Go application to their customers enabling them to use their O2 mobile number to call or text over the WiFi network[1]. In this way users can avail of a wider service offering, while enabling network operators load release from their core network.

However, the overall experience is still far from optimal as providing high quality mobile video services with good QoS level 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 wide range of the video-centric applications (e.g. VoD, 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.

In order to increase QoS level for multimedia services, many adaptive mechanisms were proposed and adopted. A well-known dynamic HTTP-based adaptive multimedia scheme, MPEG-DASH [73], is standardized in 2014. MPEG-DASH server can smoothly adapt the different bit-rate streams based on network conditions enabling smooth video quality streaming to their clients.

DOAS, a Device-Oriented Adaptive multimedia Scheme for LTE networks was proposed in section 4.3. DOAS is built on top of the LTE downlink scheduling mechanism, and adapts the video streams based on the mobile device characteristics (e.g.

[1]TU Go: `http://www.o2.co.uk/tugo/`

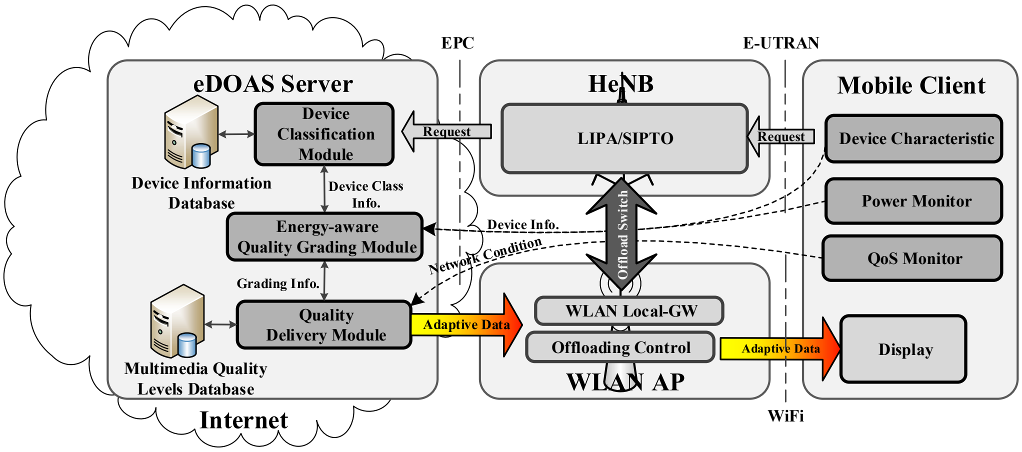


Figure 4.11: eDOAS -Framework

screen resolution) while maintaining an acceptable user perceived quality level. However, the energy consumption of the mobile devices was not considered. A battery and stream-aware dynamic multimedia control mechanism (BaSe-AMy) was proposed in [169]. BaSe-AMy monitors the power consumption of the mobile device and lowers the stream quality if the battery lifetime is not enough to finish the video playout. However the device heterogeneity was not considered. Most of the adaptive schemes proposed in the literature are either network-aware or QoS-based. Despite the amount of research done in this area, not little much focus has been placed on the impact of device heterogeneity on the energy consumption for multimedia transmission over a wireless environment.

This section introduces an enhanced **Energy-aware DOAS** (**eDOAS**) in the context of WiFi offloading, which enables the dynamic adaptation of multimedia delivery to mobile clients based on their device characteristics, energy consumption and underlying network conditions, in order to improve the perceived video quality of users and prolong the battery lifetime of the mobile device. eDOAS classifies the devices in different categories based on their resolutions and by using a real test-bed measurement setup and the energy consumption of each device class is measured.

4.4.1 eDOAS Framework

The framework for the proposed Energy-aware Device-Oriented Adaptive multimedia Scheme is illustrated in Figure 4.11. eDOAS is distributed and consists of two main parts: the Mobile Client or UE and the eDOAS server. The exchange of information between the two components is enabled by the LTE femtocell Home-eNodeB (HeNB) and WLAN Access Point (WiFi AP).

The **UE side** includes several essential functional modules:

- **Device Characteristic module** which stores the device characteristics (e.g. screen resolution, screen brightness, operating system);
- **Power Monitor module** which monitors the device battery and sends the battery-related information (e.g., battery remaining capacity, energy consumption rate, etc.) to the eDOAS server overSIP when the mobile user requests a multimedia service;
- **QoS Monitor module** periodically provides network condition information to the eDOAS server via Evolved Packet System bearer [3];
- **Display block** enables the presentation of the multimedia content to the users.

The LTE femtocell HeNB undertakes the basic functionalities of LTE eNodeB, and manages the data offload by switching from the cellular network to WLAN. The data offload function is defined in 3GPP Release-10 and includes an important module: **Local IP Access and Selected IP Traffic Offload (LIPA/SIPTO)** [68]. The LIPA/SIPTO, which is considered in the eDOAS architecture, mainly provides a local gateway and data offloading from LTE to WiFi. For example, the IP data traffic requested by the attached UEs is offloaded to the nearby wireless network access points, such as WLAN APs. In this work, the IP-based multimedia streams for mobile devices are offloaded from LTE HeNB to the WLAN network. The role of the offloading control module in WLAN AP is to manage the offloaded traffic from HeNB. eDOAS will be evaluated in this data offloading scenario.

As illustrated in Figure 4.11, the **eDOAS server side** is divided into three functional modules:

- **Device Classification Module** classifies the attached mobile devices according to the device information feedback (e.g. screen resolution) by using a *Mobile Device Classification Scheme (MDCS)*, and then stores the classified information in the database;
- **Energy-aware Quality Grading Module** makes use of an *Energy-aware Video*

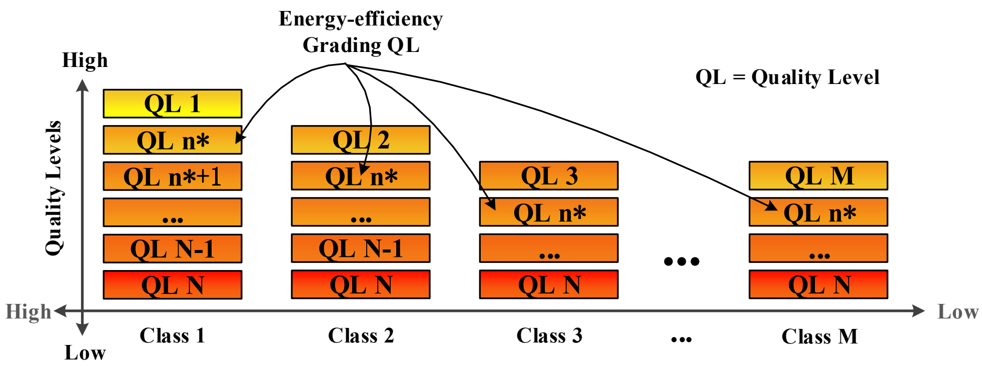


Figure 4.12: eDOAS - Energy-aware Video Quality Level Allocation

Quality Grading Scheme (eVQGS) to grade a set of video quality levels based on mobile device battery information;

- **Quality Delivery Module** selects and delivers a multimedia stream level from the Multimedia Quality Levels Database based on the *Video Quality Delivery Control Scheme (VQDCS)*.

4.4.2 Mobile Device Classification Scheme (MDCS)

According to different device characteristics, MDCS on the server side classifies the mobile devices into different classes. The classification is done according to the device screen resolution as indicated in Table 4.4 and was described in details in section 4.3.2 in the context of DOAS.

4.4.3 Energy-aware Video Quality Grading Scheme (eVQGS)

Energy-aware Video Quality Grading Scheme consists of two mechanisms: (1) the basic *video quality grading mechanism* and (2) the *energy-aware video quality grading mechanism*. The basic video quality grading mechanism allocates an adequate set of video clips with different quality levels to the corresponding devices, which is similar to the list of quality levels with respect to different classes illustrated in section 4.3.3. However, the final desired quality level assigned to UE also depends on the device energy consumption. The allocation list of different video quality levels to different classes of devices is illustrated in Figure 4.12.

The mobile device battery lifetime can be estimated by its remaining battery capacity, energy consumption rate and other parameters (e.g. working voltage and current) as in eq.(4.11):

$$\mu[sec] = \frac{C_B[mAh] \cdot V_B[V] \cdot 3600}{Power[mW]} \tag{4.11}$$

where μ is the battery lifetime expressed in second, C_B and V_B represent the battery capacity and battery voltage, respectively. When the mobile device plays an online video clip, the average power consumption $Power$ can be computed by using eq.(4.12) based on eq.(4.2) [190].

$$Power = \frac{E_J}{\lambda} = \frac{r_d \cdot D + r_t \cdot T + c}{\lambda} = r_d \cdot R + r_t + c' \tag{4.12}$$

where E_J is the consumed energy in Joule, λ is the duration of the online video clip in seconds; r_d is the energy consumption rate for data in $Joule/Mbit$, and r_t is the energy consumption per unit time in $Watt$; the total data of the received video clip is D ($Mbit$) and the average bitrate of this video clip is R in $Mbps$; both of c and c' are constants which are the tunable values for background energy consumption of the devices. In order to compute the values r_d and r_t, the real test-bed energy consumption measurements for each device class were performed as will be discussed in Chapter 5.

According to eq.(4.11) and eq.(4.12), it can be noted that the device battery lasts longer if the device plays a video clip with a lower bitrate. In order to guarantee the perceived video quality to the mobile users, the energy-aware video quality grading mechanism adapts the multimedia streams with the appropriate bitrate to the corresponding mobile clients depending on the remaining battery capacity of the mobile devices. Therefore, when a mobile user intends to watch a movie online, but the length of the movie is longer than the mobile device battery lifetime, the best energy-efficiency grading quality level will be selected from the allocation list assigned by the basic video quality grading mechanism as indicated in (4.13).

$$QL_{n^*}^{(m)} \Longleftrightarrow R_m^{n^*} = \underset{R \in (0, R_m^m]}{\arg min}\, \mu(R) = \{R | \mu(R) \geq \lambda \cdot \theta\} \tag{4.13}$$

where $QL_{n^*}^{(m)}$ is the best energy-efficiency grading quality level of class m which ensures the mobile user has enough battery life-time to finish the video clip, $R_m^{n^*}$ is the corresponding bitrate of $QL_{n^*}^{(m)}$; and $m \in \{1, 2, 3, \cdots, M\}$ represents the device class index. For example, the highest quality level of mobile device in Class 2 is $QL_2^{(2)}$

as listed in Figure 4.12; n represents the quality level index $m \leq n < n+1 \leq N$. Considering the fact that mobile users might want to still be able to use their mobile devices after finishing the movie playout, the estimated battery lifetime λ should be a little longer than the length of the video clip, and the extending duration factor $\theta = 1.1$ was introduced.

4.4.4 Video Quality Delivery Control Scheme (VQDCS)

After the best energy-efficiency grading quality level QL_n is selected by **eVQGS**, the **VQDCS** has to adapt the video stream to the mobile device depending on the QoS conditions of the current channel. If the available channel bandwidth is good, **VQDCS** will adapt the QL_{n^*} to the corresponding quality level in order to maintain an acceptable user perceived quality level. If the network condition is changing and the available bandwidth becomes low, the **VQDCS** will decrease step by step the quality level from $QL_{n^*}^{(m)}$ to $QL_N^{(m)}$. The network-aware quality level selection process can be described by using eq.(4.14).

$$QL_m^* = \begin{cases} QL_{n^*}^{(m)} & , r_{m,k} \in \left[R_m^{n^*}, +\infty\right), \\ QL_{n^*+1}^{(m)} & , r_{m,k} \in \left[R_m^{n^*+1}, R_m^{n^*}\right), \\ QL_N^{(m)} & , r_{m,k} \in \left(0, +R_m^N\right) \end{cases} \tag{4.14}$$

where $r_{(m,k)}$ is the available video bitrate of the k-th mobile device in Class m, which is computed in eq.(4.15).

$$r_{m,k}(t) = \Phi_{Avail}(t) \cdot \frac{R_k^{n^*}}{\sum\sum R_{m,k}^{n^*}} \tag{4.15}$$

where Φ_{Avail} is the available system bandwidth at time instant t; $k \in K_m$ is the device index within Class m. Similarly, the available system bandwidth Φ_{Avail} can be predicted by the well-known bandwidth estimation tools studied in [195].

The detailed procedure of Energy-aware Video Quality Grading Scheme (eVQGS) and Video Quality Delivery Control Scheme (VQDCS) is described in Algorithm 4.3. The complexity of this algorithm from step 3 to step 13 is $O(n^2)$.

Algorithm 4.3 eVQGS and VQDCS

Input: M, the number of classes of UEs; $\mathcal{K} = K_1 \cup K_2 \cup \cdots \cup K_m \cdots \cup K_M$, the set of all the UEs from all the classes, K_m is the set of UEs in class m; $\Phi(t)$, the available system bandwidth at time instant t; TTI, scheduling unit; The energy consumption parameters r_d and r_t of each mobile device; λ, video playout duration

Output: QL^*, the proper energy-efficient qulity level video stream to be allocated.

Initialization $t = 0$
Number of Classes, M;
Number of UEs of each class, K_m;
Let k_m be the index of UEs in class m, and $k_m \in K_m$;

while *Streaming Service not Stop* **do**
  while $\mathcal{K} \neq \emptyset$ **do**
    for *each* $m \in \mathcal{M}$ **do**
      for *each* $k_m \in K_m$ **do**
        Select the energy-optimal grading quality level: $QL_{n^*} \leftarrow$ eq.(4.13)
        Compute $R_{m,k} \leftarrow$ (4.15);
        Select $QL^* \leftarrow$ (4.14)
      end
    end
  end
  $t \leftarrow t + TTI$
  Compute $\Phi_{Avail}(t) \leftarrow$ Network Conditions
end

4.5 Evolved QoE-Aware Energy-Saving Device-Oriented Adaptive Scheme (e^{3}DOAS)

Balancing user QoE level and energy consumption of mobile devices represents the main challenge for video distribution in the future mobile and wireless environments. In this thesis, e^{3}DOAS , an Evolved QoE-aware Energy-saving Device-Oriented Adaptive Scheme for wireless networks is proposed, which optimizes the trade-off between QoE and energy savings and enables coalition-oriented game-based rate allocation of multimedia delivery to the mobile clients based on their device characteristics and underlying network conditions within the Small Cell environment. In Chapter 5 and Chapter 6, an Arduino-based power consumption measurement testbed and a crowdsourcing-based subjective video quality assessment method have enabled the introduction of utility functions to relate QoE and energy-saving factors for different device classes. In addition, simulation-based testing in a near-real OFDM-based scenario presented in Chapter 7 will show how e^{3}DOAS finds the best trade-off between system fairness,

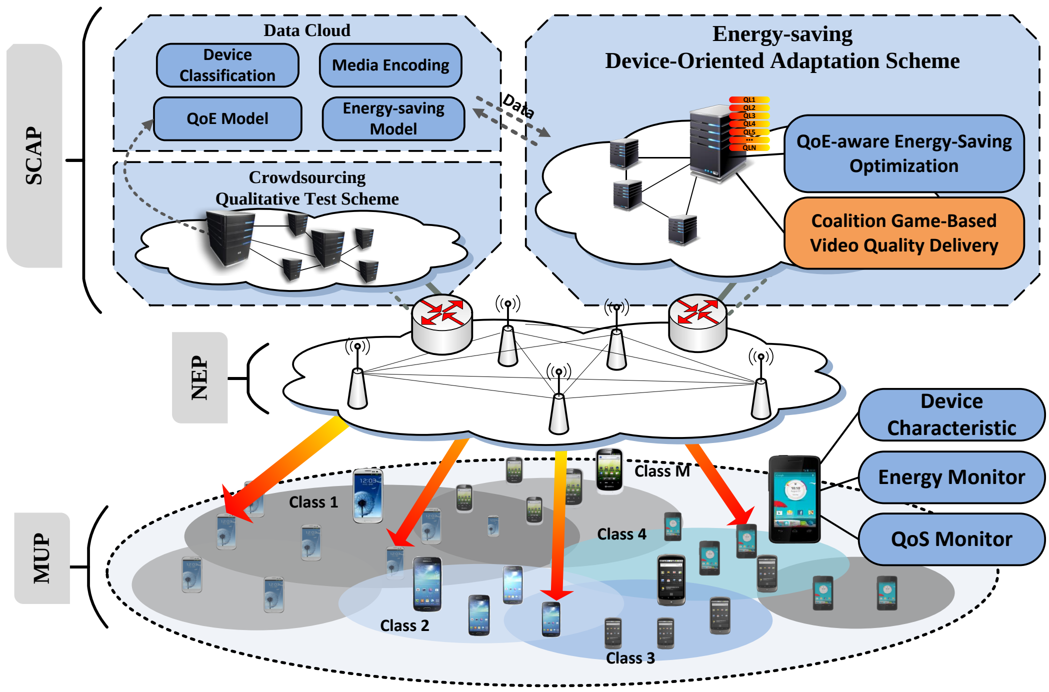


Figure 4.13: E^{3}DOAS Architecture

end-user QoE and energy savings when compared to other state of the art adaptive video delivery solutions.

4.5.1 e^{3}DOAS Framework

The system architecture of E^{3}DOAS is illustrated in Fig. 4.13 and consists of three main planes: the Mobile User Plane (**MUP**), the middle-layer Network Environment Plane (**NEP**) and the Service and Control Adaptation Plane (**SCAP**).

MUP includes heterogeneous mobile devices accessing VoD services. The mobile devices integrate several essential functional modules:

- **Device Characteristics** – stores device related information (i.e. screen resolution, maximum battery capacity and voltage, operating system, etc.);
- **Energy Monitor** – stores power consumption related parameters (i.e. energy consumption rate per unit data, background energy consumption while the device is in the idle state);
- **QoS Monitor** – provides periodic network conditions information to **SCAP**.

E^{3}DOAS is to be deployed in a multi-device heterogeneous wireless network environment similar to eDOAS and DOAS. It is assumed that the IP-based multimedia streams are delivered over the **NEP**, which maintains basic IMS signalling services. Therefore, E^{3}DOAS reduces the complexity of deployment in terms of the conventional multimedia delivery scheme.

SCAP is briefly described here. It consists of several main working subsystems:

- **Data Cloud** (**DC**) - which stores the classification information of mobile devices, encoded media streams, the QoE and Energy-saving models of different device classes;
- **Crowd-sourcing Qualitative Test System** (**CQTS**) - a cloud-based video delivery and subjective quality assessment system that provides an agile process to collect and analyze the QoE-related information of different types of mobile devices from a large group of persons through crowdsourcing;
- **Energy-Saving Device-Oriented Adaptation System** (**ESDOAS**) - classifies the quality levels of the multimedia streams based on different mobile devices types, then selects and adapts the specific quality levels at the mobile users' side according to the optimization problem and based on the device energy saving and the perceptual quality information obtained from **CQTS**. Depending on the channel conditions and the coalition game-based fairness model, the adaptive video content is streamed to the corresponding devices automatically.

CQTS and **ESDOAS** could be deployed on the same server or distributed on different physical servers. The functionality and the subjective data collection of **CQTS** are described in Chapter 6, thus the following sub-sections will introduce the **Data Cloud** and **ESDOAS** only.

4.5.2 Data Cloud (DC)

DC is E^{3}DOAS repository and consists of several database storing information related to the device characteristics, the quality levels of the encoded video streams for each device class, the QoE models, and the energy consumption models. It also provides the interface to update the QoE models and Energy consumption parameters periodically, and enables **ESDOAS** to access the QoE parameters and the energy consumption models efficiently. **DC** consists of four functional modules: Device Classification, Media Encoding, QoE Models and the Energy-saving Model.

The **Device Classification Module** classifies the registered mobile devices into several classes based on their device characteristics (i.e. device screen resolution). The device classification information is stored in **DC**.

Definition 4.1. *A registered mobile device belongs to the set of Class m (i.e. $1 \leq m \leq M$, $\forall m \in \mathcal{M}$ and $\mathcal{M}$ is a set of classes) when its screen resolution range is $RES_{m-1} > RES_m > RES_{m+1}$ and $RES_0 = \infty$, where $RES_m \equiv RES_m(WI_m, HI_m)$ and WI_m and HI_m are the screen width and height in pixels, respectively. M is the total number of device classes.*

The **Media Encoding Module** is capable of transcoding the original quality video clip into different quality level sequences $\mathcal{Q}^{(m)}$ with multi-step playback bit rates, frame rates and resolutions based on the different device classes m. Information about the characteristics of the encoded quality levels of the multimedia streams is stored in **DC**.

Definition 4.2. *The $QL_q^{(m)}(R_q^{(m)}, FR_q^{(m)}, RES_q^{(m)})$ denotes the q-th quality level video ($0 < q_m \leq q \leq N, q \in \mathcal{Q}^{(m)}$) with playback bitrate $R_q^{(m)}$, frame rate $FR_q^{(m)}$, resolution $RES_q^{(m)}$ for Class m. Where q is the quality level, N is the lowest coded quality level, and $N = M + \Delta$, where $\Delta \in \mathbb{Z}$ and $\Delta > 0$ is **Encoding Degree**. q_m refers to the highest quality level with $q_m = m$. Thus, the number of quality levels allocated to Class m is $|\mathcal{Q}^{(m)}| = N^{(m)} = N - q_m + 1$.*

Normally, **Encoding Degree** Δ can be defined by operators meaning greater encoding degree allows more quality levels for each class.

The **QoE Model** stores the QoE models of the different device classes which are updated from **CQTS** after the data processing, based on the method in [84] [20]. According to the logarithmic law of the QoE model presented in [92] [196], the specific QoE parameters for α_m and β_m of Class m are modelled, and a non-reference perceptual quality model for Class m is described as follows:

$$\Gamma_m = \alpha_m \cdot \ln(R_q^{(m)}) + \beta_m, \tag{4.16}$$

where $\Gamma_m \in (0, 1)$ is the average $PerceptualScore$ (which represents a QoE factor) of Class m at playback bitrate $R_q^{(m)}$, $\alpha_m > 0$ and β_m are constants. This QoE model will be referred to as QoE and energy-saving optimization in the following sections.

The **Energy-Saving Model Module** provides the parameters of energy consumption and saving, modelling the different mobile device classes for **ESDOAS**. Following the exponential law used for the application of risk-aversion utility [107] and sensitive energy consumption characteristic of mobile device studied in [197], an energy-saving model for a mobile device of Class m when receiving the multimedia stream is proposed as follows:

$$E_m^S = 1 - \exp(\zeta_m \cdot (\hat{P} - \eta_m)), \tag{4.17}$$

where $E_m^S \in (0, 1)$, and $\zeta_m > 0$ and $\eta_m > 0$ are the specific parameters. $\hat{P} \in [0, 1]$ is the normalized power consumption of the mobile device when receiving the multimedia stream:

$$\hat{P} = \frac{P_{q,m} - P_{min}}{P_{max} - P_{min}}, \tag{4.18}$$

where $P_{q,m}$ is the power consumption of Class m when receiving the multimedia stream with bitrate $R_q^{(m)}$. According to Definition 4.2, P_{max} has the maximum value when receiving the highest quality level (i.e. $R_{q_m,m}$. $P_{min} = 0$ when the mobile device is switched off). Therefore, eq.(4.18) can be simplified as $\hat{P}$ in eq.(4.19). The formula for power consumption is described as below [190]:

$$\hat{P} = {}^{P_{q,m}}/{}_{P_{max}} \tag{4.19}$$

$$P_{q,m} = r_{d,m} \cdot R_q^{(m)} + r_{t,m}, \tag{4.20}$$

where $r_{d,m} > 0$ is the energy consumption rate for streaming data rate ($mJoule/kbit$) of Class m; $r_{t,m} > 0$ is the energy consumption rate per time unit ($mWatt$) of Class m. Note, when $\hat{P} > 1$, then $\eta_m = 1$ and when $\hat{P} \leq 1$, then $\eta_m > 1$. This avoids E_m^S reaching its extreme low point that will stop the resource allocation in E^{3}DOAS .

4.5.3 Crowd-sourcing Qualitative Test System (CQTS)

In this thesis, **CQTS** is a prototype QoE measurement system which involves video delivery, participant and device registration, and subjective questionnaire and score modelling functions based on the cloud platform. This system enables a low-cost, flexible, fast-iterative method for future user experiment qualitative measurement and modelling [198] [199] [179]. In more detail, **CQTS** provides a web-based online assess-

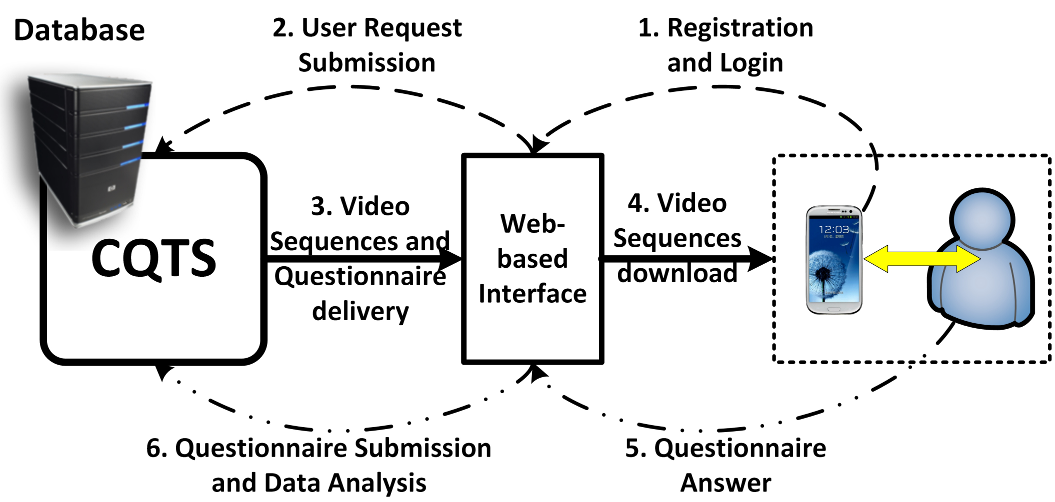


Figure 4.14: CQTS Principle

ment platform to mobile users who volunteer to register their mobile devices, download the specific testing video clips, watch those video clips on their registered devices and then score the subjective quality of those videos by filling an online questionnaire. **CQTS** makes use of the information from the **Data Cloud** (see Section 4.5.2) which consists of Device Classification and Media Encoding to model the QoE parameters for the current registered mobile devices periodically and iteratively. The procedure employs CQTS which is illustrated in Figure 4.14:

1. *Registration and Login* - First, the volunteers have to access the **CQTS** website and register their gender, age, and mobile device models (i.e. device brands, model numbers).

2. *User Request Submission* - The registration information of participants is submitted to the **CQTS** server side.

3. *Video Sequences and Questionnaire Delivery* - After the user request submission is received, the **CQTS** server will allocate the encoded video sequence to the corresponding mobile device by using the Device Classification Module. A perceived quality scoring questionnaire and specific viewing condition recommendation (i.e. view distance, screen luminance, background room illumination) are generated.

4. *Video Sequences Download* - The allocated video sequences can be downloaded to the corresponding mobile devices directly, or shared with other mobile devices by scanning the Quick Response (QR) code of the download link.

5. *Questionnaire Answer* - Following a Single-Stimulus-based (SS) experimental quality assessment method [84] [85], the participants score the video quality by taking a the web-based questionnaire. In order to reduce the effects of the extreme scores of some participants, a normalized perceptual video evaluation scheme is used in this thesis. The perceptual video quality score used in this thesis is mapped to the Mean Opinion Score (MOS) defined in the Absolute Category Rating (ACR) [85] method as in eq.(4.21):

$$MOS = \lceil 4 \cdot PerceptualScore + 1 \rceil. \tag{4.21}$$

6. *Questionnaire Submission and Data Analysis* - After completing the questionnaire, subjective data is uploaded to the **CQTS** server. Based on the logarithmic law of the QoE model in eq.(4.16). After gathering a large data set, the data is processed and screened following the processing method described in [84] [85]. The specific values for α_m and β_m of Class m are modelled. This QoE model will be referred to as QoE and energy-saving optimization next in E^3DOAS .

Moreover, the detailed real experiment setup based on CQTS description will be presented in the experimental subjective tests chapter.

4.5.4 Energy-Saving Device-Oriented Adaptation System (ESDOAS)

ESDOAS uses the same Device Classification module as **CQTS**. The mobile devices attached to the adaptive multimedia server are classified into several classes according to Definition 4.1 and the requested multimedia content is encoded at several specific quality levels based on Definition 4.2. Furthermore, **ESDOAS** consists of two main mechanisms:

- *QoE-aware Energy-Saving Optimization Scheme* (**QESOS**) which exploits the QoE and Energy-saving model in eq.(4.16) and eq.(4.17), respectively;
- *Coalition Game-based Video Quality Delivery Scheme* (**CGVQDS**).

4.5.4.1 QoE-aware Energy-Saving Optimization Scheme (QESOS)

QESOS - provides a cooperative game model to obtain the optimal video quality level for the trade-off between the perceptual quality of the mobile user and the energy-savings of the mobile device. From eq.(4.16) and eq.(4.17), the multiplicative exponent weighting (MEW) trade-off utility function of the individual mobile user and device of Class m is formulated as in eq.(4.22):

$$U_m = [\Gamma_m]^{w_q} \cdot [E_m^S]^{w_{es}}, \tag{4.22}$$

where w_q and w_{es} are the non-negative weighting coefficients of the particular mobile user and device based on their preferences of perceived quality, energy saving and performance. Note, $0 \leq w_q \leq 1$ and $0 \leq w_{es} \leq 1$ and $w_q + w_{es} = 1$. The parameter values of perceptual video quality models of different device classes are given by **CQTS**.

In order to obtain the optimal value of the video quality level for the individual Class m, the optimization game problem can be formulated as follows:

$$\begin{aligned} \underset{R_q^{(m)}}{\text{maximize}} \quad & U_m(R_q^{(m)}) = [\Gamma_m(R_q^{(m)})]^{w_q} \cdot [E_m^S(R_q^{(m)})]^{w_{es}}, \\ \text{subject to} \quad & R_q^{(m)} \in \{R_N^{(m)}, R_{N-1}^{(m)}, \ldots, R_{q_m}^{(m)}\}, \\ & \forall m \in \mathcal{M}, \\ & \forall R_q^{(m)} > 0. \end{aligned} \tag{4.23}$$

Lemma 1 asserts that $U_m(R_q^{(m)})$ is a strictly concave optimization problem satisfying the conditions defined in Definition 4.1 and Definition 4.2, and thus has a unique maxima.

Lemma 1. $U_m(R_q^{(m)})$ *is a concave optimization problem satisfying the conditions defined above with a unique maxima.*

Proof. Let $\varphi(x)$, $g_1(x)$, $g_2(x)$, $f_1(x)$ and $f_2(x)$ denote $U_m(R_q^{(m)})$, $\Gamma_m(R_q^{(m)})$, $E_m^S(R_q^{(m)})$, $[\Gamma_m(R_q^{(m)})]^{w_q}$and $[E_m^S(R_q^{(m)})]^{w_{es}}$, respectively, i.e., $x = R_q^{(m)}$, $x_{max} = R_{q_m,m}$ and $x_{min} = R_{N,m}$. $\varphi(x) = f_1(x) \cdot f_2(x)$ is said to be strictly concave down and has a unique maxima at $x \in \{x_{min}, \ldots, x_{max}\} \wedge \forall x > 0$ if eq.(4.24) is satisfied [200]:

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{\partial^2 f_1}{\partial x^2} \cdot f_2 + 2 \cdot \frac{\partial f_1}{\partial x} \cdot \frac{\partial f_2}{\partial x} + f_1 \cdot \frac{\partial^2 f_2}{\partial x^2} < 0, \tag{4.24}$$

According to the definitions of eq.(4.16), eq.(4.17) and eq.(4.20), the two functions $f_1(x) = [g_1(x)]^{w_q}$ and $f_2(x) = [g_2(x)]^{w_{es}}$ are non-negative. The first derivatives of $f_1(x)$

and $f_2(x)$ can be expressed as follows:

$$\frac{\partial f_1(x)}{\partial x} = \alpha_m \cdot w_q \cdot \frac{1}{x} \cdot \frac{f_1(x)}{g_1(x)}, \tag{4.25}$$

$$\frac{\partial f_2(x)}{\partial x} = -\frac{\zeta_m \cdot r_{d,m}}{P_{max}} \cdot \exp(\zeta_m \cdot (\hat{P} - \eta_m)) \cdot w_{es} \cdot \frac{f_2(x)}{g_2(x)}, \tag{4.26}$$

In the context, α_m, $r_{d,m}$, $r_{t,m}$, w_q and w_{es} are non-negative constants. From eq.(4.16) and eq.(4.17), $g_1(x)$, $g_2(x)$ are non-negative as well. By using the properties of the exponential function [201], this implies that $f_1(x) > 0$ and $f_2(x) > 0$. Thus eq.(4.27) can be achieved:

$$\frac{\partial f_1(x)}{\partial x} \cdot \frac{\partial f_2(x)}{\partial x} < 0, \forall x \in \{x_{min}, \cdots, x_{max}\}, \tag{4.27}$$

Next, in order to satisfy eq.(4.24), we have to prove that $f_1(x)$ and $f_2(x)$ are strictly concave with a maxima at $x \in \{x_{min}, \cdots, x_{max}\} > 0$. Thus, the derivatives of eq.(4.25) and eq.(4.26) with respect to x are given by eq.(4.28) and eq.(4.29),

$$\frac{\partial^2 f_1(x)}{\partial x^2} = -\frac{\alpha_m \cdot w_q}{(x \cdot g_1(x))^2} \cdot f_1(x) \cdot \eta_m \text{ , with } \quad \gamma = g_1(x) + \alpha_m(1 - w_q). \tag{4.28}$$

$$\frac{\partial^2 f_2(x)}{\partial x^2} = -\left(\frac{\zeta_m \cdot r_{d,m}}{P_{max} \cdot g_2(x)}\right)^2 \cdot \exp(\zeta_m \cdot (\hat{P} - \eta_m)) \cdot f_2(x) \cdot \epsilon \text{ ,}$$
$$\text{with} \quad \epsilon = g_2(x) + (1 - w_{es}) \cdot \exp(\zeta_m \cdot (\hat{P} - \eta_m)). \tag{4.29}$$

As $0 < w_q < 1$ and $0 < w_{es} < 1$, along with the above conditions, implies that $\gamma > 0$ and $\epsilon > 0$. This proves that:

$$\frac{\partial^2 f_1(x)}{\partial x^2} < 0, \frac{\partial^2 f_2(x)}{\partial x^2} < 0, \forall x \in \{x_{min}, \ldots, x_{max}\} \tag{4.30}$$

Based on the two non-negative functions $f_1(x)$ and $f_2(x)$, eq.(4.25) and eq.(4.30), eq.(4.24) can be proved, namely $\frac{\partial^2 \varphi}{\partial x^2} < 0$. Thus, $\varphi(x)$ is strictly concave down with a unique maxima in $\{x_{min}, \ldots, x_{max}\} > 0$. □

Hence, the utility model of the individual Class m is a concave optimization problem with a unique optimal video quality level for the trade-off between perceptual video quality and the energy savings of the mobile device. In conclusion, the optimal video quality level requested by the individual mobile users of device Class m at index $OPT(q)$

can be denoted as in eq.(4.31)

$$OPT(QL_q^{(m)}) :\Leftrightarrow R_{OPT(q)}^{(m)}$$
$$= \arg\max_{R_q^{(m)}} U_m(R_q^{(m)}), \quad (4.31)$$
$$\forall q \in \mathcal{Q}^{(m)}, m \in \mathcal{M}. \quad (4.32)$$

4.5.4.2 Coalition Game-based Video Quality Delivery Scheme (CGVQDS)

After the optimal video quality level $OPT(QL_{q,m})$ of Class m is selected by **QESOS**, the **Coalition Game-based Video Quality Delivery Scheme (CGVQDS)** adapts the multimedia stream to the current QoS conditions periodically. In this thesis, only the streaming mobile users distributed within the same network (e.g. the users located within the coverage area of the same wireless cell) are considered. Fig. 4.15 illustrates

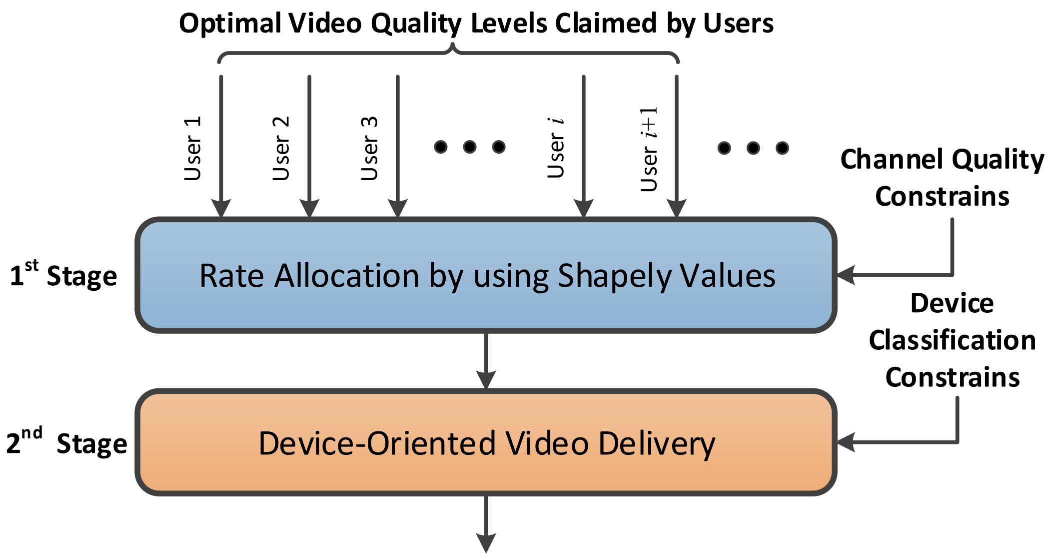


Figure 4.15: **VDQS** - Two-Stage Rate Allocation and Video Delivery

CGVQDS is a two-stage rate allocation and delivery structure which includes in 1^{th} Stage the feasible *rate allocation sub-scheme* for users based on a coalition game between the optimal video quality levels from **QESOS**, the channel quality constraints, and the device-oriented video delivery sub-scheme by using the multi-step device classification algorithm.

1^{th} Stage: Coalition Game-based Rate Allocation

The game theory provides a set of mathematical tools to study the complex interaction among rational players in network applications [202]. In general, game theory can be divided into two main branches: non-cooperative and cooperative (i.e. coalition) game theory. In this work, a coalition-based game approach was considered and used to solve the fair rate allocation problem among the network users of different device classes. This work is restricted to the Transferred Utility (TU) games [202].

A cooperative game is a competition between coalitions (i.e. group) of players, rather than between individual players. The individual decisions made by the players will affect each member of the coalition. Normally, a coalition game contains a pair $(\mathcal{I}, v)$ which involves a list of players, denoted by $\mathcal{I} = \{1, \ldots, I\}$, the cardinality $I = |\mathcal{I}|$, and the coalition value, denoted by v that quantifies the worthiness of a coalition in a game. The coalition value v in TU games can be defined as the characteristic function over the real line, namely $v : 2^{\mathcal{I}} \rightarrow \mathbb{R}$ with $v(\varnothing) = 0$ [203]. This characteristic function is associated with every coalition $\mathcal{S} \subseteq \mathcal{I}$, which quantifies the gains of $\mathcal{S}$. In addition, $\mathcal{I} \backslash \mathcal{S}$ denotes the complement set of $\mathcal{I}$. Every coalition game has $2^{\mathcal{I}}$ possible coalitions.

In this thesis, the problem of the channel rate shared by the streaming mobile users in the same network is formulated as a bankruptcy game or Talmud's allocation game [106], one of the coalition game models. The set of the streaming mobile users, namely the players, is referred to as $\mathcal{I}$ and its characteristic function of coalition $\mathcal{S}$ can be denoted by $v_\Phi(\mathcal{S})$. According to the O'Neill approach [204], the value of $v_\Phi(\mathcal{S})$ can be formulated as:

$$v_\Phi(\mathcal{S}) = \max \left\{ \Phi - \sum_{i \in \mathcal{I} \backslash \mathcal{S}} R^{(m)}_{i,OPT(q)}, 0 \right\} \quad \text{for} \quad \mathcal{S} \subseteq \mathcal{I}. \tag{4.33}$$

where Φ is the feasible system channel bandwidth estimated from the periodic channel quality conditions, $R_{i,OPT(q),m}$ is the bitrate of the requested optimal video quality level q of the mobile user i from device Class m given by eq.(4.31). The value $v_\Phi(\mathcal{S})$ of the coalition of users $\mathcal{S}$ is the remaining benefit of the channel resources after allocating the rates to the rest of the users in the complementary coalitions.

The Shapley value proposed by L. S. Shapley [205] solves the problem on how to obtain an unique solution and the fairness in the resource allocation process for each player and for each coalition in the coalition games. Thus, the Shapley value $\psi_i(v)$ of player $i \in \mathcal{I}$ in the TU game $(\mathcal{I}, v)$ is given by eq.(4.34):

$$\psi_i(v) = \sum_{\mathcal{S} \subseteq \mathcal{I} \backslash \{i\}} \frac{|\mathcal{S}|!(|\mathcal{I}| - |\mathcal{S}| - 1)!}{|\mathcal{I}|!} \left[v \left(\mathcal{S} \cup \{i\} \right) - v(\mathcal{S}) \right] \tag{4.34}$$

Generally the Shapley value is given by a unique mapping in TU games and satisfies the following set of axioms [206]:

Axiom 1. Efficiency: $\sum_{i \in \mathcal{I}} \psi_i(v) = v(\mathcal{I})$.

Remark: The first axiom implies the group rationality which requires the players to precisely distribute the available resources of the grand coalition. In this work, the total rate allocated to the mobile users (i.e. the users claim the video streams within the same network) equals the available network system channel bandwidth Φ. Thus, this axiom guarantees that a user cannot obtain a greater rate allocation without decreasing the rate of another user.

Axiom 2. Symmetry: If $v(\mathcal{S} \cup \{i\}) = v(\mathcal{S} \cup \{j\})$ for all $\mathcal{S} \in \mathcal{I} \backslash \{i, j\}$, then $\psi_i(\mathcal{I}, v) = \psi_j(\mathcal{I}, v)$.

Remark: The symmetry axiom requires symmetric players share the resources equally. In other words, the mobile users in the game equally share the available system bandwidth and their rate allocations do not depend on their order of entering the network.

Axiom 3. Dummy: If $v(\mathcal{S}) = v(\mathcal{S} \cup \{i\})$ for all $\mathcal{S} \in \mathcal{I} \backslash \{i, j\}$, then $\psi_i(\mathcal{I}, v) = 0$.

Remark: The dummy axiom requires that zero sharing resource should be assigned to the players whose utilities do not improve the value of any coalition. For the proposed video delivery system, there is no rate allocation assigned to the users who have stopped the video streaming or left the current video delivery system or network already.

Axiom 4. Additivity: Given any two games $(\mathcal{I}, v)$ and $(\mathcal{I}, w)$, if their characteristic function is defined as $(v + w)(\mathcal{S}) = v(\mathcal{S}) + w(\mathcal{S})$, then the Shapley value is $\psi_i(\mathcal{I}, v + w) = \psi_i(\mathcal{I}, v) + \psi_i(\mathcal{I}, w)$.

Remark: The additivity axiom requires that the Shapley value be an additive operator on the space of all games. Thus for our proposed video delivery system, if the users are in a heterogeneous networks environment with multi-network interfaces, then they request the video services from the same remote multimedia server via the multi-network interfaces simultaneously. For example, if the request is made via Networks A and B, then, the rate allocation of Networks A and B based on the game should be an additive function for the operator. Thus, their sum equals to the corresponding rate allocated on the remote server side.

Satisfied to these 4 Axioms, the proposed rate allocation scheme of **CGV-QDS** will have the appropriate rate allocated to streaming mobile user i belonging to the device Class m based on eq.(4.33)-(4.34), which is strict to eq.(4.35)-(4.36):

$$\mathcal{R}_i^{(m)} = \psi_i(v_\Phi(\mathcal{S})). \tag{4.35}$$

$$\text{s.t.} \quad \sum_{i \in \mathcal{I}} \mathcal{R}_i^{(m)} \leq \Phi. \tag{4.36}$$

2^{nd} Stage: Device-Oriented Video Delivery

If the available channel bandwidth of the current network is good, **CGVQDS** will adapt the $\mathcal{QL}_{i,q}^{(m)*} = OPT(QL_{i,q}^{(m)})_i$, namely the corresponding quality level to mobile user i. If the available bandwidth reduces, the **CGVQDS** will adapt down step by step the quality level from $OPT(QL_q^{(m)})_i$ to $QL_{i,N}^{(m)}$. This is done using eq.(4.37).

$$\mathcal{QL}_{i,q}^{(m)*} = \begin{cases} OPT(QL_{i,q}^{(m)})_i, & \text{if } \mathcal{R}_i^{(m)} \in \left[R_{i,OPT(q)}^{(m)}, +\infty\right), \\ QL_{i,OPT(q)+1}^{(m)}, & \text{if } \mathcal{R}_i^{(m)} \in \left[R_{i,OPT(q)+1}^{(m)}, \right. \\ \vdots & \qquad \left. R_{i,OPT(q)}^{(m)}\right), \\ \vdots & \qquad \vdots \\ QL_{i,N}^{(m)}, & \text{if } \mathcal{R}_i^{(m)} \in \left(0, R_N^{(m)}\right). \end{cases} \tag{4.37}$$

Details of the Energy-Saving Device-Oriented Adaptation System are presented in Algorithm 4.5.4.2. For example, assume that UE A belongs to Class 1, then streaming to UE **A** can be adapted with 6 adaptation levels or 6 QLs (i.e. 3840 kbps, 1920 kbps, 960 kbps, 480 kbps, 240 kbps, and 120 kbps). Considering the trade-offs between QoE and energy-saving, assume that the bitrate of the optimal QL for UE **A** is 1920 kbps. Based on the bandwidth allocation scheme which uses Shapely values, the available bitrate of UE **A** is calculated fairly. The highest QL with 1920 kbps will be assigned to UE **A**, if its available bitrate is greater than 1920 kbps. If the available bitrate is less than 1920 kbps, a lower QL with 960 kbps will be allocated to UE **A**, and so on. If UE **B** is of Class 2, streaming to UE **B** can be adapted with 5 QLs (i.e., 1920 kbps, 960 kbps, 480 kbps, 240 kbps, and 120 kbps). Based on the optimization of the trade-off

Algorithm 4.4 Energy-Saving Device-Oriented Adaptation Scheme

Input: Pre-defined $\mathcal{M}$, the set of device classes with corresponding Energy-Saving Model Parameters (ζ_m,η_m); Mobile Devices $\mathcal{I}$ requesting video streaming in the same network at time constant t; Pre-defined $\mathcal{Q}$, the set of Quality Levels with Parameters (α_m, β_m) and their corresponding pre-coding video dataset $\{QL_q^{(m)}\}$, $\forall m \in \mathcal{M}$ and $\forall q \in \mathcal{Q}$

Output: $\mathcal{QL}_{i,q}^{(m)*}$

1 **for** $i \leftarrow 1$ **to** I **do** get the optimal bitrates
2 $\quad RES_i \leftarrow$ Get resolution of mobile device i
$\quad m \leftarrow$ Get device classes for mobile device i by using RES_i
$\quad (\alpha_m, \beta_m) \leftarrow$ Get QoE modelling parameters of device i
$\quad (\zeta_m, \eta_m) \leftarrow$ Get Energy-saving modeling parameters of device i
$\quad$ **for** $q \leftarrow q_m$ **to** N **do**
3 $\quad\quad$ Compute the Utility based on α_m, β_m, ζ_m, η_m, $QL_q^{(m)}$ using eq.(4.17)-eq.(4.23)
4 $\quad$ **end**
5 $\quad OPT(QL^{(m)}i,_q) \leftarrow$ Get optimal quality level by eq.(4.31)
6 **end**
7 **for** $j \leftarrow 1$ **to** 2^I **do** compute 2^I coalition values
8 $\quad v_\Phi(j) \leftarrow$ Compute coalition values based on $OPT(QL^{(m)}i,_q)$ using eq.(4.34)
9 **end**
10 **for** $i \leftarrow 1$ **to** I **do**
11 $\quad \mathcal{R}_i^{(m)} \leftarrow$ Compute Shapley Values based on $\{v_\Phi\}$ using eq.(4.35)-eq.(4.36)
$\quad \mathcal{QL}_{i,q}^{(m)*} \leftarrow$ Get adapted quality level based on $\mathcal{R}_i^{(m)}$ using eq.(4.37)
12 **end**

between QoE and energy-saving, assume that the optimal QL for UE **B** is 960 kbps. In a similar way, the available bitrate of UE **B** will be calculated using Shapely values. If the available bitrate is greater than 960 kbps, the highest QL with 960 kbps will be allocated to UE **B**. A lower QL with 480 kbps is assigned to UE **B**, if its available bitrate is less than 960 kbps, and so on. A similar adaptation is performed for UEs of other classes.

4.5.4.3 Discussion

The complexity of **ESDOAS** algorithm is given by $O(2^n)$ since there is an exponential loop within the steps from 7 to 9 in Algorithm 4.5.4.2. In the practical deployment of E^{3}DOAS , the operators are suggested to distribute the **CQTS** and **ESDOAS** on different servers in order to increase performance. **CQTS** aims to collect and model the mobile users regionally and periodically (e.g. per week per and sub-area within the service coverage). Information of general energy models can be obtained from the mobile device manufacturers. Depending on the complexity of **ESDOAS**, **QESOS** and **CGVQDS** are suggested to be deployed to serve a small number of users (e.g. the LAN or wireless small cell with under 50 users). In Chapter 5 and Chapter 6, an energy measurement test-bed and a prototype based CQTS experiment were set up in order to identify the values of the following parameters of QoE and Energy-saving Models: α_m, β_m, $r_{d,m}$ and $r_{t,m}$.

4.6 Chapter Summary

This chapter introduced the proposed system architecture together with the basic principles and detailed algorithms of each of the proposed solutions. The four-fold main contributions of this research presented in this chapter are listed below:

- **Utility-based Priority Scheduling (UPS)** mechanism is a novel resource allocation scheme for LTE eNobeB access networks systems (E-UTRAN). UPS uses a cross-layer approach which not only considers the network conditions (e.g. loss and delay caused by channel distortion and interferences), but also takes into consideration characteristics of the mobile devices (e.g. screen resolution and power consumption). UPS makes use of utility functions in order to provide prioritization and multimedia service differentiation while maintaining an acceptable user perceived quality under dynamic network conditions.

- **Device-Oriented Adaptive Multimedia Scheme (DOAS)** is a cost efficient and fast-deployed solution built on the eNodeB scheduler. DOAS makes efficient use of the network resources and provides a superior QoE to multi-screen end-users. DOAS differentiates between the mobile devices based on their screen resolution and adapts the video transmission accordingly. DOAS jointly works with any scheduling mechanism (e.g. PF and M-LWDF) for downlink transmissions in LTE systems.

- **Energy-aware Device-Oriented Adaptive Multimedia Scheme (eDOAS)** makes use of the mobile device heterogeneity in order to provide smooth energy-aware adaptive streaming to mobile devices within a WiFi offload scenario. eDOAS prolongs the battery life of mobile devices by considering their energy consumption rate while accessing VoD.

- **Evolved QoE-aware Energy-saving Device-Oriented Adaptive multimedia Scheme (e^3DOAS)** takes into accounts the perceived video quality and power consumption rate of mobile device, and fairly allocates the different balanced quality levels to fit the different requirement of mobile users within a small-scale wireless coverage area. E^{3}DOAS makes use of the Coalition Game approach in order to balance the fairness between mobile users and to find the best QoE - energy saving trade-off.

Next chapter will introduce a real experimental test-bed setup used to conduct energy measurements when streaming different video quality levels to five mobile devices, each representing a different device class. The subjective test and simulation results and result analysis for each proposed solution are introduced in future chapters, respectively.

Chapter 5

Energy Experimental Testing: Platform, Results & Analysis

In order to model energy consumption pattern of the mobile devices, an experimental test-bed was setup and used for measuring the dynamically changing voltage and current of the mobile devices when performing Video on Demand over both cellular and broadband wireless networks (i.e. LTE and WLAN). This chapter presents the energy measurements experimental test-bed setup, testing scenarios results and an in-depth result analysis.

5.1 Experimental Test-Bed Setup

The experimental test-bed setup is illustrated in Figure 5.1 and consists of:

1. A **Belkin N wireless router**;
2. several **mobile client devices**, one device from each of the previously defined classes running VLC[1] as client video application;
3. **Power measurement functional block** that measures the mobile device power consumption;
4. **laptop** that stores the measurements, computes the energy consumption.
5. **Server** that delivers content on the VLC-based application.

[1]VLC Player: `www.videolan.org/vlc`

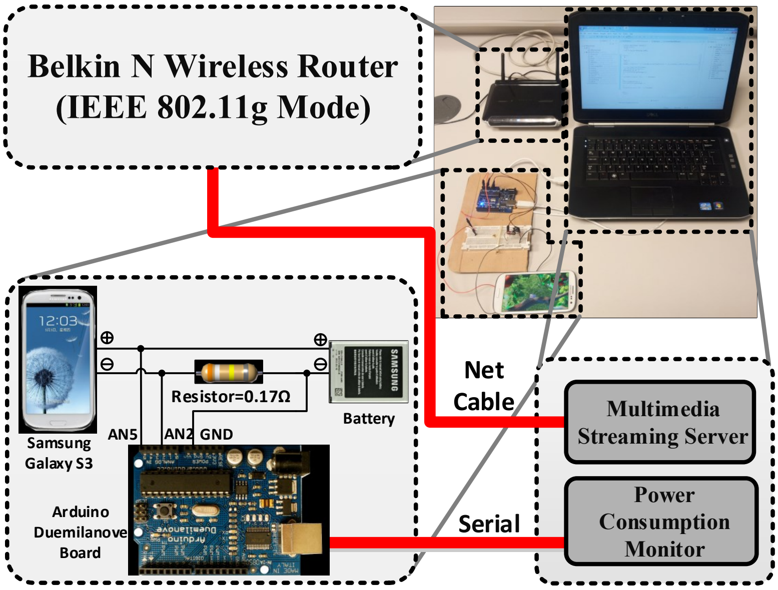


Figure 5.1: Energy Experiment Test-bed over WLAN

5.1.1 Test-bed Specifications

- **Belkin N Wireless Router** : The router was configured to run on Channel 13 (2.472GHz) with no other networks running on the same channel, in order to avoid interferences and it was configured to support IEEE 802.11g mode. The WLAN router is disabled, while the tests over LTE are performed.

- **VLC Multimedia Server and Client**: The VLC multimedia server was running on the Dell Latitude E5420 with Intel Core i3-2310M, 4 GB RAM, 10/100/1000 BG Ethernet and Windows 7 Enterprise 64bit. Five VLC client instances were running on five mobile devices, each device representing a different device class. The detailed features of the mobile devices are listed in Table 5.1. In particular, there are two selected mobile devices involved in Class 2, namely Tablet Viliv X70EX and LTE smartphone Samsung Galaxy S4mini. This is as the screen resolutions of most tablets are varying within Class 2 and LTE support is required as well as WLAN for the energy measurement in the experiment.

Table 5.1: Classification of Mobile Devices

Device Classes	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Resolution Ranges	$\leq 1024 \times 768$	$(1024 \times 768, 800 \times 600]$	$(800 \times 600, 480 \times 360]$	$(480 \times 360, 320 \times 240]$	$< 320 \times 240$
Device Models	**Samsung Galaxy S3**	1. **Viliv 70X EX** 2. **Galaxy S4 mini**	**Samsung Galaxy S2**	**Vodafone Smart Mini**	**Vodafone 858 Smart**
Model Images		1.  2. 			
Operating System	Android 4.2.2	1. Windows XP 2. Android 4.2.2	Android 4.1.2	Android 4.1.1	Android 4.0.4
Screen Types	Super AMOLED	1. WSVGA 2. Super AMOLED	Super AMOLED	TFT	TFT
Resolution	720×1280	1. 1024×600 2. 540×960	480×800	320×480	240×320
Battery Capacity	2100 mAh	1. 3920 mAh 2. 1900 mAh	1650 mAh	1400 mAh	1200 mAh
Battery Voltage	3.8 V	1. 7.4 V 2. 3.8 V	3.7 V	3.7 V	3.7 V
VLC Player Version	0.2.0-git	1. 2.1.1 2. 0.1.4	0.1.4	0.1.4	0.2.0-it

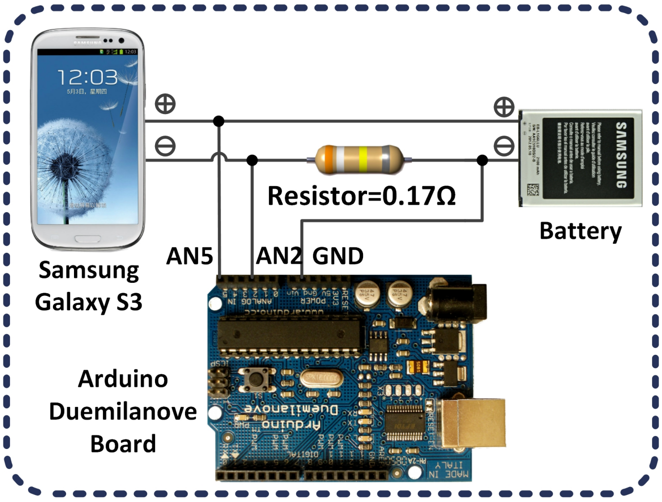


Figure 5.2: Power Measurement Functional Block

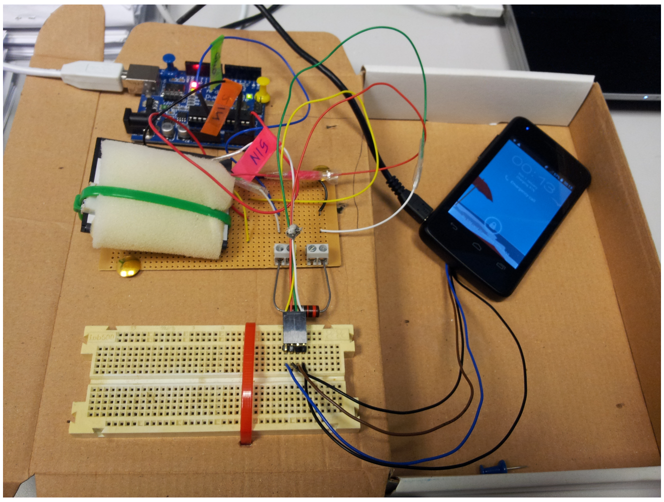


Figure 5.3: Arduino Board and Smartphones Setup

- **Power Measurement Functional Block**: Figure 5.2 and Figure 5.3 show the details of the power measurement functional block which includes the mobile devices (as described in Table 5.1), a micro-controller board namely Arduino Duemilanove[2], a low-value resistor and in-house developed power monitor software running on Dell Latitude E5420. Arduino Duemilanove is one of the Arduino products based on the ATmega168 or ATmega328 chips, and consists of: an open-source microcontroller (a 14 digital input/output pin), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The power monitoring program gathers the dynamically changing current and the voltage information measured on the mobile devices and sends it to

[2]Arduino board: `https://www.arduino.cc/en/Main/arduinoBoardDuemilanove`

Table 5.2: Arduino Board Setup Parameters

Parameters	Values
Voltage input ranges	7-12V, ±4V
Input pin	2, 5, GND
DC Current per I/O pin	40 mA
AnalogRead Speed	1000 bit/s
Series port Sampling rate	100 Hz - 0.1 Hz

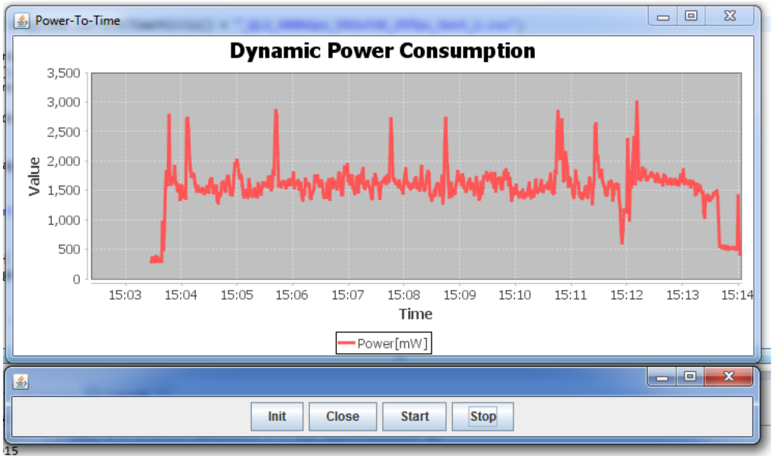


Figure 5.4: Energy Measurement Output Example: Video over UDP transmission to Class 2 device

the open-source JAVA-based monitoring program[3] running on the Dell Latitude E5420. The power monitoring program retrieved the data from the series-port format and converted them to decimal format, then computed the consumed power of the mobile devices by using Ohm's Law. The characteristics of Arduino board setup in the experiments and the output UI example from the measurement tool are given in Table 5.1.1 and Figure 5.4, respectively.

5.1.2 Multimedia Encoding and Streaming

A 10 minute long animation movie, Big Buck Bunny[4], was used for encoding and streaming. Four snapshots of the video clip content with different encoding complexity levels are presented in Figure 5.5. The **Snapshot (a)** shown in Figure 5.5 presents a nearly static background and slow moving scene. **Snapshot (a)** has low spatial and temporal complexity. **Snapshot (b)** has low temporal complexity as it moves slowly with many detailed information and the never changing background. **Snapshot**

[3]Open-sourcing Energy Monitoring and Measurement Tool: `https://github.com/allengzmm/Smartphone_PowerMonitor`

[4]Peach Blender: `https://peach.blender.org/`

(a) Low Spatial Low Temporal

(b) High Spatial Low Temporal

(c) Low Spatial High Temporal

(d) High Spatial High Temporal

Figure 5.5: Selected Snapshots of *Big Buck Bunny*

(d) has the highest encoding complexity because of both the fastest changing scene and dynamic background elements. The complexity of **Snapshot (c)** is similar to **Snapshot (b)**, but includes low spatial scene and high moving temporal background elements. The full video was transcoded into several different quality levels for each of these device classes which were stored on the server, resulting in a total number of 80 testing video clips. Table 5.3 lists the encoding parameters and characteristics of each multimedia quality level for the corresponding class. In order to maintain a consistent level of compression quality, the encoded resolution was varied together with the bitrate and frame rate. H.264/MPEG-4 AVC video compression and no audio compression were used together with the MP4 container format.

Different quality level videos stored in the multimedia server side were streamed to the corresponding mobile devices via TCP or UDP over wireless connections (i.e. WLAN or LTE), in order to analyze the impact of the transport protocols on the energy consumption of the mobile devices. The open-source VLC media player produced by VideoLAN was used to set up the Server-Client link between the server and the mobile devices. The VLC media player on the server-side streamed the videos to the VLC player embedded on the mobile device which is the client over the transport protocols either HTTP (based on TCP) or RTP (based on UDP). A detailed introduction to

Table 5.3: Encoding Formats for Multimedia Content

Device Classes	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Original Formats	H.264/MPEG-4 AVC Baseline Profile, total duration 597 seconds;				
QL1 - 3840 kbps	1280 × 720, 30fps	–	–	–	–
QL2 - 1920 kbps	800 × 448, 30fps	960 × 544, 30fps	–	–	–
QL3 - 960 kbps	512 × 228, 25fps	592 × 366, 25fps	800 × 448, 25fps	–	–
QL4 - 480 kbps	320 × 176, 20fps	368 × 208, 20fps	480 × 272, 20fps	480 × 320, 20fps	–
QL5 - 240 kbps	320 × 176, 15fps	368 × 208, 15fps	288 × 160, 15fps	300 × 200, 15fps	320 × 240, 15fps
QL6 - 120 kbps	320 × 176, 10fps	368 × 208, 10fps	288 × 160, 30fps	300 × 200, 10fps	320 × 240, 10fps

transport layer protocols can be found in Chapter 2.

5.1.3 Experimental Test Scenarios

In order to study the impact of different video quality levels streamed to different class mobile devices on energy consumption, non-network connection local playback, a near WLAN AP connection and a connection with real LTE network scenario were tested, respectively. The aim of experimental tests is to analyze the tradeoff between energy consumption and the video quality levels, and the impact of the transport protocols on the energy consumption over different wireless access environments. Four test scenarios were considered as described next. The scenarios use the configurations described in Table 5.4.

- **Scenario 1 – Local Playback**: the energy consumption was measured for local playback of each video quality level and for each device class, having "Airplane Mode" activated and no network connectivity. Additionally, to decrease the impact of the background applications running on the mobile devices, the Advanced Task Killer[6] was used to switch off all the background activity on each Andriod device. On the Windows tablet all the background processes where closed from the Task Manager window.

[6]Advanced Task Killer: `http://advanced-task-killer.en.softonic.com/android`

Table 5.4: Test Scenarios Configuration

Scenarios	Local Playback	WLAN	LTE
Device Config.	Airplane mode, All background applications disabled	Only WiFi enabled, background applications disabled	LTE enabled, background application disabled, Galaxy S4 mini tested only
Network Details	N/A	Device: IEEE 802.11g	Device: LTE Cat 3[5], Operator: Meteor Ireland
Signal Strength	N/A	-45dbm to -56dbm	-93dbm to -94dbm
Transport Protocol	N/A	UDP and TCP	TCP
Screen Brightness	80 to 120 *lux*, auto-brightness disable and set to ≈ 30%		

[5]Galaxy S4 mini Specs: `http://www.samsung.com/uk/consumer/mobile-devices/smartphones/galaxy-s/GT-I9195ZKABTU`

- **Scenario 2 – Streaming via RTP over WLAN**: the energy consumption was measured when streaming each video quality level from the VLC server over RTP/UDP to the mobile devices. In this case the "Airplane Mode" was inactive and the devices were connected to the WiFi network. All other testing conditions were kept the same as in Scenario 1.

- **Scenario 3 – Streaming via HTTP over WLAN**: Similarly to Scenario 2, the energy measurements in this case were conducted when streaming each video quality level to all the mobile devices **over HTTP/TCP**. All other testing conditions were kept the same.

- **Scenario 4 – Streaming via HTTP over LTE**: As the limited ports and protocols provided by the operator (i.e. Meteor Ireland[7]), only HTTP/TCP was available for LTE transmission in the experiments of this thesis. The Samsung Galaxy S4 Mini LTE smartphone was only tested in this scenario.

Additionally, in order to reduce the impact of the device display brightness on the power consumption, the brightness level for all the devices in each experiment was set to 30%. Each individual measurement experiment was repeated three times, with a total of 240 tests performed. The average values for all the results are presented in the

[7]Meteo Ireland: `https://www.meteor.ie/`

next section.

5.2 Experimental Results and Analysis

The experimental test results from the four scenarios are listed in Appendix A at the end of this thesis, as follows:

1. Table A.1 shows the energy measurement results for the multimedia content played locally on the mobile devices.

2. Table A.2 and Table A.3 show the energy measurement results when the multimedia content is streamed to the mobile devices over WLAN via TCP and UDP, respectively. Two Class 2 devices which run different operating system were tested.

3. Table A.5 and Table A.6 show the corresponding traffic monitoring results for the TCP and UDP tests over WLAN, respectively. Wireshark[8] was used to collect and retrieve data.

4. Table A.4 presents energy measurement results for the Class 2 Galaxy S4 Mini device while playing on-demand video via TCP over an LTE network.

The result analysis and discussion are presented in the following subsections. The goal is to analyze the energy measurement results in order to identify the impact of:

- device class (i.e. hardware/software performance of mobile devices) on the energy consumption;
- video quality level on the energy consumption for different device classes;
- transport protocol on the energy consumption for different device classes;
- wireless technologies (i.e. WLAN and LTE) on the energy consumption for different device classes.

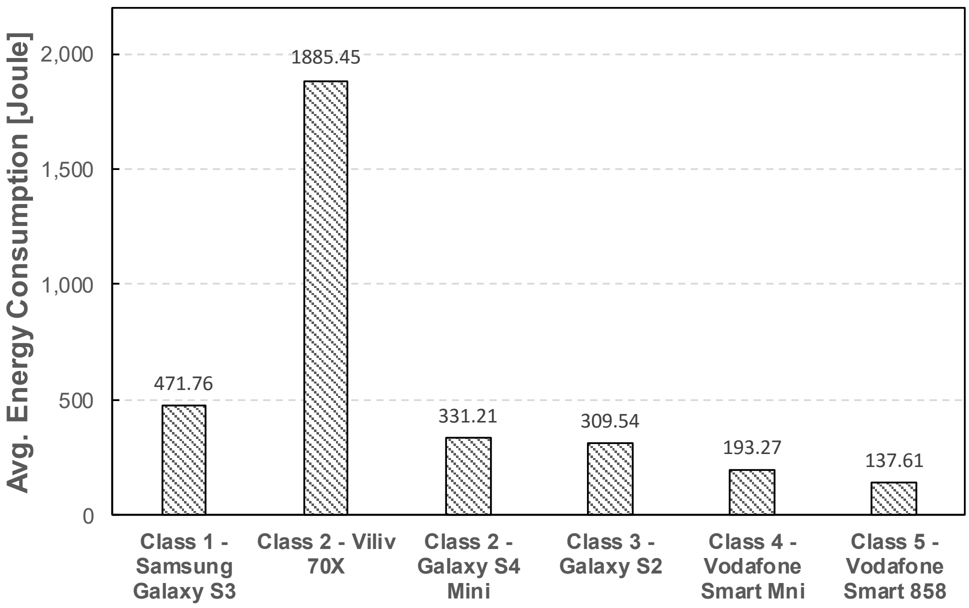


Figure 5.6: Average Energy Consumption of Different Devices while Playing Video Locally

5.2.1 Impact of Mobile Device Performance on Energy Consumption during Local Video Playback

In order to analyze the impact of the mobile devices with different hardware/software performance on energy consumption, Scenario 1 was considered where the energy measurements were tested with the different quality levels for each device class. The comparison among the different device classes is illustrated in Figure 5.6. Viliv 70EX, the tablet in Class 2 running the Windows XP operating system, has almost 300% higher energy consumption than the others. Samsung Galaxy S4 mini in the same class but running the Andriod OS has much lower energy consumption. Additionally, by looking at the results of Class 1, Class 2-Galaxy S4mini, Class 3, Class 4 and Class 5 from the figure, it can be noted that by decreasing the class level of the mobile devices (i.e. lower mobile device performance and screen resolution), we see a decrease in energy consumption of between 28.80% (i.e. From Class 4 to Class 5) and 37.45% (i.e. From Class 3 to Class 4) is achieved.

[8] Wireshark: `http://www.wireshark.org/`

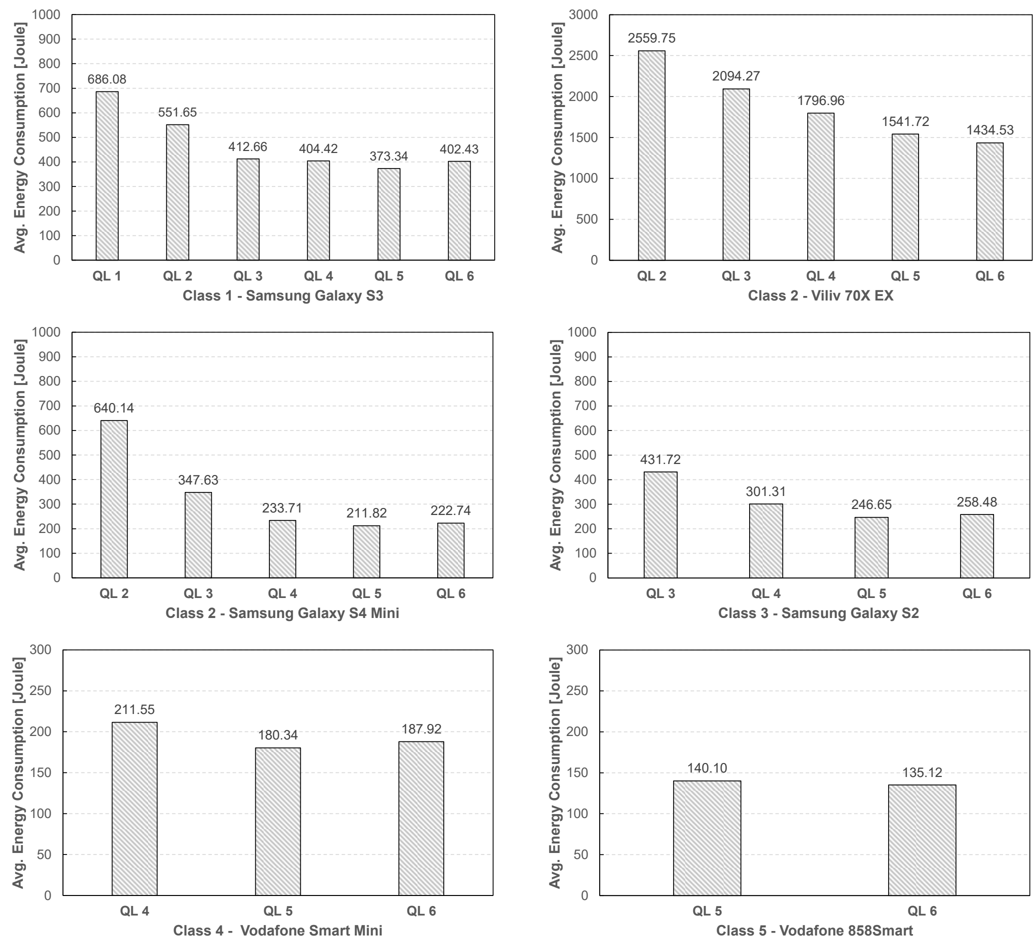


Figure 5.7: Comparisons of Energy Consumption of Different Classes while Playing Different Quality Level Videos Locally

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

In order to study the impact the differences of video quality levels have on energy consumption during local video playing without any wireless connectivity, the results from Scenario 1 were retrieved and processed (see Table A.1). Figure 5.7 shows these comparative results for each of the tested devices when different content encoded quality levels are used in turn. For instance, the results of Class 2 - Viliv 70X EX (i.e. with Windows XP OS) indicates how 40.39% of energy is saved when quality level drops from the highest to lowest one (i.e. From QL2 to QL6). Similarly, the other class devices (i.e. Class 1, 2-Galaxy S4mini, 3 and 4) presented the same energy saving behaviours except the lowest one.

Additional experiments were performed to test playing video clips using the default video players on various Android devices. CPU usage was monitored during video playout while playing different quality video clips. The tests show that the CPU usage of some of testing devices (i.e. Class 1 - Galaxy S3, Class 2 - Galaxy S4 mini, Class 3 - Galaxy S2 and Class 4 - Vodafone Smart Mini shown in Figure 5.7) increased when the player processed video streams at lower bitrate than the bitrate required according to the device resolution. This is as a de-blocking filter would also work to reduce the video blockiness and increase the displayed quality of the video. This filter consumes additional energy (see the results of QL 6 adapted for Class 1, Class 2 - Galaxy S4, Class 3 and Class 4 shown in Figure 5.7). In the tests, the energy consumption of the Class 5 device was not affected by the de-blocking filter as the filter was not running because the Class 5 device (i.e. Vodafone 858 Smart) has low display resolution and very small size screen.

5.2.3 Impact of Transport Protocols on Energy Consumption While Streaming Video over WLAN

In this subsection, Scenario 2 and Scenario 3 were considered for the study of impact of the different transport protocols (i.e. TCP and UDP) on energy consumption during WLAN streaming. In these experiments, VLC as the multimedia server, is able to provide several types of transmission protocols for streaming, such as RTP, HTTP, RSTP and FTP. Moreover, most of them are based on TCP or UDP. RTP based on UDP and HTTP based on TCP are used for the video streaming respectively as testing showed that they are working more stably than the others. The results of energy consumption while performing video stream over TCP and UDP are presented in Table A.2 and Table A.3, respectively. The data retrieved from the actual traffic monitoring information by using Wireshark was also illustrated in Table A.5 and Table A.6, respectively.

Similar to the local playback, higher quality video streaming over WLAN caused higher energy consumption as shown in Table A.2 and Table A.3. However, streaming over TCP saved a little more energy than that over UDP. For example in the results of Class 1, the QL1 video over TCP achieved almost 9% energy saving more than that over UDP. An observation from traffic statistics of TCP and UDP (see Table A.5

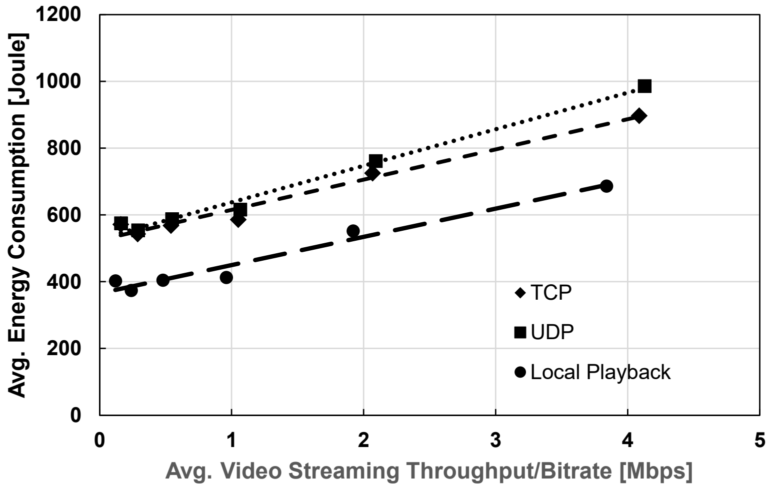


Figure 5.8: Class 1 (Samsung Galaxy S3) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

and Table A.6) that could be one of the reason why TCP performs better, is that the average packet size of TCP is distributed from 1292.79 to 1503.24 bytes, which means sometimes there are fewer packets to be transmitted, and lower overhead. The average packet size of UDP is 1370 bytes which caused more packets to be transmitted and higher overhead. Additionally the average throughput of UDP shown in Table A.3 is larger than that of TCP for the same video quality level as shown in Table A.6.

Similar conclusions (i.e. energy consumption when employing UDP is higher than when TCP was used) were also reported in [207] whose authors performed similar energy measurement experiments. Note that the size of UDP and TCP packet size could not be controlled in these tests, and the impact of TCP ACK packets were ignored, as they are small in size in comparison with the video data packets. This is also done in other similar works [208].

Note that it was zero packet loss for TCP (i.e. no retransmission) or UDP (i.e. no dropping packets) in the tests as the experiment environment has no background traffic, and only one client tested in the same time.

In order to compare the energy consumptions increased by playing videos over the different scenario distinctly, the relationships between energy consumption and video bitrate or streaming throughput of different devices are presented in the Figures 5.8 - 5.13.

Figure 5.8 shows how higher energy consumption for higher throughput of the

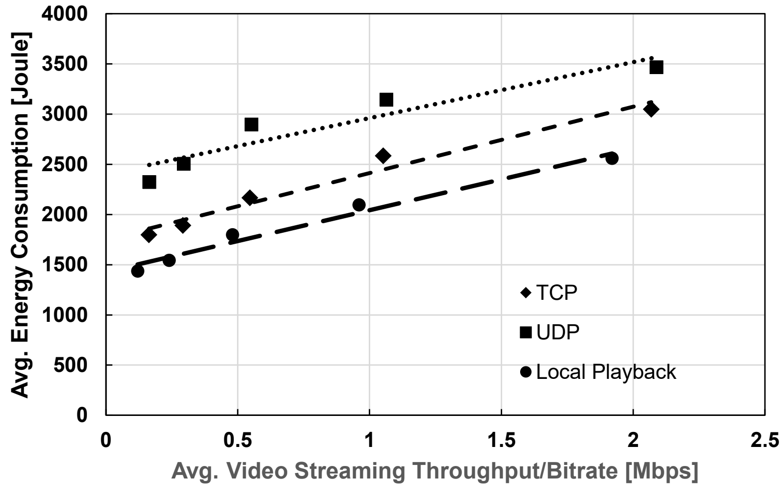


Figure 5.9: Class 2 (Viliv 70X EX) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

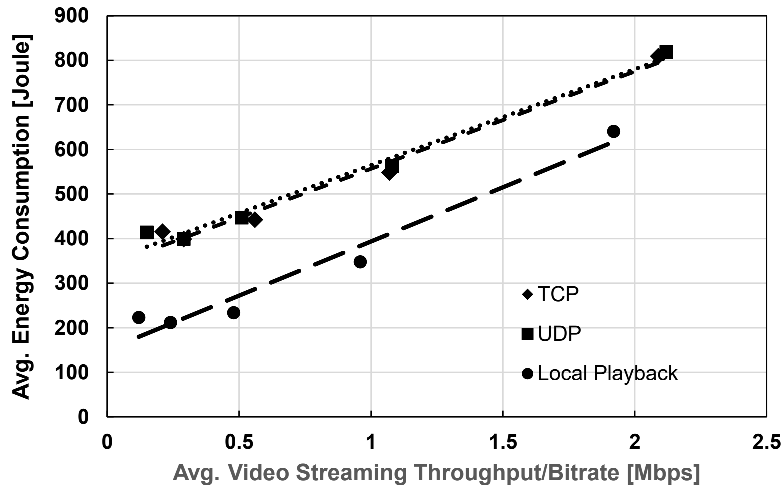


Figure 5.10: Class 2 (Samsung Galaxy S4 Mini) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

streaming over UDP was recorded compared to TCP streaming and local playback. Similar relationships were also found in the other device Classes. Additionally, the fitting lines for energy consumption against the varying video streaming throughput were plotted. Considering the modelling in eq.(4.12), the changing energy consumption is linear based on the varying streaming bitrate. Therefore, it is noted that the energy consumption is increasing positively when the bitrate/avg. throughput is increasing.

In terms of the fitting lines in Figure 5.8, 5.9, 5.10 and 5.11 (i.e. the devices in Class 1, Class 2 and Class 3) respectively, the slope of these lines was steep. Accordingly, it

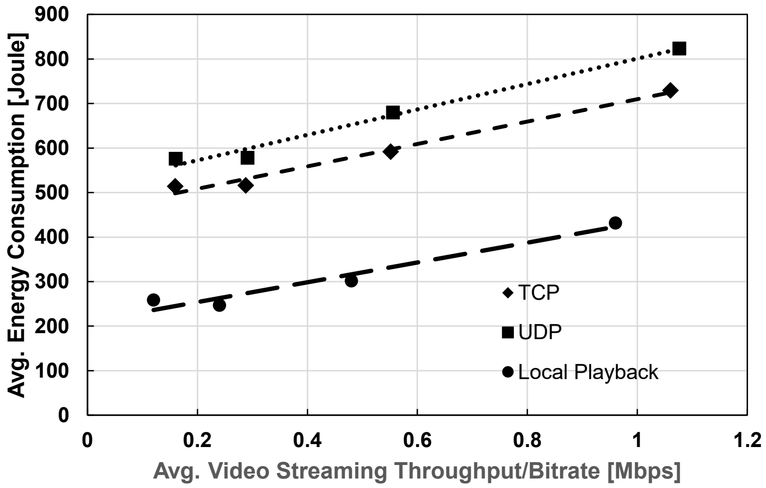


Figure 5.11: Class 3 (Samsung Galaxy S2) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

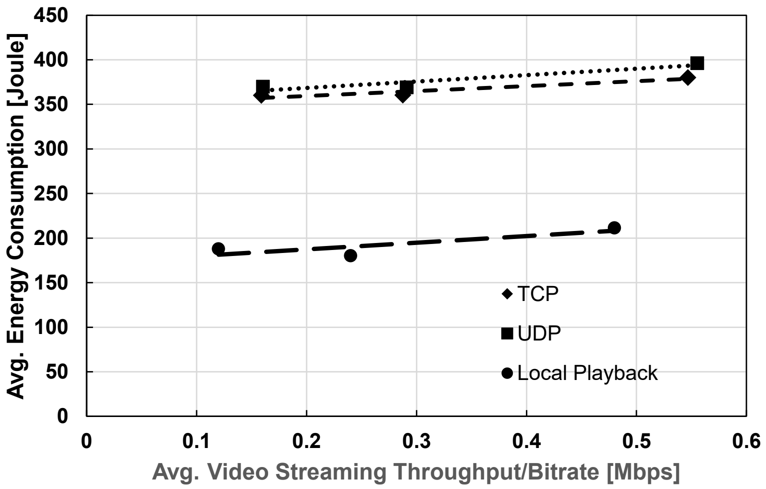


Figure 5.12: Class 4 (Vodafone Smart Mini) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

can be considered as a reason why the changing bitrate/avg. throughput affects energy consumption which was sensitive for the video quality levels. However, the fitting lines in other two figures (i.e. Class 4 in Figure 5.12 and Class 5 in Figure 5.13) look more flat rather than the lines for higher Class devices. Higher performance mobile devices have higher amounts of energy when performing quality level decreases than the low performance devices.

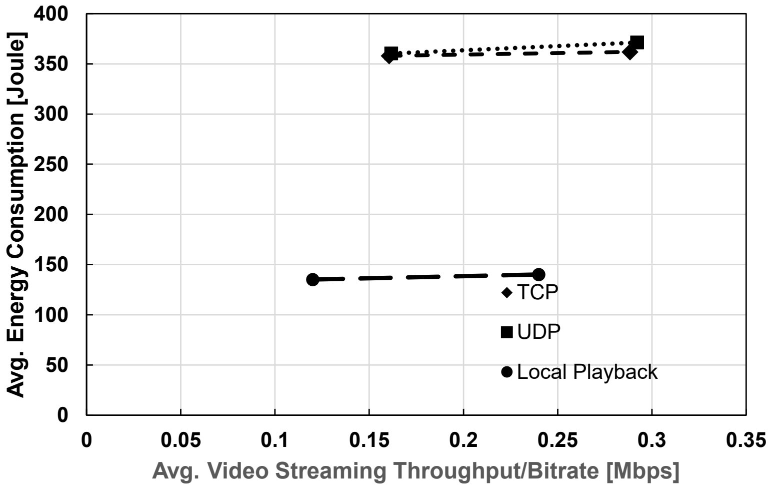


Figure 5.13: Class 5 (Vodafone 858 Smart) - Energy Consumption vs. Video Bitrate/Received Streaming Throughput

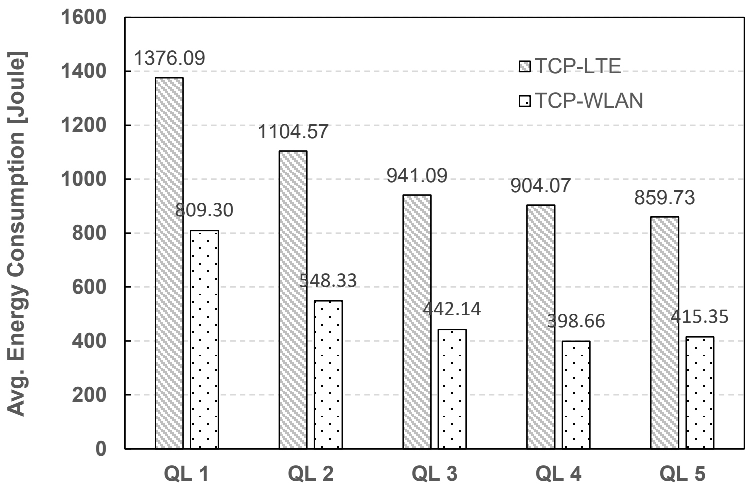


Figure 5.14: Comparisons of Avg. Energy Consumption between LTE and WLAN while streaming multimedia to Galaxy S4 Mini (TCP)

5.2.4 Impact of Different Wireless Environments on Energy Consumption while Streaming Video

In this thesis, only HTTP/TCP was available to be used for streaming experiments over the LTE network provided by the Irish operator. Additionally due to the limited device availability, a single LTE smartphone, Samsung Galaxy S4 mini, was employed. Moreover, a similar energy testing for comparison of LTE and WiFi was studied in [208], which indicates in general LTE consumes more energy than WiFi by transmitting the same content because LTE employs more complicated working procedure and wider coverage.

The energy measurement results of LTE transmission testing are presented in Table A.4. A comparison between LTE and WLAN while streaming the same quality level videos is shown in Figure 5.14. Similarly, energy consumption decreases when the streamed quality level is degraded. For example, when the highest quality QL 1 is streamed via LTE, the energy consumption is 41.2% greater than that via WLAN. In this experiment, using WLAN for VoD saves on average 50.4% energy over LTE.

5.3 Chapter Summary

This chapter presents the experimental test-bed setup for energy measurements and an in-depth analysis of the results obtained. The energy consumption measurements were conducted for different device classes while performing video on demand.

A total of 240 energy tests were carried out on six mobile devices, with one device representing each device class (except Class 2 which is represented by two phone models), as previously defined. A different number of video quality levels were streamed from a multimedia server over a WiFi or LTE network to the corresponding mobile devices. Two different transport protocols TCP and UDP were considered. The aim of the experimental energy measurements is four-fold:

- Study the impact of the device class on energy consumption;
- Study the impact of the video quality level on the energy consumption for each device class;
- Study the impact of the transport protocol on the energy consumption for each device class;
- Study the impact of different wireless environments on the energy consumption for Galaxy S4 Mini which streams multimedia content.

The experimental results show that higher performance mobile devices consume more energy, the lower the video quality level the higher the energy savings and video streaming over TCP achieves more energy savings than that over UDP. Finaly LTE-based delivery incurs higher energy consumption than a similar video transmission over WLAN network.

In addition, the energy consumption models of different transport layer protocols

Table 5.5: Test Scenarios Configuration

	Devices	TCP		UDP	
		r_d $[mJoule/kbps]$	r_t $[mW]$	r_d $[mJoule/kbps]$	$r_t[mW]$
Class 1	**Galaxy S3**	0.1652[1]	870.57[1]	0.2018[1]	907.28[1]
Class 2	**Viliv 70X EX**	1.1567[1]	2892.75[1]	0.9171[1]	2867.93[1]
	Galaxy S4 mini	0.4101[1] 0.4714[2]	570.46[1] 1403.77[2]	0.2723[1]	666.67[1]
Class 3	**Galaxy S2**	0.4981[1]	745.77[1]	0.3624[1]	880.57[1]
Class 4	**Vodafone Smart Mini**	0.1377[1]	571.51[1]	0.5011[1]	531.65[1]
Class 5	**Vodafone 858 Smart**	0.0537[1]	594.21[1]	0.1449[1]	596.59[1]

[1]via WiFi connection
[2]via LTE connection

(i.e. TCP and UDP) based on eq.(4.12) for different mobile devices are fitted in Figures 5.8 - 5.13 and then solved with a linear function. And their parameters (i.e. r_d and r_t) tested in WiFi and LTE networks are listed in Table 5.5, which will be used for the modelling of the proposed algorithms and network simulation in Chapter 7.

Chapter 6

Subjective Experimental Testing: Environment, Results & Analysis

In order to analyze the impact of video quality levels (QL) and device classification on the perceived user experience, subjective experiment involving multi-device and multi-resolution diverse complexity content was performed. This chapter describes QoE experimental testing and presents the results and then analysis.

6.1 Overview of Subjective Test

Before subjective testing, the tested mobile devices and encoded video clips are prepared. In addition, an available testing venue must be selected, and participants recruited and testing scheduled before starting the tests. A sample video and a quality rating scheme are used to train the participants before they start a formal video rating procedure. After all the tests are completed, the results will be imported from the web-based questionnaire system and then processed. The final screened results are analyzed and studied for the impacts on user perceptual quality, and QoE models proposed in e^{3}DOAS. The details of the subjective tests are presents in the following sections.

6.2 Subjective Experiment Setup

6.2.1 Mobile Devices

This subsection introduces how to classify the mobile devices into several groups, namely classes, based on the different display resolutions referring to E^3DOAS . Similar to the device classification in Chapter 4, five mobile devices which belong to the five different classes were used in the subjective test, see Table 6.1. These five mobile devices were the flagship models in the past five years or the favourite products published by the operators. These devices were selected for the test as they are the most popular mobile devices in the current market. Detailed characteristics of theses mobile devices can be found in Table 5.1 in Chapter 5.

Table 6.1: Mobile Devices in Five Classes used in Subjective Tests

Device Classes	Class 1	Class 2	Class 3	Class 4	Class 5
Resolutions	$\geq 1024 \times 768$	$(1024 \times 768, 768 \times 480]$	$(768 \times 480, 480 \times 360]$	$(480 \times 360, 320 \times 240]$	$< 320 \times 240$
Device Models	Samsung Galaxy S3	Samsung Galaxy S4 Mini	Samsung Galaxy S2	Vodafone Smart Mini	Vodafone 858 Smart

6.2.2 Video Sequences Selection and Quality Level Encoding

Due to the limitation in test duration recommended by ITU-T R. P.913 [85], four 10 second video clips were selected from *Big Buck Bunny*, as listed in Table 6.2. The **Clip A** and **Clip D** present nearly static background, which is encoded with low spatial and temporal complexity. **Clip C** displays the list of credits slowly at the end of the movie. Therefore **Clip C** displays the details of the rolling dense text with very high complexity. **Clip B** presents low spatial scene and rapid moving temporal elements. The comparison of the clips spatial-temporal information computed by TISI Calculator[1] are shown in Figure 6.1.

In order to achieve higher accuracy of QoE modelling, multiple quality levels were considered in the subjective tests, more entries than those presented in the video quality classification in Table 5.3. Thereafter, each of the 4 video clips was encoded at six different quality levels[2] for each of the five device classes and was stored on the server,

[1]Subjective Video Tools: `http://www.inf.ufrgs.br/~lcdaronco/svq/`
[2]Smooth Streaming Calculator: `http://alexzambelli.com/WMV/MBRCalc.html`

Table 6.2: Selected Video Clips

Video Clip Types	A	B	C	D
Play Duration	<0:01~0:11>	<7:10~7:19>	<9:00~9:10>	<4:45~4:55>

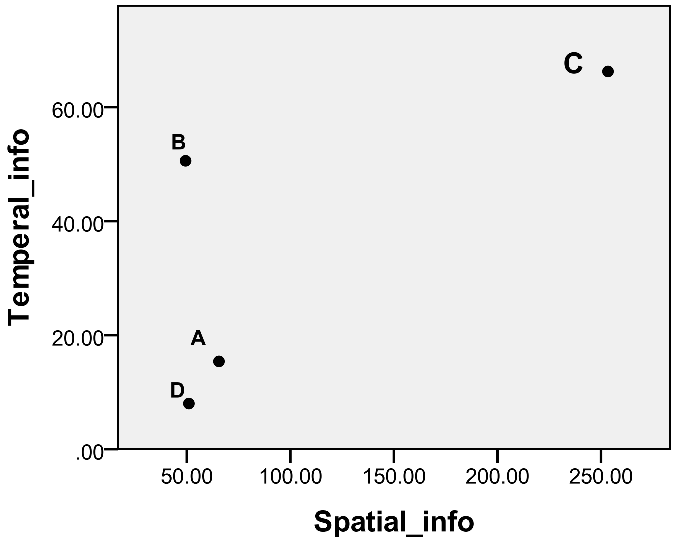


Figure 6.1: Temporal Information vs. Spatial Information

Table 6.3: Encoding Formats of Multimedia Streams for Subjective Tests

Device Classes	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**
Original Formats	H.264/MPEG-4 AVC Baseline Profile, without audio encoding; 4 Types of Video Clips				
QL1 - 3840kbps	1280 × 720, 30fps	960 × 544, 30fps	800 × 448, 25fps	480 × 320, 20fps	320 × 240, 20fps
QL2 - 1920kbps	800 × 448, 30fps	960 × 544, 30fps	800 × 448, 25fps	480 × 320, 20fps	320 × 240, 20fps
QL3 - 960kbps	512 × 228, 25fps	592 × 366, 25fps	800 × 448, 25fps	480 × 320, 20fps	320 × 240, 20fps
QL4 - 480kbps	320 × 176, 20fps	368 × 208, 20fps	480 × 272, 20fps	480 × 320, 20fps	320 × 240, 20fps
QL5 - 240kbps	320 × 176, 15fps	368 × 208, 15fps	288 × 160, 15fps	300 × 200, 15fps	320 × 240, 15fps
QL6 - 120 kbps	320 × 176, 10fps	368 × 208, 10fps	288 × 160, 30fps	300 × 200, 10fps	320 × 240, 10fps

resulting in a total number of 120 (i.e. $4 \times 6 \times 5$) testing video clips. Table 6.3 lists the encoding parameters and characteristics of each multimedia quality level for all device classes. In order to maintain a consistent level of compression quality, the encoded resolution was varied together with the bitrate and frame rate. H.264/MPEG-4 AVC video compression was used together with an MP4 container. The video clips were played with the VLC player[3] on the different mobile devices (see Table 5.1). Additionally, different delivery channel conditions were also considered, which designed four different simulated transmission scenarios associated with different network congestion levels. By using the *dummynet* tool[4], the 120 video clips were subjected to 4 different packet loss ratios (i.e. 0%, 0.1%, 0.5% and 1%). Therefore, total 480 video clips were generated and used in the subjective tests. However, each participant has watched 24 video clips randomly selected from the video clips for each mobile device. Testing duration was roughly 30 minutes (the participants have a 2-minute break between two different device). The order in which the various mobile devices are used is also random.

6.2.3 Test Venue and Environment

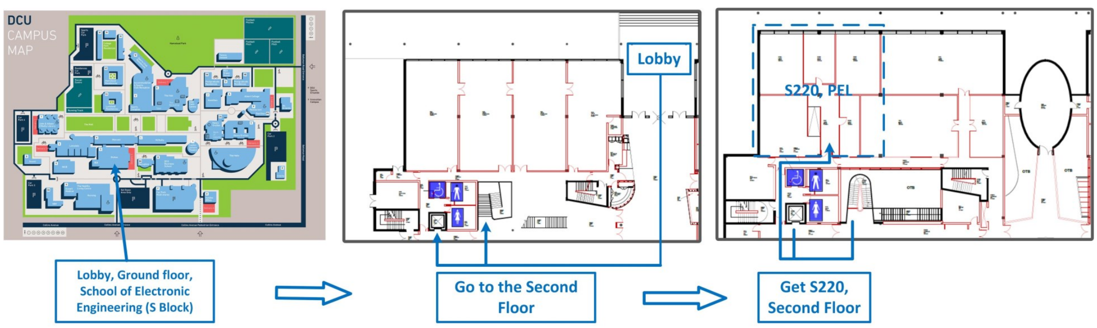


Figure 6.2: The Test Venue Location in DCU Campus

The test venue is located in the Performance Engineering Laboratory (Room S220), School of Electronic Engineering, Dublin City University (i.e. PEL@S220), see Figure 6.2. The indoor environment of the test room is illustrated in Figure 6.3. The indoor illumination was set to $15{-}18lux$ and the display brightness level of each device was set to 30%. (i.e. $180{-}250\ cd/m^2$). Figure 6.3 also shows the major equipment used in the test: a platform for online collection of questionnaire reports, the testing mobile device, and a test monitor that observes the real-time status of the testing. The online

[3]VLC website: `http://www.videolan.org/vlc/`
[4]dummynet: `http://info.iet.unipi.it/~luigi/dummynet/`

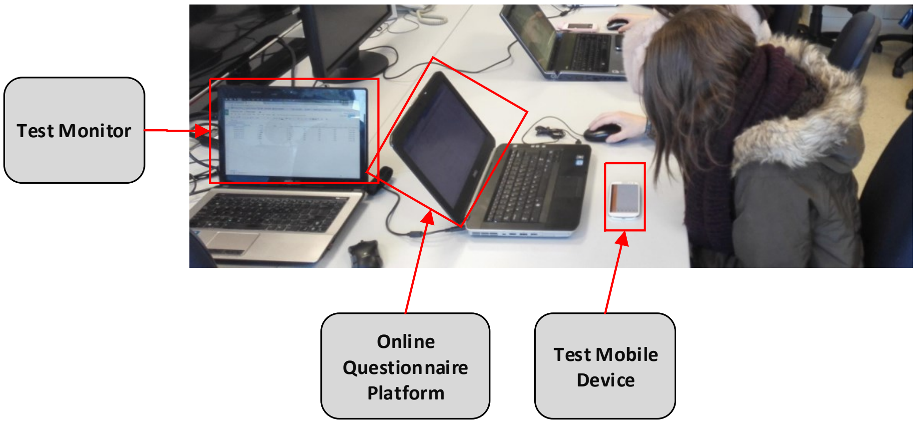


Figure 6.3: The Test Venue Environment Overview

questionnaire form was created based on the *Google Form*[5] which enables data collection and processing more conveniently. The questionnaire form design is presented in Appendix B.

6.2.4 Volunteer Recruitment and Test Scheduling

The experiment was started on 2 March and finished on 9 March 2015. Total 73 persons from DCU Business School attended the test venue in S220 of PEL@DCU. The main participants were master students of Next Generation Management Program by Business School of Dublin City University. The Doodle online event scheduler[6] was used for participant time-slot allocation. The participants who were willing to sit the tests received an email with the scheduler link and they were asked to select from the available time slots the ones in which they could attend. Each time slot was 30 minutes. The participants who succeeded to choose the time slots will receive a confirmation email which involves the time allocated at the test venue. All the participants in the tests are the university students, and their gender and age distributions are shown by the histogram presented in Figure 6.4 and Figure 6.5.

6.2.5 Subjective Test Rating Scheme

In this subjective test, the nine-grade rating scale was used for the assessment of low bit-rate video codec [85]. The comparison and transformation between nine-grade and

[5]Google Form: `https://www.google.com/forms`
[6]Doodle: `http://doodle.com/`

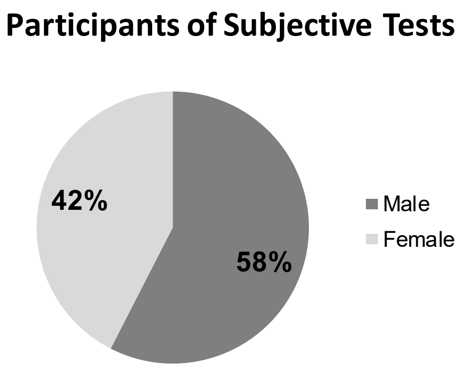


Figure 6.4: The Gender of the Test Participants: 73 persons

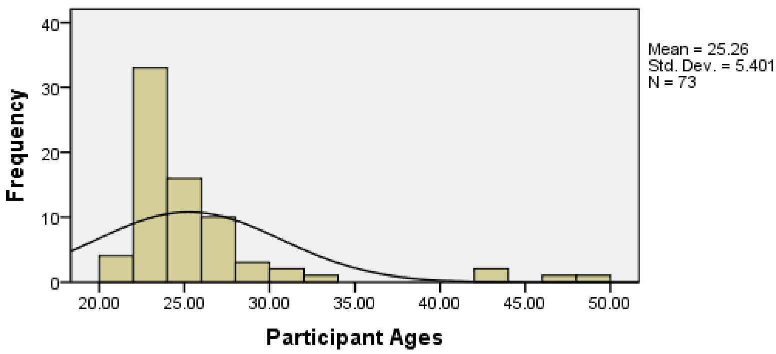


Figure 6.5: Ages of Participants

Table 6.4: Mapping between Five Grade and Nine Grade Scales for Quality Assessment

Grading Scheme	Five-grade	Nine-grade
Excellent	5	9 8
Good	4	7 6
Fair	3	5 4
Poor	2	3 2
Bad	1	1

five-grade is illustrated in Table 6.4. And subjective test method is Single Stimulus introduced in Section 2.4.2 in Chapter 2.

6.3 Data Processing and Screening

According to the recommendation from [84] and [85], the data processing consists of data completeness checking, outliers and information from inconsistent participants removing. The participants grading can be processed into the QoE metric **Mean Opinion Score (MOS)** which is used for grading in the single-stimulus tests, calculated as the average of all the grades recorded for a processed video clip (each video clip was scored by 15 - 17 participants on average). For example, let OS be the individual opinion score, i be the participant index (a total of $\mathbf{I}$ participants), k be the video sequence index of a total of $\mathbf{K}$ video sequences. Therefore, the calculations of the key parameters are performed as in eq.(6.1)-eq.(6.5):

- Mean Score − The mean score for the $k-$th video sequence is:

$$MOS_k = \frac{1}{|\mathbf{I}|}\sum_i OS_{i,k} \tag{6.1}$$

- Standard Deviation − The standard deviation of MOS_k is:

$$SD_k = \sqrt{\sum_i \frac{(MOS_k - OS_{i,k})^2}{|\mathbf{I}| - 1}} \tag{6.2}$$

- Confidence Interval for outlier detection in subjective test [209] is:

$$[MOS_{i,k} - 2SD_k, MOS_{i,k} + 2SD_k] \tag{6.3}$$

  If data distribution is not normal, the Confidential Interval [85] is:

$$\left[MOS_{i,k} - \sqrt{20}SD_k, MOS_{i,k} + \sqrt{20}SD_k\right] \tag{6.4}$$

- Kurtosis Coefficient − The Kurtosis Coefficient $KURT_k$ used to verify whether the data distribution of the $k-$th video sequence is normal (i.e. $KURT_k \in [2, 4]$), is calculated as:

$$KURT_k = \frac{|\mathbf{I}|\sum_i (MOS_k - OS_{i,k})^4}{\left[\sum_i (MOS_k - OS_{i,k})^2\right]^2} \tag{6.5}$$

In order to remove some possible extreme opinion scores rated by potential inconsistent participants (e.g. outliers), the algorithm used for outlier detection is explained in Algorithm 1, here Γ is mapped to MOS based on eq.(6.6), and m is the index of device classes:

$$MOS = \lceil 4 \cdot \Gamma_{k,i} + 1 \rceil. \tag{6.6}$$

Algorithm 1: Outlier Removing for Data Screening

1 **for** *each* $k, i^{(m)}$ **do**
2   **if** $KURT_k \in [2,4]$ **then**
3   **if** $\left(\Gamma_{k,i^{(k)}} < \overline{\Gamma_k} - 2SD_k \cap \Gamma_{k,i^{(k)}} > \overline{\Gamma_k} + 2SD_k\right)$ **then**
4   remove participant $i^{(k)}$;
5   **end**
6   **end**
7   **else**
8   **if** $\left(\Gamma_{k,i^{(k)}} < \overline{\Gamma_k} - \sqrt{20}SD_k \cap \Gamma_{k,i^{(k)}} > \overline{\Gamma_k} + \sqrt{20}SD_k\right)$ **then**
9   remove participant $i^{(k)}$;
10   **end**
11   **end**
12 **end**

Algorithm 1 in line **2** verifies whether the data distribution of the $i-$th participant of $k-$th video sequence is normal or not. Lines **3-8** verify whether the individual opinion score is between the confidence interval or not. If the opinion score does not satisfy the conditions listed above, that score is considered an outlier and then removed (see line **3** and **8**). In this thesis, MATLAB[7], SPSS[8] and Microsoft Excel were used for the data collection, processing and result visualization.

After employing the outlier removal algorithm, between 10% 14% of the original results for each video clip were detected as inconsistent results, and were removed. The remaining data was analyzed and graphed in the next section.

[7]MATLAB:http://www.mathworks.com/products/matlab/
[8]SPSS: http://www-01.ibm.com/software/analytics/spss/

6.4 Results and Analysis

6.4.1 Participant Background Information

Before the participants rated the video clips, they have answered some important basic questions about their background (see Appendix B). This information was collected in order to understand the results in the context of user QoE in real world situations. The answers to these basic questions are summarized in Table 6.5.

Table 6.5: Background Information Summary

1. Gender	**Male**	42
	Female	31
2. Do you use glasses or contact lenses?		
	YES	24
	NO	49
3. Do you have other visual conditions that may affect your perception of movies (e.g. colour blindness)?		
	YES	4
	NO	69
4. How familiar are you with subjective video quality evaluation?		
	YES	7
	NO	66
5. Are you using any electronic devices with display (e.g. PCs, Laptops, Smartphones or Tablets)		
	YES	73
	No	0

A. Frequency of Watching Video or DVD/HD Movies

Previous subjective tests organized by PEL@DCU investigated the frequency of watching movies or HD videos in questionnaire forms [207], namely the question to respond to was ***"How often do you watch Movies, Video Clips or any other types of video media?"***. Accordingly, Figure 6.6 shows the varying frequencies of watching videos or HD movies by tracking the answers over the years. The percentage of "Every Day" answers in 2015 of almost 90% indicates watching video or movies has become a the very popular activity in people's daily lives.

B. Frequency of Using Mobile Devices and The Time Spent in Front of a Screen Every Day

The question about how often the participants use mobile devices to watch video online

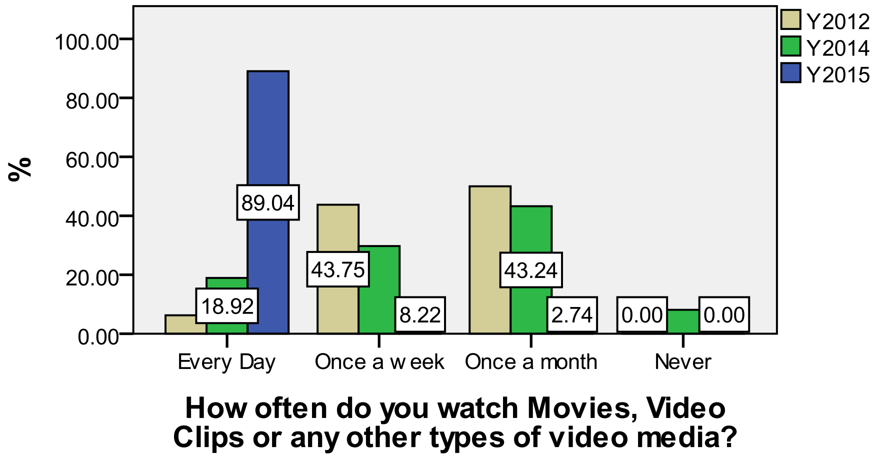


Figure 6.6: Frequency of Watching Video or DVD/HD Movies

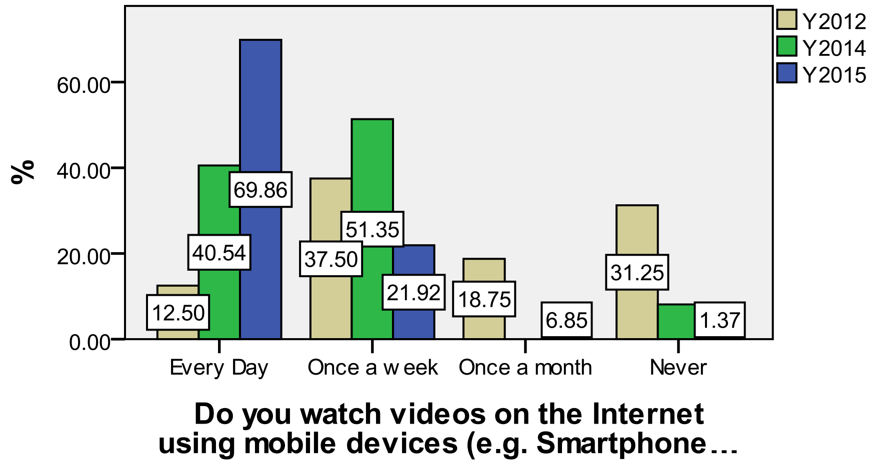


Figure 6.7: Frequency of Using Mobile Device to watch Video Online

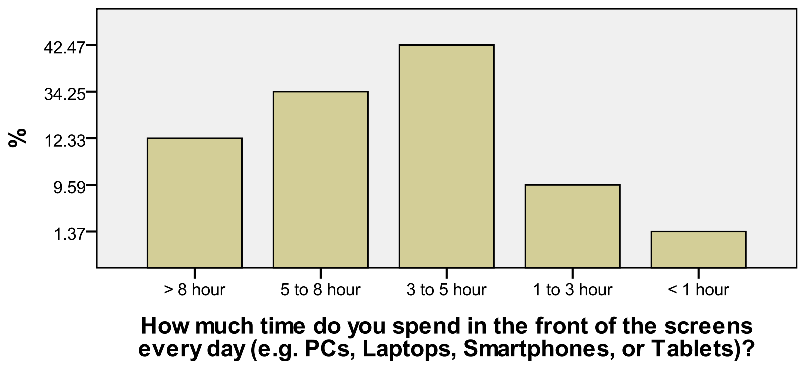


Figure 6.8: The time spent in the front of the screen every day

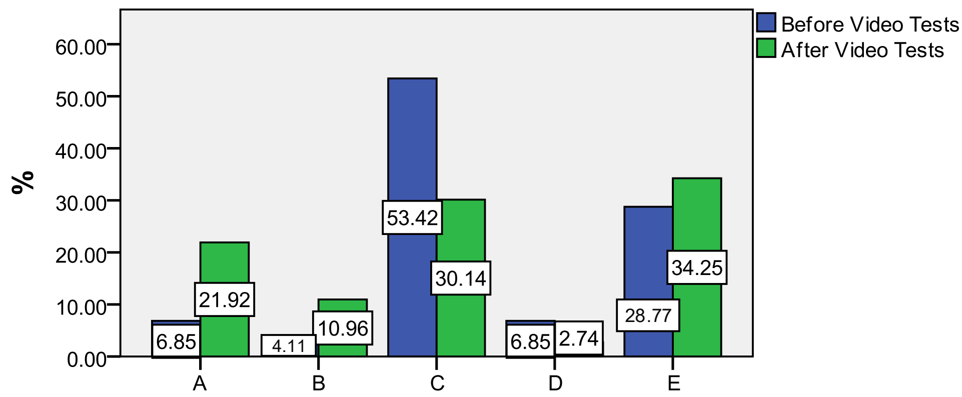


Figure 6.9: Energy Saving vs. Quality

and how long they spend in front of the screen every day are highly relevant, as an increasing amount of time is being used for this activity and with higher frequency. Figure 6.7 illustrates an increase of over 50% frequency of watching video online on mobile devices daily in 2015 against that in 2012. The values of "Never" indicating some participants have never watched video on mobile devices in 2015 has dropped to almost 0% compared to a very high 31% in 2012.

Furthermore, the data in Figure 6.8 indicates that in 2015 over 85% of participants work/consume entertainment in front of the screen (e.g. mobile phones, tablets, laptop, TV sets) for over 3 hour per day, which implies that the display and its characteristics are one of the essential factors that may affect the perceived user quality of daily working or entertainment.

C. Energy Saving vs. Quality

In the questionnaire, a special question was designed for the participants to assess their preference for energy-saving or video quality when using mobile devices to watch videos. The detailed question is shown as follows:

"Please rate your preference in the following situation. Suppose you want to watch a 5 min long high-quality Internet video on your mobile device but you have limited battery level to see the full video clip at high quality. You have the option to select between different video quality levels at the risk of running out of battery, but with the possibility of watching the video later on. Please indicate which option you prefer?

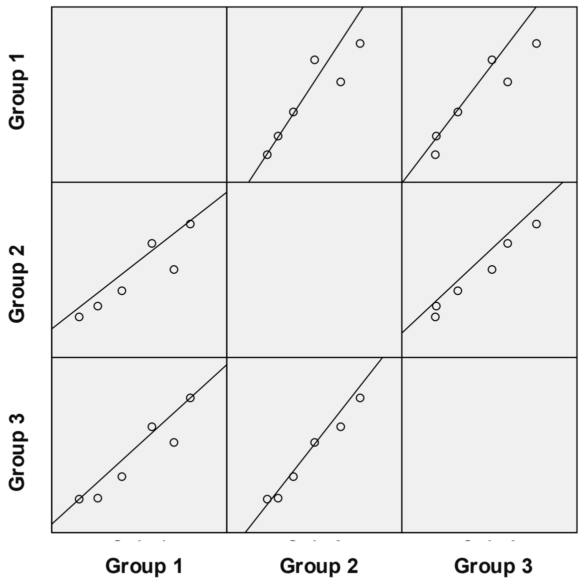


Figure 6.10: Comparison among Different Tested Device Groups (scatter matrix)

A High quality, no battery left and watch the video later

B Good quality, no battery left and watch the video later

C Fair Quality and 10% battery left

D Poor Quality and 22% battery left

E Watch the video later

”

Figure 6.9 presents a comparison between the results to this question between “Before” and “After” the subjective video tests which indicates that around 40% participants changed their mind after watching the different quality level videos. This demonstrates that it is difficult to balance the energy saving and video perceived quality for users in the real world. Therefore, solutions to the optimal trade-off between battery life and video quality levels in real applications are very useful.

6.4.2 Results and Analysis

6.4.2.1 Impact of Device Performance on User Experience

In the subjective tests, the participants were divided into three groups, namely **Group 1**, **Group 2** and **Group 3**. The participants in **Group 1** watched the test video clips following the order from Class 1 device (i.e. Galaxy S3) to Class 5 (i.e. Vodafone Smart 875). The participants in **Group 2** started to watch from Class 5 to Class 1,

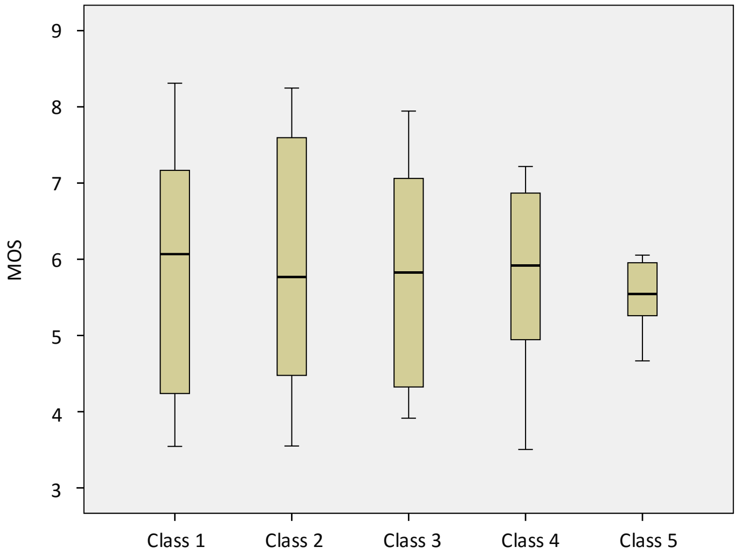


Figure 6.11: Boxplot of Average MOS vs Device Class

whereas the participants in **Group 3** were randomly allocated with mobile devices. Since the people in real world working/entertainment in front of the screens often have to switch from a large screen (e.g. PC or laptop with high resolution display) to a small screen (e.g. making phone call, watching video or reading SMS on mobile devices), the performance/characteristic of mobile devices may impact the perceived user quality in varying use scenarios. Figure 6.10 presents a comparison among the different groups which is based on the average MOS of Class 1. The trend lines in the scatters imply that the influence of different usage order in the real world on the perceived user experience is limited. Similar results are obtained for other device classes.

Figure 6.11 shows that the impact of the mobile device performance on the participants rating is very important. It shows that many devices with higher resolutions results in higher rating scores. Note that the deviation of results increases with the increasing device class (i.e. from Class 5 to Class 1).

6.4.2.2 Impact of Different Quality Level Videos on Perceived User Experience

In order to study the relationship between MOS and different video bitrates, the SPSS Regression tool was used to do logarithmic fitting for the different video bitrates. In Figures 6.12-6.16, the x-axis represents the encoding bitrates (kbps) of different video quality levels, and y-axis represents the MOS values. The points plotted on these five

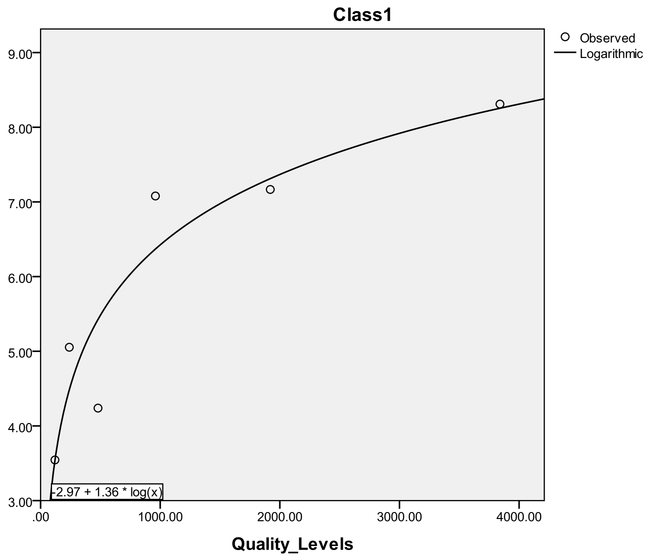


Figure 6.12: Class 1 - Logarithm Fitting of MOS vs Different Quality Levels (i.e. Video Bitrates)

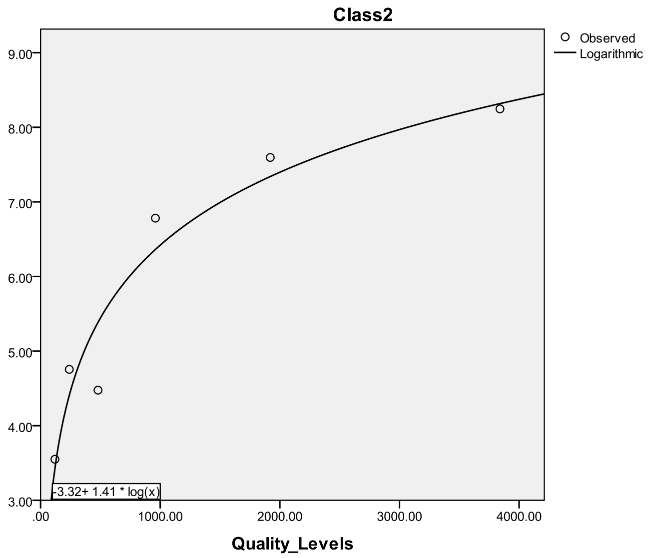


Figure 6.13: Class 2 - Logarithm Fitting of MOS vs Different Quality Levels (i.e. Video Bitrates)

figures are the averaged MOS values based on the results of the four testing video clips without any packet losses. From Figure 6.12 to 6.16, most of logarithm curves show the good fit for the trend of MOS based on video bitrate, and their fitting R-squared values are greater than 0.85. These results validate the logarithmic function is suitable for video perceptual quality modelling. They are also used to model the QoE factor introduced in e^3DOAS.

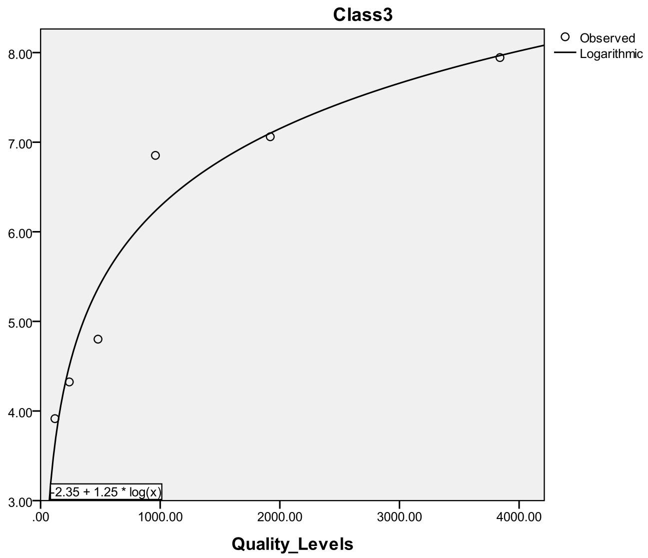


Figure 6.14: Class 3 - Logarithm Fitting of MOS vs Different Quality Levels (i.e. Video Bitrates)

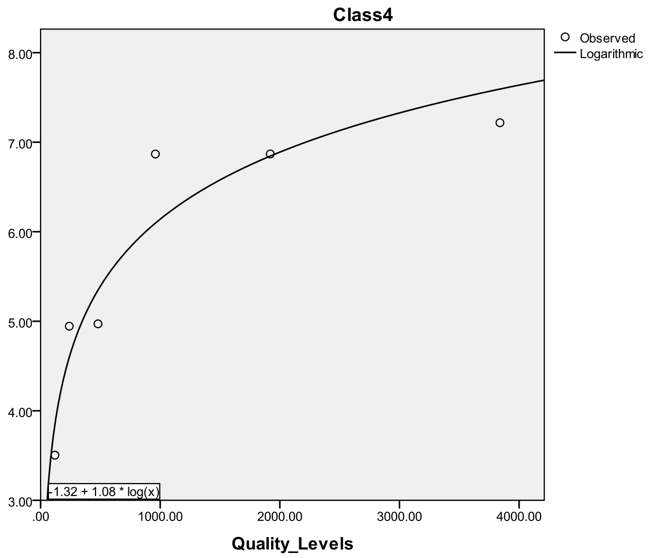


Figure 6.15: Class 4 - Logarithm Fitting of MOS vs Different Quality Levels (i.e. Video Bitrates)

6.4.2.3 Impact of Network Conditions on Perceived User Experience

Figures 6.17-6.21 present comparisons among the averaged MOS values of different video quality levels considering different network congestions for each of the five device classes. Loss1 shown in these figures indicates lossless network conditions, namely the original clips. Loss2, Loss3 and Loss4 refer to video clips affected by 0.1%, 0.5 and 1% packet loss rates, respectively.

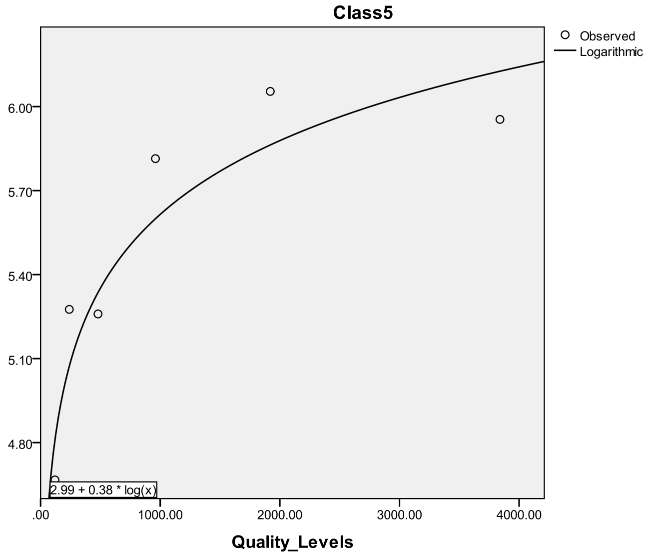


Figure 6.16: Class 5 - Logarithm Fitting of MOS vs Different Quality Levels (i.e. Video Bitrates)

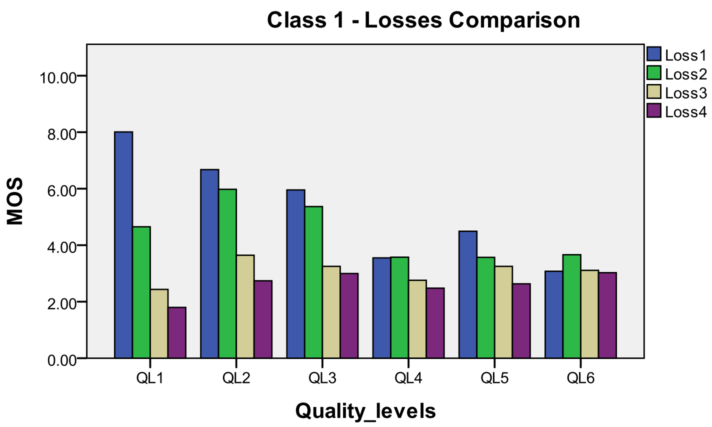


Figure 6.17: Class 1 - Comparisons of MOS against the different network conditions (i.e. Packet Losses)

For lossless video clips, the MOS results have an expected descending trend from high quality levels (i.e QLs) to low quality levels. However, when the losses added, even some high quality videos obtain worse perceptual assessment scores than those of the lower QL ones. This is caused by more packet information of higher QL videos lost than for the lower ones in the same network conditions. The results demonstrate that a video streaming process affected by bad network condition needs to perform adaptive delivery, decreasing the quality level to lower bitrates. This also reduces data traffic pressure on the network, increasing network load.

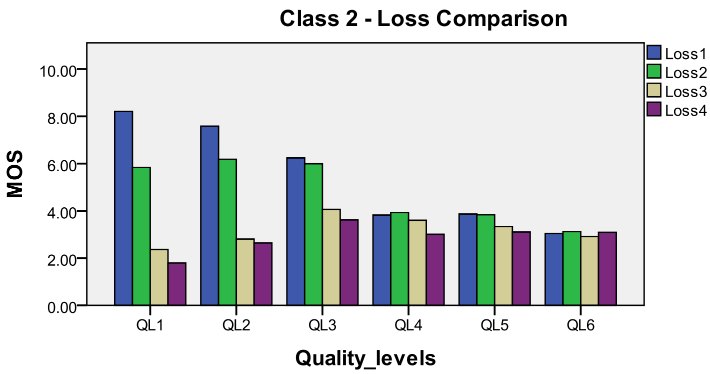


Figure 6.18: Class 2 - Comparisons of MOS against the different network conditions (i.e. Packet Losses)

Figure 6.19: Class 3 - Comparisons of MOS against the different network conditions (i.e. Packet Losses)

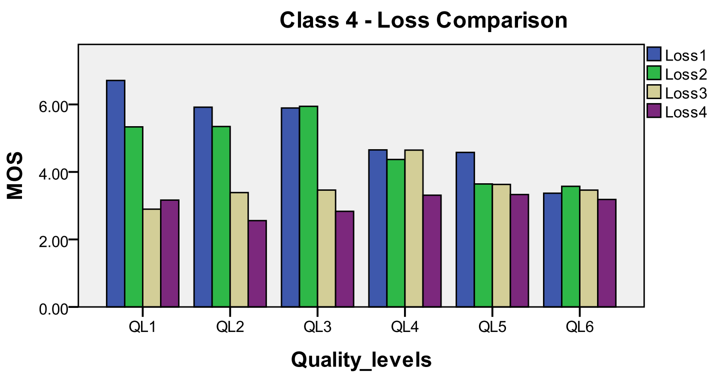


Figure 6.20: Class 4 - Comparisons of MOS against the different network conditions (i.e. Packet Losses)

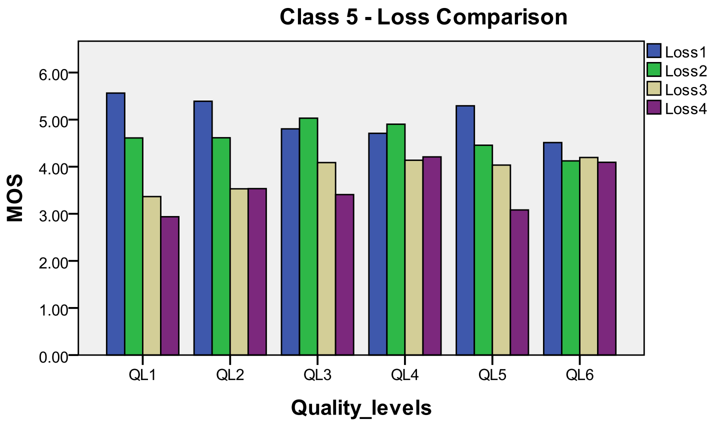


Figure 6.21: Class 5 - Comparisons of MOS against the different network conditions (i.e. Packet Losses)

6.5 Chapter Summary

This chapter presents CQTS-based subjective experimental testing which involves: the preparation of testing mobile devices and video clips, testing venue selection, volunteer recruitment and time-slot scheduling, results presentation and their analysis. The impact of device performance, quality levels and network conditions on user experience were studied. The perceptual quality assessment results demonstrate that a logarithmic model is feasible for the QoE factor modelling proposed in e^3DOAS. The QoE modelling results will be exploited and configured in network simulation of e^3DOAS in Chapter 7.

Chapter 7

Network Simulation: Testing and Results

This chapter presents the simulation-based environment scenarios, testing results and result analysis for the evaluation of the four main contributions of this thesis previously introduced in Chapter 4: (1) Utility-based Priority Scheduling Scheme for LTE downlink system (UPS); (2) Device-Oriented Adaptive Scheme for LTE networks (DOAS); (3) Energy-aware Device-Oriented Adaptive Scheme for WiFi Offload (eDOAS); and (4) Evolved QoE-aware Energy-saving Device-Oriented Adaptive Scheme (e^3*DOAS) for wireless multimedia streaming. The performance evaluation of these solutions is done in comparison with other state-of-the-art solutions from the literature.*

7.1 Performance Analysis of UPS

In this section, the proposed scheduling scheme (**UPS**) for LTE packet downlink system in Chapter 4 is verified by both a numeric example and network simulation in LTE-Sim[1]. UPS is a cross-layer MAC packet scheduler in LTE which provides a differential multimedia streaming service by making use of characteristics of mobile devices (i.e. screen resolution and power consumption) and network condition (i.e. packet loss rate). In this thesis, only Resource Allocation Type 0 is considered [12].

[1]LTE-Sim: `http://telematics.poliba.it/LTE-Sim`

Table 7.1: Parameters of Device Classes

	Class 5	Class 4	Class 3	Class 2	Class 1
Resolution	120 × 180	320 × 240	480 × 360	768 × 480	1024 × 768
$E_C[mJ]$	2000	4000	5920	7770	48000
$r_d[mJ/Mbit]$	0.05	0.1	0.1	0.2	0.4
$r_t[mW]$	0.001	0.002	0.002	0.005	0.02
c	0	0	0	0	0
w_r	0.2	0.2	0.3	0.4	0.4
w_e	0.4	0.4	0.3	0.2	0.2
w_{plr}	0.4	0.4	0.4	0.4	0.4

E_C- current energy capacity of mobile device;
r_d- energy consumption per unit data;
r_t- energy consumption per unit time;

Table 7.2: Classification of the Different Quality Video Streams in QOAS Server

Video Clips (Quality Levels)	Resolution	Bitrate $[kbps]$	Length $[s]$
Quality Level 5	120 × 180	120	100
Quality Level 4	320 × 240	240	
Quality Level 3	480 × 360	480	
Quality Level 2	768 × 480	960	
Quality Level 1	1024 × 768	1920	

7.1.1 Numeric Example

A simple scenario is designed to analyze UPS, and a series of numerical results will be presented to see how the scheduler works. Five different types of mobile devices are considered with the parameters shown in Table 7.1. The weights of the different utilities are dependent on the user requirements and are set as in the table.

Assume five class devices are served in a single cell of LTE network, and request the same video content from the server. The modified QOAS server first receives the classification of service request from eNodeB, and then it delivers the videos encoded at five different quality levels, depending on the resolutions of these five devices. For example, QL 5 encoded video will be delivered to the Class 5 device., QL 4 encoded clip to Class 4 device, etc. The different quality of the video used during QoAS adaptation is presented in Table 7.2.

The proposed scheduler computes the default QoS utilities by using the packet loss ratio values. The values of the utilities are shown in Table 7.3 after calculations

Table 7.3: Classification of the Different Quality Video Streams Delivered to Diverse Device

	Class 5	**Class 4**	**Class 3**	**Class 2**	**Class 1**
u_r	0	0.25	0.5	0.75	1
u_e	1	0.277	0.374	0	0.737
u_{plr} ($\alpha = 2.418$, $\beta = 4.436$)	1	1	1	1	1
Overall U	0	2.356	2.557	0	2.941
P	0	565.4	1227.3	0	5646.7

employing eq.(4.1)-eq.(4.4). As the QoS utility function illustrated in Figure 4.7 shows that a progression begins slowly (i.e. small variation of utilities with low network congestion, namely low packet loss rate), and then accelerates faster and approaches to lower utility with high packet loss rate caused by network congestion. In addition, a inflection point splits the concavity and convexity region. At this point, the second derivative of QoS utility function is zero, namely as expressed in eq.(7.1):

$$\frac{\partial^2 u_{plr}}{\partial plr^2} = 0 \tag{7.1}$$

Let $plr = plr_2 = 2\% = 0.02$. And solving eq.(4.4) gives the values of α and β listed in Table 7.3.

Additionally, it is assumed the transmission between the server and eNodeB is error free and the channel state of UEs is ideal, and therefore CQI and the modulation scheme are at the highest levels. In this condition, the average instantaneous rate of the scheduled multimedia stream delivered to the UE equals the bit rate of the multimedia stream.

It can be seen in Table 7.3 how the highest priority is given to the Class 1 device because its resolution, energy and packet loss ratio tolerance utilities are the highest and consequently has the highest overall utility U. To this device the best channel resource will be allocated preferentially. The Class 3 device gets the second highest priority and will get the next best channel resource. The Class 4 device follows in inverse order of the overall utility U and priority P and will be allocated the third best channel resource. Class 5 and Class 2 devices have equal priorities and are allocated the next available channel resources in random order. Then one resource block is allocated to each UE served at this resource allocation iteration. Assume that the channel bandwidth is 1.4

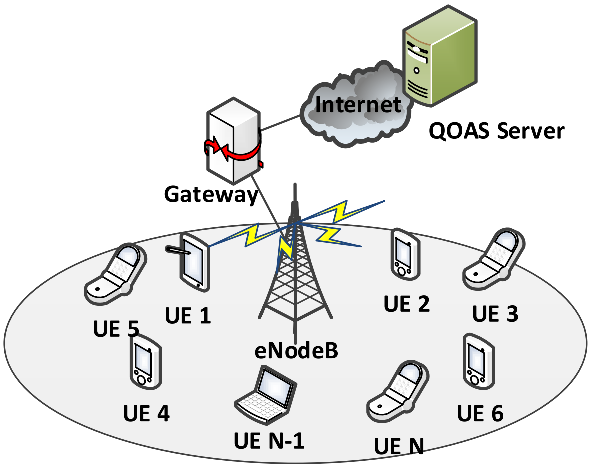


Figure 7.1: Single Cell Scenario in UPS Simulation

MHz with 6 Resource Blocks, and the descending order of these available Resource Blocks is RB 1, RB 3, RB 2, RB 5, RB 4, RB 6 based on their CQI reports (i.e. sorted by SINR values). Then the prioritized order of scheduled devices is Class 1, Class 3, Class 4, Class 2 and Class 5 which are mapped to RB 1, RB 3, RB 2, RB 5 and RB 4, respectively.

When the same UEs described in Table 7.3 are tested in the same scenario but UPS is not deployed, the resource blocks will be allocated to the UEs proportional to the bitrates of their requesting video streams, as the scheduler is unable to differentiate the streaming service based on the UEs' different requirements. Therefore, when a Class 5 device requests a very high bitrate video stream and suffers from bad channel condition, it will compete for bandwidth resources with other Class devices. This approach results in other Class devices with good channel quality be negatively affected.

7.1.2 Simulation Environment

This subsection describes the simulation environment for the proposed scheduling mechanism. A 250-metre single cell network with one LTE eNodeB is set up, which assumes the CQI reporting are error free and that equal downlink transmitting power is allocated to each Physical Resource Block. A brief illustration of the simulation scenario is presented in Figure 7.1. The scenario involves a QOAS server, one eNodeB and varying numbers (from 10 to 150) of UEs. The total number of UEs consists of random number of devices from each of the five devices classes.

Table 7.4: Simulation Parameters - UPS

Parameters	Values
eNodeB Configuration	1 eNodeB; Single Cell; Radius=250m
UEs Configuration	Min No.=10; Max No.=150; Interval=10; Random Direction; 3 km/h
Physical Configuration	Carrier frequency=2.0 GHz; Bandwidth=20 MHz; Cyclic prefix=7 Symbols; Modulation: QPSK, 16QAM, 64QAM; Transmission Mode: SISO
Path Loss Model	Friis Propagation Model
Video Traffic Model	Five Quality Levels (Bitrate: 1920kbps, 960kbps, 480kbps, 240kbps, 120kbps)
TTI	1 millisecond
t_w	10 TTIs

The parameters of simulator configured in LTE-Sim are listed in Table 7.4. LTE-Sim is C++ based open source network simulation which enables packet-level network traffic simulating on the LTE system. The simulation scenario consists of a 250 metre single cell with 1 eNodeB serving a varying number of UEs (e.g., from 10 to 150) with random distribution. These UEs are divided into five different classes according to Table 7.1. Based on the UPS mechanism the QOAS server will adapt between five quality levels video streams when transmitting to the UEs accordingly. When UPS is not invoked, the highest bitrate video stream will be transmitted to all the UEs. The performance of the proposed scheduler UPS is compared against the Proportional Fair (PF) Scheduler and the M-LWDF scheduler [127], in terms of average system throughput, average packet loss ratio and average PSNR. In order to avoid the scheduling starvation, the lowest utilities of display resolution, energy and QoS are configure as values which is closest to 0, i.e. 0.0001, in the network simulation.

7.1.3 Simulation Results

Figure 7.2 and Figure 7.3 present the average system throughput and packet loss ratio of the downlink video traffic delivered by the LTE system for various numbers of UEs. By using the UPS mechanism, the modified QOAS server transmits different quality levels of the requested video streams to the UEs of different classes such as lower resolution devices are likely to be scheduled with lower priority. However, when using M-LWDF and PF, the highest quality video streams are delivered to all the UEs. Therefore, the maximum number of UEs served without packet loss is 20 and 30 when using M-

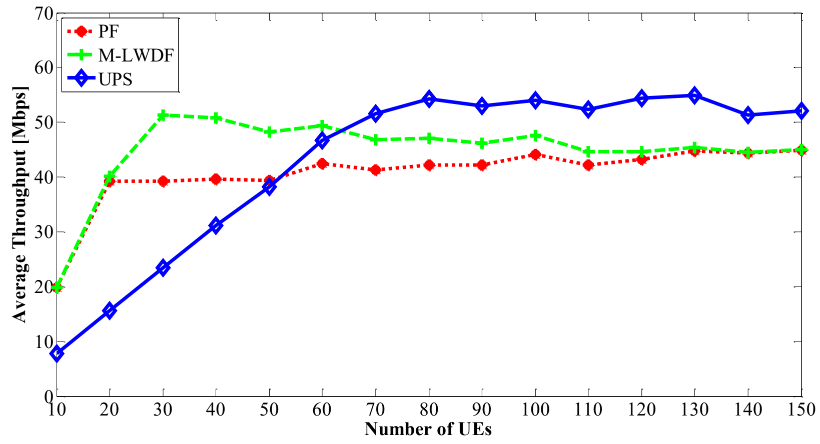


Figure 7.2: UPS Assessment: Average System Throughput

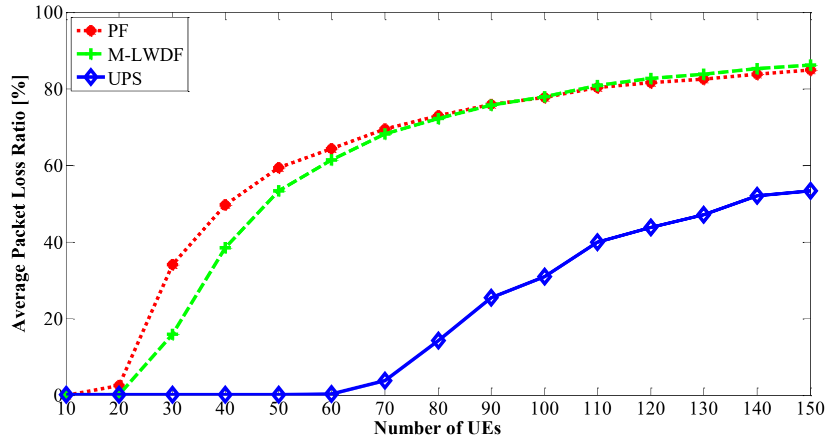


Figure 7.3: UPS Assessment: Average Packet Loss Ratio

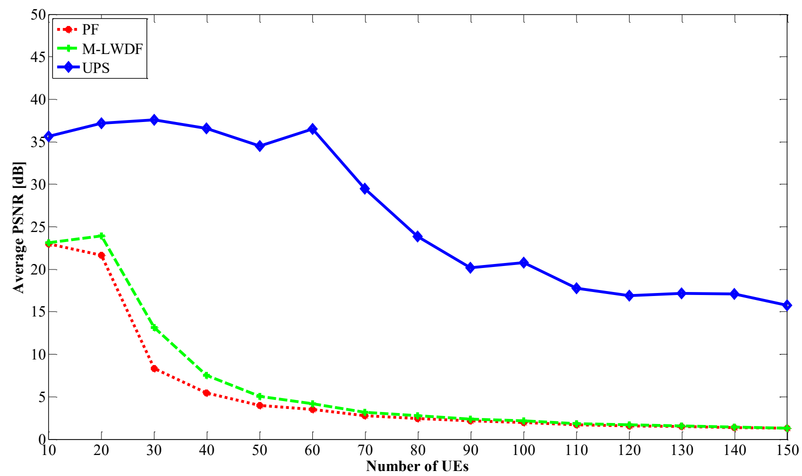


Figure 7.4: UPS Assessment: Average Video Quality

LWDF and PF, respectively. However, by considering the utility of QoS and prioritizing the scheduled users with the lowest packet loss ratio, UPS achieves a 18% increase in the system throughput and a 60% decrease in packet loss ratio in comparison with M-LWDF and PF. When employing UPS the maximum number of UEs supported reaches 70 without any packet loss. Similarly, UPS still achieves higher throughput and lower packet loss ratio when compared against the other two scheduling schemes when the number of UEs is increased from 70 to 150. In conclusion, UPS can accommodate a larger number of users and still provide increased system throughput and decreased packet loss in comparison with the other two approaches. This is as UPS employs a modified QOAS server which decreases step-wise the quality levels of the video streams when delivered to the UEs from Class 1 to Class 5, accordingly. It is noted that this will reduce network congestion.

In order to analyze the quality of received video stream, the Peak Signal-to-Noise Ratio (PSNR) is considered, which is based on an estimation method introduced in [94]. The PSNR estimation is given in eq.(7.2).

$$PSNR = 20 \cdot \log_{10}\left(\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr - CRT\_Thr)^2}}\right) \tag{7.2}$$

where $MAX\_Bitrate$ is the average encoded bitrate of the video traffic, EXP_Thr is the average throughput expected to be achieved when delivering the adaptive video traffic and CRT_Thr is the actual measured throughput during the transmission. This indirect method estimates PSNR based on the results from network simulation which does not transmit real video clips, but video traces.

Figure 7.4 illustrates the average PSNR achieved when the three scheduling algorithms are used in turn for increasing numbers of UEs. Note that, the best estimated video quality of between 35 dB and 40 dB is achieved for up to 60 UEs when employing UPS, whereas for the other two solutions the maximum quality reaches 25dB when serving simultaneously up to 20 UEs only.

Figure 7.4 also shows how as the number of UEs simultaneously served grows, the competition for resources increases as well, but UPS always provides a much better video quality with respect to the other two scheduling schemes. This is because of the joint usage of the innovative scheduling algorithm and adaptive multimedia delivery solution. Note that the UPS supports higher numbers of UEs for the same quality of the video service. In Figure 7.4 , for an average PSNR of 18dB when using PF approximately 22 UEs are supported, 25 UEs when using M-LWDF and 110 UEs when using UPS. For a lower target level of video quality of 9dB 30 UEs can be supported when using PF, 40 UEs when using M-LWDF and over 150 UEs when employing UPS.

7.2 Performance Analysis of DOAS

The proposed DOAS in Chapter 4 is an adaptive multimedia streaming solution built on the current LTE eNodeB downlink scheduler, which considers device heterogeneity of UEs and network conditions. In this section the simulation setup and the scenarios used to evaluate the performance of the proposed DOAS in comparison with another non-adaptive multimedia delivery scheme are described. The LTE-Sim was used as the simulation platform as well.

7.2.1 Simulation Setup

Figure 7.5 illustrates the simulation scenario in which various UEs served in a single cell network request multimedia service from DOAS server via an LTE eNodeB. It is assumed that the CQI reporting is error free and the downlink transmitting power is allocated to each Physical Resource Block equally. The scenario considers the coverage area of one eNodeB of a LTE network with the simulation parameters listed in Table 7.5.

A total number of 30 LTE mobile devices are considered to perform video streaming from the DOAS server. The LTE mobile users are divided into five classes according to their device capabilities, as previously explained. For each class, 6 identical UEs were considered. The geographical location of the mobile devices is randomly generated, so that the devices are randomly spread throughout the network moving at a speed of 3km/h in random directions. The DOAS server stores the video content encoded at five different quality levels (i.e. five different bitrates) in total. Along with the video traffic generated by the 30 mobile users, there is background traffic generated by two extra users in addition to the 30 UEs at random periods of time and duration.

Depending on the network conditions, the DOAS server adapts the multimedia streaming dynamically. In this thesis, network simulations employ bandwidth estima-

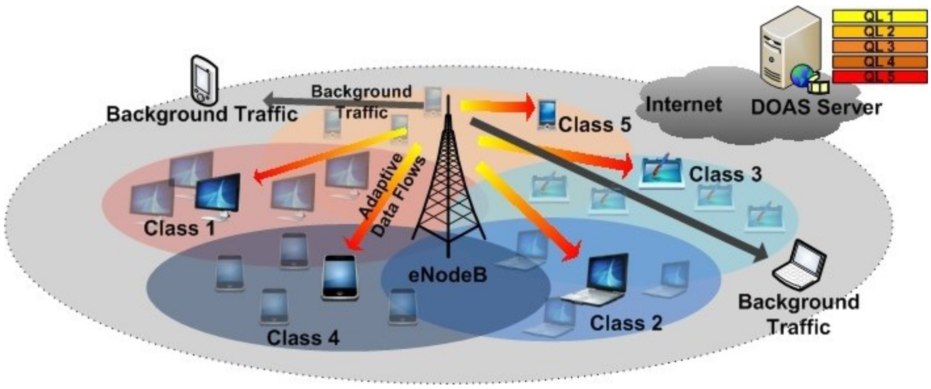


Figure 7.5: Simulation Scenario of DOAS

Table 7.5: Simulation Parameters - DOAS

Parameters	Values
Simulation Length	2000 seconds
Number of UEs	Total 30 UEs of 5 Classes; 6 UEs in each Class
UE Mobility Random	Direction; Speed = 3km/h
Cell Layout	Single Cell; Radius = 250 meters
Carrier Frequency	2.1 GHz
Downlink Bandwidth	10 MHz; Number of RBs = 50
Modulation Scheme	QPSK, 16QAM, 64QAM
Physical Transmission	Tx power = 43 dBm; FDD; SISO
Antenna Model	Isotropic Antenna Model
Path Loss Model	Friis Propagation Model
Traffic Model	Near Real Time Traffic; CBR

tion by using probing, namely **Probe Rate Model** introduced in [210].. For example, if one sends probe traffic at a rate lower than the available bandwidth along the path, then the arrival rate of probe traffic at the receiver will match their rate at the sender. In contrast, if the probe traffic is sent at a rate higher than the available bandwidth, then queues will build up inside the network and the probe traffic will be delayed [210].

7.2.2 Video Traffic Model

In order to analyze the performance of DOAS, a Near Real Time Video (NRTV) traffic model [7] is used. Additionally, the truncated Pareto Distribution is considered for modelling the variability of the frame size, with probability density function computed as in eq.(7.3):

$$f_X(x) = \begin{cases} \alpha \cdot \dfrac{k^{\alpha}}{x^{\alpha+1}} & k \leq x < m \\ \left(\dfrac{k}{m}\right)^{\alpha} & x = m \end{cases} \tag{7.3}$$

Five video traffic traces, each corresponding to a different quality level (i.e. QL1-QL5) are generated using eq.(7.3). The values for the distribution parameters α, k and m are listed in Table 7.6.

Table 7.6: Video Traffic Model Parameters [7]

	QL 1	**QL 2**	**QL 3**	**QL 4**	**QL 5**
Video Bitrate	1920kbps	960kbps	480kbps	240kbps	120kbps
Frame Rate			25fps		
Pareto Distribution	α =1.2, k =4800, m =26100	α =1.2, k =2400, m =13100	α =1.2, k =1200, m =6500	α =1.2, k =600, m =3300	α =1.2, k =300, m =1654

7.2.3 Occurrence of the Background Traffic

Background traffic in wireless networks is highly variable. In the scenario, 100 occurrences of background traffic during 2000 seconds if time duration were simulated. In order to do this, the truncated Pareto Distribution Model is used and the variability of the background traffic is simulated using a Uniform Distribution. The values of the parameters for this particular distribution are given in Table 7.7.

Table 7.7: Background Traffic Model Parameters - DOAS

Parameters	**Values**
Duration of Occurrence	$\alpha = 1.2, k = 15, m = 28; mean \approx 20sec$
Utilization of Background Traffic	$Min = 5\%,\ Max = 90\%$

7.2.4 Benchmark Performance

The proposed adaptive mechanism, DOAS is compared against a non-adaptive multimedia delivery scheme which streams the multimedia content at the encoding rate without taking current network conditions into consideration. In this case the encoding rate used was 1.920Mbps, the highest quality level considered by DOAS. The evaluation is done in terms of throughput, packet loss, delay and PSNR.

In order to analyze the impact of the scheduling algorithm on the video transmission, the use of two different scheduling algorithms that jointly work with DOAS was considered, namely PF and M-LWDF, introduced in Chapter 3, summarizing PF and M-LWDF principles behind the two algorithms is listed in eq.(7.4) and eq.(7.5):

$$\text{PF: } i^* = \arg\max_i \frac{r_i(t)}{\overline{R_i}(t)} \tag{7.4}$$

$$\text{M-LWDF: } i^* = \arg\max_i \frac{\gamma_i \cdot W_i(t) \cdot r_i(t)}{\overline{R_i}(t)} \tag{7.5}$$

where $i*$ presents the scheduled user prioritized to allocated the resource, $r_i(t)$ is the state of the channel of UE i at instant t and $\overline{R_i}(t)$ denotes the historical channel rate of UE i at instant t. $W_i(t)$ is the Head-of-Line packet delay of UE i at instant t. In addition, γ is a weight dependent on different UE delay requirements.

DOAS was compared against a non-adaptive approach when using two different scheduling algorithms. When DOAS is used, the multimedia server delivers the highest video quality level associated to each class to the devices within that specific class. When the non-adaptive solution is used, the quality level (the highest) is transmitted regardless of the device class. When the traffic becomes congested DOAS will adapt the transmission rate accordingly, whereas the non-adaptive solution continue to deliver content at the highest level, regardless of network conditions.

7.2.5 Simulation Results

Figure 7.6 and Figure 7.7 illustrate the average throughput and packet loss ratio of the video traffic for each class, respectively. When PF and M-LWDF are used in turn with and without DOAS, respectively. DOAS maintains high bitrate transmission to high resolution devices and sends less traffic to the devices with lower resolution. Consequently, it can be seen that it reduces considerably the packet loss ratio for all transmission in the network. When compared with the non-adaptive scheme, DOAS reduces by at least 65% the packet loss ratio when jointly working with PF, and by almost 55% when used with M-LWDF, for the devices in Class 1 only. For the other classes the packet loss ratio is negligible when using DOAS compared to the non-adaptive scheme in both cases with PF or M-LWDF.

In terms of delay, Figure 7.8 illustrates the average delay for each class. The results

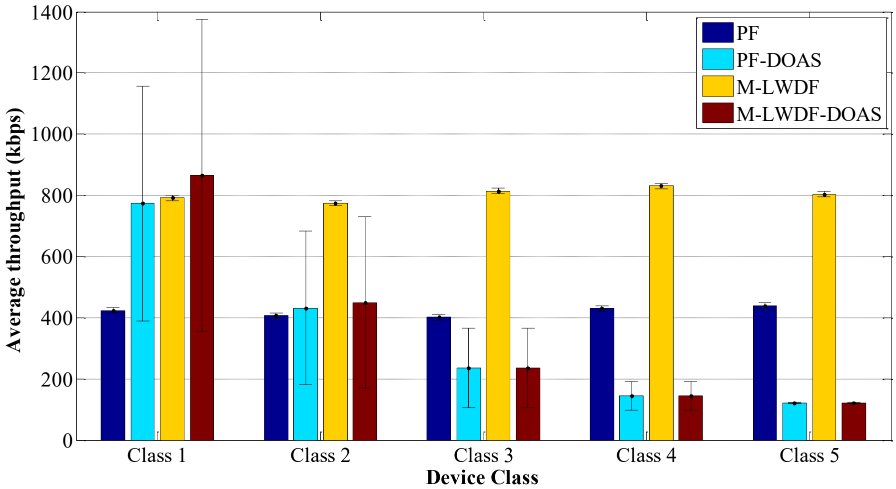


Figure 7.6: DOAS Assessment: Average Video Streaming Throughput

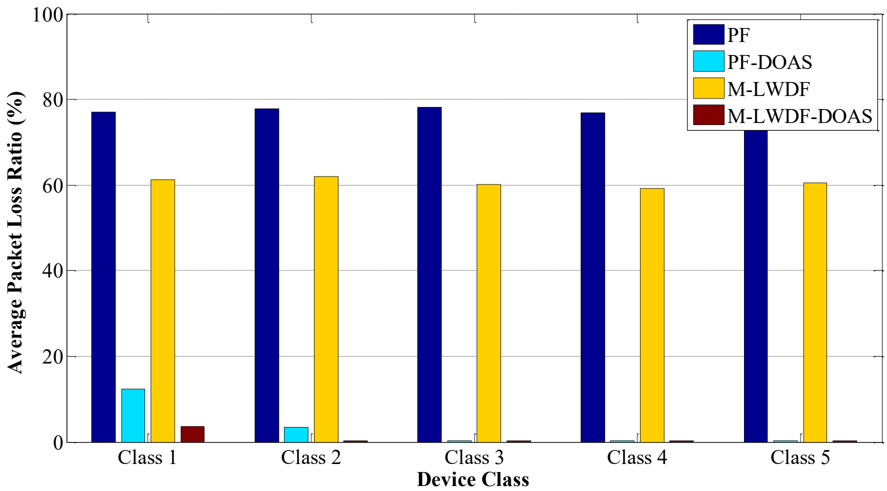


Figure 7.7: DOAS Assessment: Average Video Streaming Packet Loss Ratio

show that when using DOAS the delay is significantly reduced at least 99.7% and 74.7% when compared with the non-adaptive solution for both cases, when using PF or when using M-LWDF, respectively. Modified Largest Weighted Delay First (M-LWDF) is a scheduling scheme which does not only consider proportional rate fairness, but also focuses on prioritization of delay-sensitive services, see eq. (7.5). Consequently, streaming services with higher delay sensitivity will be served with higher priority and therefore there will be lower overall delay. However, this will cause loss which affects the performance from this point of view and therefore will decrease the quality.

In order to analyze the quality of the received video trace, Peak Signal-to-Noise Ra-

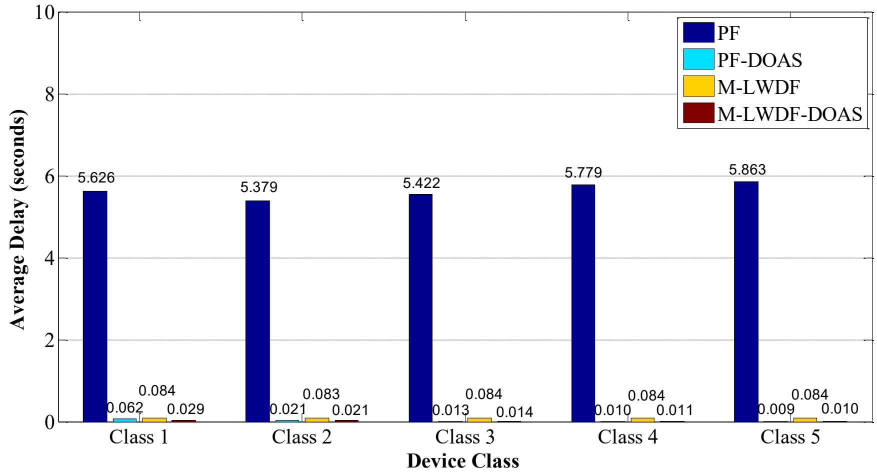


Figure 7.8: DOAS Assessment: Average Video Streaming Delay

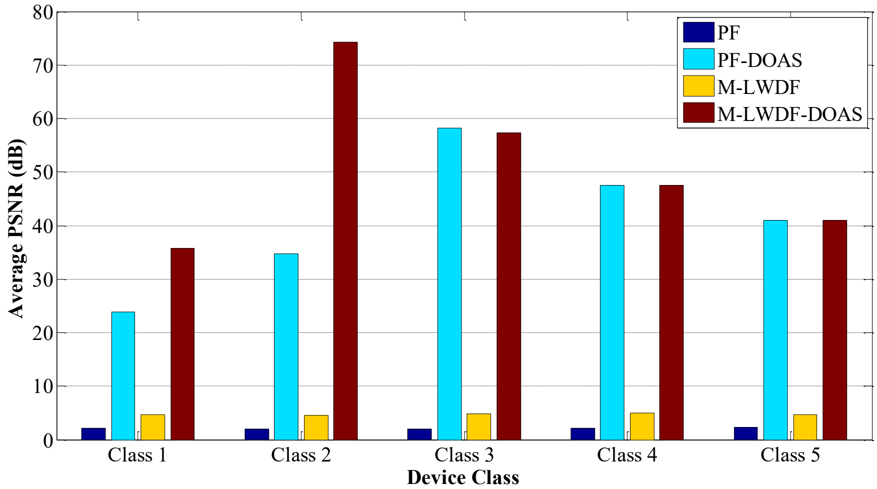


Figure 7.9: DOAS Assessment: Average Received Video Quality

tio (PSNR) was employed using the estimation method described in [94]. The average PSNR for each class plotted in Figure 7.9. For example for Class 1, when using PF-DOAS there is an improvement of 22 dB obtained in comparison with the non-adaptive PF. Additionally, DOAS used with M-LWDF reaches a very good quality level of 30dB in terms of PSNR compared to when the non-adaptive scheme is employed and poor quality level is recorded (PSNR≈5dB). Similarly, the video quality obtained when using DOAS with both PF and M-LWDF is significantly improved when compared with the non-adaptive scheme as shown in other device classes. However, when compared to other device classes the average PSNR for Class 1 is lower, this is because the packet loss ratio for this class is higher as the higher bitrate video is streamed to Class 1 which competes more bandwidth share and increases the network congestion, as illustrated in Figure 7.6 and Figure 7.7.

7.3 Performance Analysis of eDOAS

eDOAS described in Chapter 4 is an energy-aware adaptive streaming scheme based on DOAS, which prolongs battery lifetime of mobile devices in a WiFi offloading environment. This section presents the performance evaluation for eDOAS. As eDOAS is energy focused, energy modelling and network simulation make use of the results of the energy testing presented in Chapter 5. Five different mobile devices and their energy consumption models derived in Chapter 5 and used in these tests are presented in Table 7.8.

Table 7.8: Energy Consumption Models used in eDOAS

UDP	**Class 1:** Galaxy S3	**Class 2:** Viliv 70X EX	**Class 3:** Galaxy S2	**Class 4:** Vodafone Smart Mini	**Class 5:** Vodafone 858 Smart
r_d $[mJ/kbps]$	0.2018	0.2723	0.3624	0.5011	0.1449
r_t $[mW]$	907.28	666.67	880.57	531.65	596.59

7.3.1 Performance Evaluation

This section describes the performance evaluation of the proposed eDOAS in comparison with the previous non-energy-aware solution DOAS and energy-aware scheme BaSe-AMy proposed in [169]. DOAS is an adaptive video delivery scheme based on device classification, but no energy aspects are considered.

DOAS makes use of the Quality Level Allocation as illustrated in Figure 4-9. For example, a video source has been pre-encoded into N video clips with the same content but different bitrates (e.g. 1920kbps, 960kbps, 480kbps, 240kbps, 120kbps and so on). Then the video clips from Quality Level 1(i.e. $QL^{(1)}$ 1) to $QL^{(1)}$ N representing the highest to lowest quality level, are assigned to the devices in Class 1. Similarly, the video clips from $QL^{(2)}$ 2 to $QL^{(2)}$ N are assigned to the devices in Class 2, etc.

The Battery and Stream-aware Adaptive Multimedia Delivery scheme, **BaSe-AMy** adapts the multimedia stream based on both the battery power level of the mobile device and network conditions. For example, the decision mechanism in BaSe-AMy involves several battery thresholds (e.g. percentage of remaining battery capacity=10% or 30%) and one packet loss threshold (e.g. loss ratio=10%). For instance, when the playing video duration is shorter than the battery lifetime, the battery remaining capacity is above 30% and the loss ratio is below 10%, then the multimedia server will send the highest video quality level. However, when the video play out duration is longer than the device battery lifetime, and any of the other thresholds cannot be satisfied, then the server will send a lower video quality level. However, in order to perform a fair comparison, 6 video streams, encoded at various quality levels (i.e. 3840kbps, 1920kbps, 960kbps, 480kbps, 240kbps and 120kbps) for each device are considered for **BaSe-AMy**. The details of these quality level video clips are presented in Table 5.3 in Chapter 5. Five battery remaining capacity thresholds (i.e. 90%, 70%, 50%, 30% and 10%) and 10% loss threshold are configured for the evaluation of BaSe-AMy. The main characteristics of the considered adaptive schemes are summarized in Table 7.9. Two main evaluation scenarios were performed as detailed next. The results are analyzed in terms of the assessment metrics: throughput, packet loss ratio, PSNR, service outage probability and energy consumption.

Table 7.9: Characteristics of the Adaptive Schemes

	Device-Oriented	**Energy-aware**
DOAS	YES	NO
BaSe-AMy	NO	YES
eDOAS	YES	YES

7.3.1.1 Scenario 1 - Energy-aware Evaluation

This scenario was setup to evaluate the energy-aware performance of the three adaptive schemes, considering an ideal network environment. This scenario assumes that there is no congestion in the network. The server delivers the 12000-second long video streams encoded with 6 different bitrates to the mobile devices with their battery remaining capacity decreasing (e.g. from 100% to 10% is step of 10%). The scenario was simulated in MATLAB, and the results in terms of average energy consumption of each device class for each adaptive scheme are detailed in the next section. When the battery

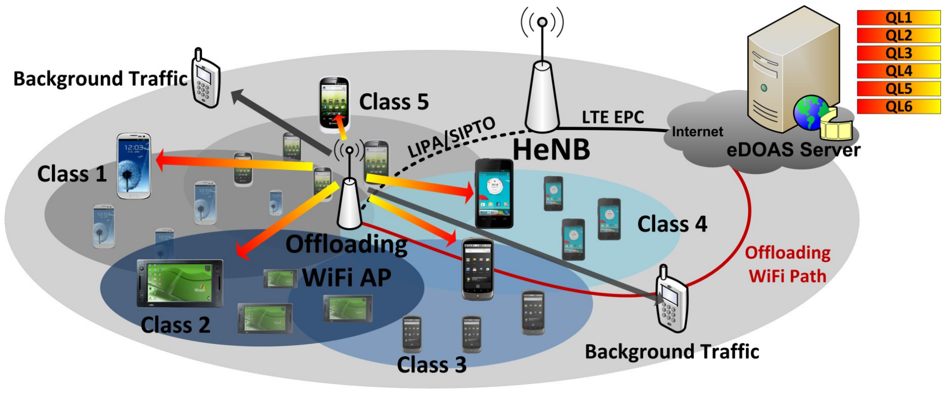


Figure 7.10: Simulation Scenario of eDOAS

Table 7.10: Simulation Parameters - eDOAS

Parameters	Values
Simulation Length	12000 seconds
Number of Mobile Devices	Total 30 Devices; 5 Classes; 6 Devices in each Class
Cell Layout	Single Cell; Radius = 100 meters
WiFi Mode	IEEE 802.11g
Antenna Model	Isotropic Antenna Model
Path Loss Model	Friis Propagation Model
Traffic Model	CBR (3840kbps, 1920kbps, 960kbps, 480kbps, 240kbps, 120kbps); Background Traffic

remaining capacity is so low that the duration of the lowest quality level video is longer than the device battery lifetime, it means the multimedia streaming service will not continue. Therefore, the results of the outage probability of delivery for each scheme are detailed in the next section.

7.3.1.2 Scenario 2 - Network Simulation

The network simulation environment is setup to evaluate the performance of the proposed eDOAS compared against the other two adaptive schemes. The LTE-Sim was used as the near-real simulation platform. A WiFi AP offloading model (based on IEEE 802.11g) was implemented in the simulator. The energy consumption model for real-time multimedia transmission [190] was also integrated in the simulation scenario based on the energy parameter values obtained from the energy-aware experimental tests as listed in Table 7.8. The simulator configuration details are listed in Table 7.10.

The simulation scenario considers the case of 30 mobile devices performing video streaming as illustrated in Figure 7.10. All devices are divided into five classes as previously explained. The geographical locations of the mobile devices are randomly distributed in a single cell with a 100 meters radius. A multimedia server stores the multimedia content represented by CBR flows with 6 level bitrates. The server adapts in turn the multimedia stream to network and energy conditions according to the three adaptive schemes considered. It is considered that the device battery remaining power decreases from 100% to 10% with a step of 10%.

Background traffic is considered to be generated by some extra mobile users at random periods of time. In this scenario, 1200 occurrences of background traffic during the 12000 seconds of the simulation length were generated based on the truncated Pareto Distribution Model [7], with probability density function computed as in (7.3). The appearance variability of the background traffic is simulated by using the Uniform Distribution. The values of the Pareto Distribution parameters α, k and m, and the parameters of the Uniform Distribution are indicated in Table 7.11. The network performance evaluation of eDOAS, DOAS and BaSe-AMy is done in terms of average throughput, packet loss ratio, PSNR and energy consumption.

Table 7.11: Background Traffic Model Parameters - eDOAS

Parameters	Values
Duration of Occurrence	$\alpha = 1.2, k = 7, m = 15; mean \approx 10 sec$
Utilization of Background Traffic	$Min = 5\%,\ Max = 95\%$

7.3.2 Results and Analysis

7.3.2.1 Scenario 1 - Energy-aware Performance Evaluation

The energy-aware performance is analyzed in Scenario 1, in terms of average energy consumption and average outage probability of multimedia streaming service at different remaining battery capacity states (e.g. from 100% to 10%) as listed in Figure 7.11 and Figure 7.12. It can be seen that by using a device-oriented adaptive mechanism (eDOAS or DOAS), the energy consumption is reduced up to 18% when compared with a non-device-oriented scheme such as BaSe-AMy. This is because the device-oriented schemes adapt the video quality requirements according to the device type. For example, when having a low resolution device it is not worthy to send a high resolution

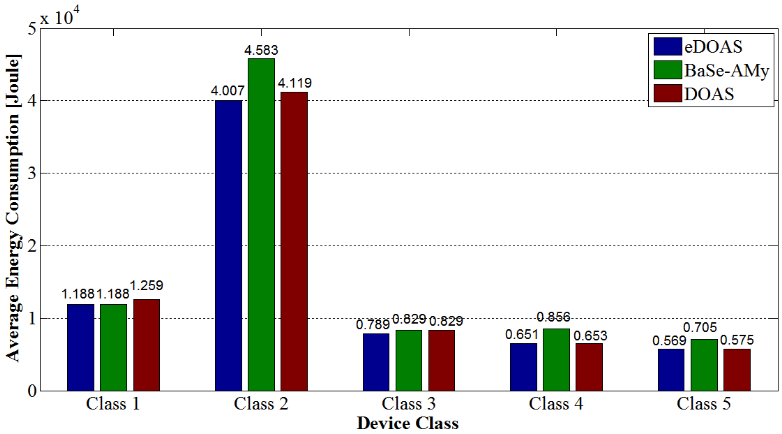


Figure 7.11: eDOAS Assessment: Average Energy Consumption of Different Classes

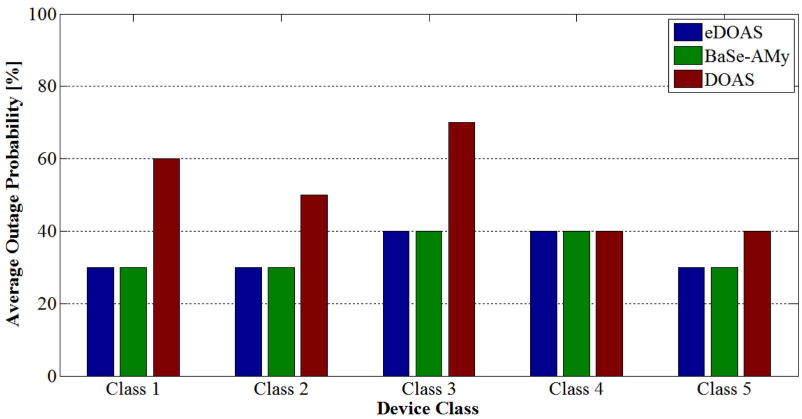


Figure 7.12: eDOAS Assessment: Average Outage Probability of Multimedia Stream

multimedia stream any way, as it will waste the energy of the mobile device without any visible benefits in terms of quality.

Additionally, when compared with the non-energy-aware adaptive scheme, DOAS, eDOAS saves at least 5% energy. This is because eDOAS adapts to a lower video quality level when the remaining device battery capacity is dropping. In this simulation, the battery lifetime threshold was set to 10%. In the energy evaluation experiments, the remaining battery lifetime of some devices is marginally greater than 10% when using eDOAS, but for some is marginally less than 10% when using DOAS. This results in some devices are noted as running out of power even though they consume similar energy with those using eDOAS.

Figure 7.12 illustrates the average outage probabilities of the three schemes. As mentioned, because the Class 2 device is using Windows XP as its operating system it consumes more energy than the other devices that are running Android OS.

7.3.2.2 Scenario 2 - Network Delivery Performance Evaluation

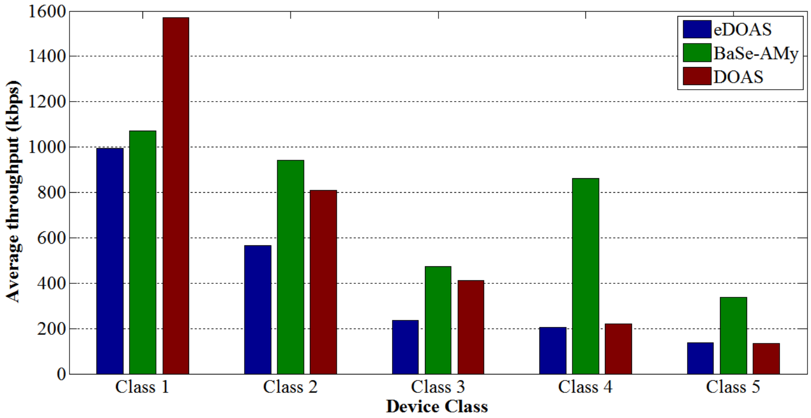


Figure 7.13: eDOAS Assessment: Average System Throughput

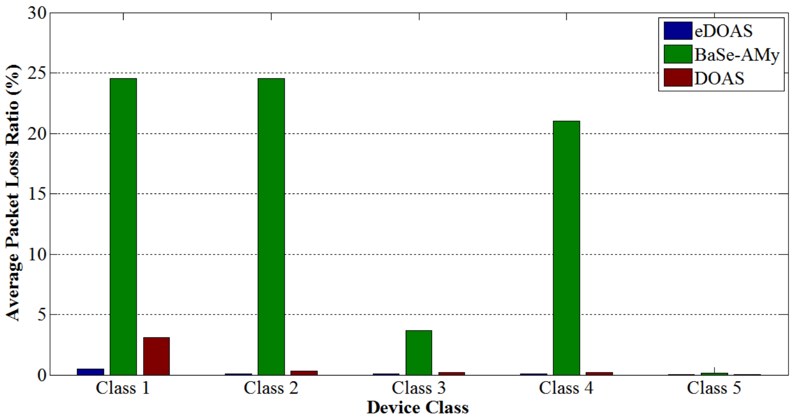


Figure 7.14: eDOAS Assessment: Average System Packet Loss Ratio

Considering the results from Scenario 2, Figure 7.13 illustrates the average throughput at different battery capacity states. As this scenario considers network congestion variations and decreasing battery capacity, eDOAS adapts the quality level of the multimedia streams according to the dynamic network conditions and remaining battery capacity of each device. Therefore when compared to BaSe-AMy and DOAS, eDOAS lowers the bitrate of the adaptive streams (as seen in Figure 7.13) to save more energy and bandwidth resources. However, eDOAS reduces with at least 38% the packet loss rate (e.g., Class 4) as shown in Figure 7.14.

See Figure 7.13 and Figure 7.14, the Class 1 UE using DOAS achieves higher

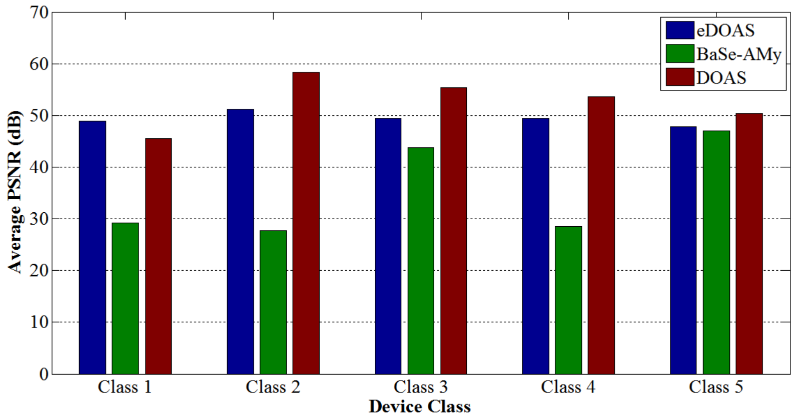


Figure 7.15: eDOAS Assessment: Average PSNR

throughput and lower packet loss ratio than when using BaSe-AMy. Basically, DOAS, the device-oriented adaptive solution which considers the characteristics of the different class users (i.e. different class users are allocated different highest quality levels for their videos). Therefore, when using DOAS the UE of Class 1 is allocated with the highest quality level but the UE of other Classes will be allocated with the lower quality, see the throughput results shown in Figure 7.13. However, BaSe-AMy only considers the energy-aware requirements of UEs and allocates bandwidth to all the UEs proportionally. Thus, all the UEs will compete for the bandwidth when using BaSe-AMy, see the average throughput of Class 2 and Class 4 shown in Figure 7.13. Then BaSe-AMy users are affected by the severe network congestion, see packet loss ratio of Class 1, Class 2 and Class 4 shown in Figure 7.14.

For example, the battery capacity of Class 3 device (i.e. Samsung Galaxy S2) is lower than both Class 1 and Class 2 devices thus its energy consumption rate is higher when compared with the devices in Class 1 and 2. Therefore it adapts to a lower video quality stream when using eDOAS. Thus, the average throughput for the Class 3 is around 30% of that of the Class 1, and around 43% of that of the Class 2. And the packet loss ratio for the Class 3 reduces around on average 47% than those of the Class 1 and 2.

In order to assess the quality of the received multimedia stream, the objective metric Peak Signal-to-Noise Ratio (PSNR) based on the estimation method in [94] was computed. Figure 7.15 illustrates the average PSNR for each device class for each of the three schemes. For example, when using eDOAS, Class 1 devices achieve 20dB and 4dB increase in PSNR when compared with BaSe-AMy and DOAS, respectively. eDOAS adapts to decreasing device battery capacity in order to prolong its lifetime, thus lowering the video quality level. However it can be noticed that the PSNR is still acceptable. Even though DOAS provides a good PSNR as well, the outage probability is very high. Thus this means that when using DOAS the mobile device battery has 52% probability to expire before finishing playing the high quality video stream.

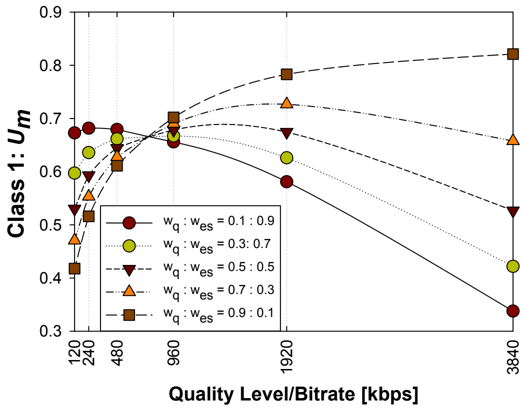
7.4 Performance Analysis of e^{3}DOAS

E^{3}DOAS presented in Chapter 4 adapts fair multimedia streaming services in wireless networks, using coalition game theory and balancing the QoE and energy saving of user requirements. This section describes the performance evaluation for E^{3}DOAS . From the energy measurement experiments and subjective tests in Chapter 5 and Chapter 6 respectively, the parameters of UDP-based energy consumption over WiFi and QoE non-reference models for the selected 5 device classes are considered, as listed in Table 7.12, which are modelled and solved based on eq.(4.16) and eq.(4.20).

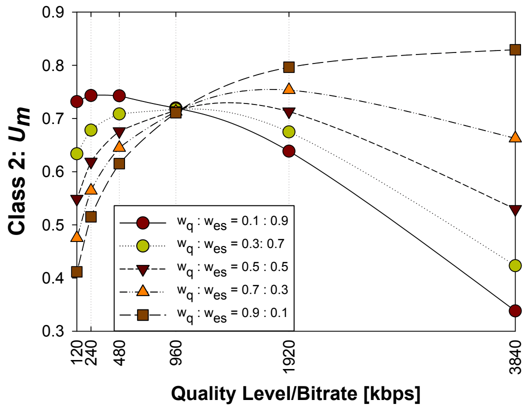
Table 7.12: Energy Consumption and QoE Models used in E^{3}DOAS

UDP	**Class 1:** Galaxy S3	**Class 2:** Galaxy S4 Mini	**Class 3:** Galaxy S2	**Class 4:** Vodafone Smart Mini	**Class 5:** Vodafone 858 Smart
r_d $[mJ/kbps]$	0.2018	0.2723	0.3624	0.5011	0.1449
r_t $[mW]$	907.28	666.67	880.57	531.65	596.59
α_m	0.1512	0.1517	0.1393	0.1202	0.0427
β_m	-0.330	-0.3690	-0.2619	-0.1469	0.3330

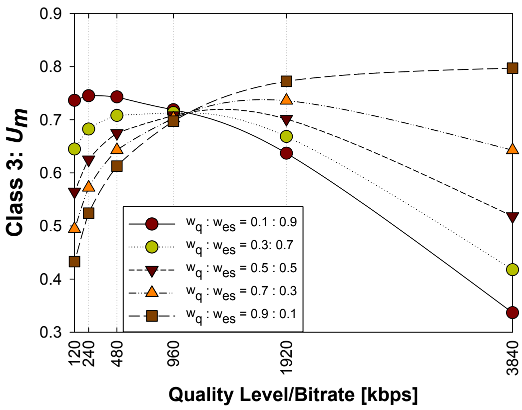
Next, the utility of different mobile devices with different weight values are solved and shown in Figure 7.16. The graphs in Figure 7.16 reveal the trade-offs between QoE and Energy-Saving with the optimal utility within the quality levels from 3840kbps down to 120kbps. The different optimal weighting coefficients provide the different options for the requirements of service operators and users. For example, the users of Class 1 with the weight coefficients $\{w_q : w_{es} = 0.1 : 0.9\}$ (i.e., energy-oriented users) get an optimal QL at 240 kbps based on the highest U_m. Similarly the users of Class 3 with coefficients $\{w_q : w_{es} = 0.9 : 0.1\}$ (i.e., quality-oriented users) should select 3840 kbps as the optimal QL.



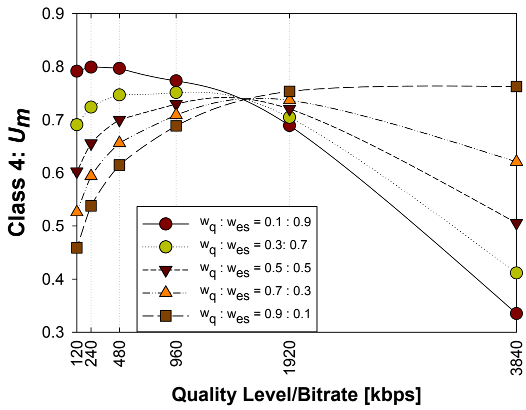
(a) Class 1



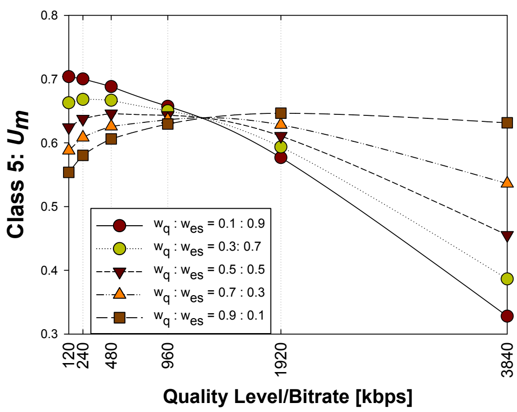
(b) Class 2



(c) Class 3



(d) Class 4



(e) Class 5

Figure 7.16: Utility Trade-Off between QoE and Energy-Saving with Different Weights (i.e. w_q and w_{es}) for different Device Classes

These QoE and Energy-Saving models were deployed into the network simulation models and used to evaluate the performance of the proposed solution, E^{3}DOAS .

Table 7.13: Simulation Parameters

Simulation Parameters	Configuration
Scenarios	6 Scenarios: TO-1, TO-2, TO-3, TO-4, TO-5 and Random TO
No. of Mobile Users	Total numbers: Randomly from 0~50; 5 Classes;
Cell Layout	Single Cell; Radius: 0~250 meters; User Location: Random Distribution; User Mobility: 3 km/h
Antenna Model	Low TxPower:30 dbm; Noise Figure: 2.5 dB; FDD; SISO
Carrier Frequency	2.0 GHz
Path Loss and Channel Model	Low Power: $Loss = 140.7 + 36.7 \log_{10} d$ in $2GHz$
Modulation Scheme	QPSK, 16QAM, 64QAM
OFDM Downlink Bandwidth	20MHz; Sub-carrier:15kHz
MAC Layer	Proportional Fair Scheduler
Transport Protocol	RTP/UDP
Traffic Model	Video Traffic: Pareto Distribution Model; 10%-90% random background load (i.e. CBR)

7.4.1 Network Simulation Setup

The C++ based simulator, LTE-Sim has been employed for e^{3}DOAS performance testing, and Table 7.13 lists the simulation parameters configured in it. In order to simulate real world network performance in a small wireless coverage layout similar to that existing in practical life (e.g. small restaurants, coffee shops, small workspace or living room at home), five classes of mobile devices were considered, based on the model presented in Table 7.12. The users are randomly distributed in a small single cell area with 250 meters coverage. The Jakes Model for Rayleigh Fading was used [211], and the mobile users were set up with a low random mobility model (i.e. 3km/h).

The number of mobile users for each device class varies from 0 to 10 with a uniform distribution. Hence the total number of mobile users varies randomly from 0 to 50, and a total of 50 scenario simulation runs with different numbers of mobile users were considered. In addition, the antenna model and path loss model were set up with low power coverage for the OFDM downlink [212].

Table 7.14: Simulation Benchmark

Adaptive Solutions	QoS-Aware	Device-Oriented	Energy-Aware	QoE-Aware
QOAS	YES	NO	NO	NO
BaSe-Amy	YES	NO	YES	NO
e^{2}DOAS	YES	YES	YES	YES
e^{3}DOAS	YES	YES	YES	YES

The performance of e^{3}DOAS was compared against that achieved when QOAS [150], BaSe-AMy [169] and e^{2}DOAS [179] were employed. Table 7.14 lists the main characteristics of each of these solutions. QOAS is an adaptive video delivery solution which adapts the stream bitrate based on channel conditions only and has no consideration of energy consumption. Furthermore, BaSe-AMy is a threshold-based energy-aware adaptive streaming solution which adjust the multimedia stream taking into consideration the battery level of the mobile device and the network conditions. The decision mechanism in BaSe-AMy includes several battery thresholds (e.g. percentage of the remaining battery capacity=10% or 30%) and one packet loss threshold (e.g. loss ratio=10%). When the video playout is shorter than the battery lifetime, and remaining battery capacity is above 30% and loss ratio is below 10%, the multimedia server will stream the highest quality level. e^{2}DOAS , a simplified version of e^{3}DOAS, is a adaptive streaming solution using the same balancing scheme for QoE and energy-saving scheme as that used in e^{3}DOAS, but using a proportional rate allocation scheme which is different from the coalition-based game for the rate allocation employed by e^{3}DOAS.

7.4.2 Simulation Scenarios Configuration

In order to study the performance of e^{3}DOAS two types of scenarios are considered. The aim of the first scenario is to test the impact of different utility trade-offs between energy-saving and QoE when all the users in the network have the same TOs (e.g. all the users were assigned with TO-1). This also enables the study in the performance of the rate allocation schemes between e^{3}DOAS and e^{2}DOAS. The second scenario was run several times where all the users in the network were assigned with random TOs. This scenario enabled the performance analysis of e^{3}DOAS against the non-device-oriented solutions.

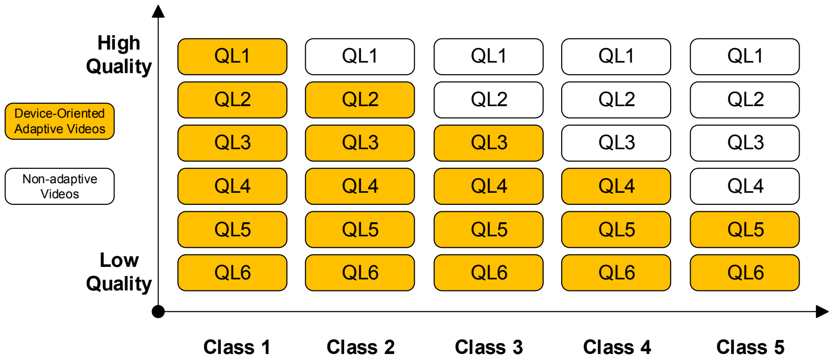


Figure 7.17: Device-Oriented Adaptive Video Set

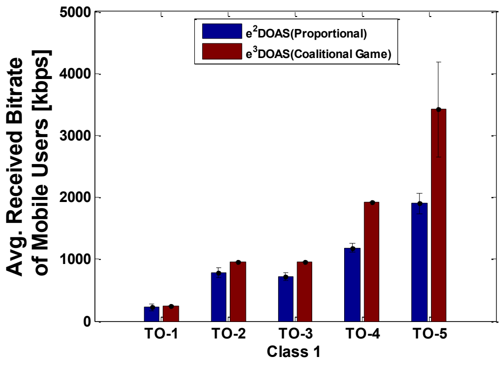
(a) **Scenario I** - all the mobile devices using E^{3}DOAS or E^{2}DOAS are evaluated under five Trade-off (TO) weighting coefficients showed in Figure 7.16: TO-1 ($w_q : w_{es} = 0.1 : 0.9$), TO-2 ($w_q : w_{es} = 0.3 : 0.7$), TO-3 ($w_q : w_{es} = 0.5 : 0.5$), TO-4 ($w_q : w_{es} = 0.7 : 0.3$), TO-5 ($w_q : w_{es} = 0.9 : 0.1$), respectively;

(b) **Scenario II** - is using the Random-TO, namely mobile devices are allocated trade-off weights randomly, to study the performance between non-device-oriented and device-oriented adaptive schemes, allowing the mobile users to select different TOs with a uniform random distribution, which simulates mobile users' behaviours in the real world. Each simulation configured with Random-TO were repeated three times.

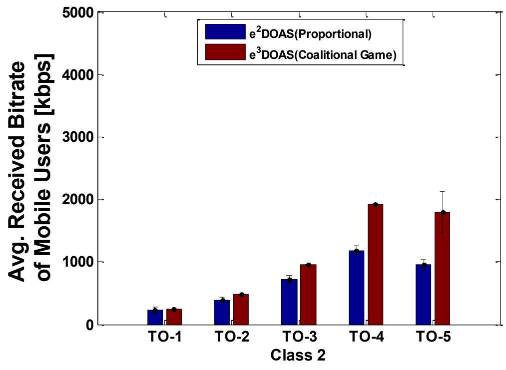
Figure 7.17 shows the video set used in the simulations which is modeled based on the Pareto distribution similar to the simulation configuration for DOAS. The device-oriented solutions (e.g. E^{2}DOAS and E^{3}DOAS) adapt the multiple quality level videos, but the non-device oriented solutions (e.g. QOAS, BaSe-Amy) use the full quality level videos (i.e. all the 6 quality levels) for all device classes. In addition, five remaining battery capacity thresholds (e.g., 90%, 70%, 50%, 30% and 10%) and 10% loss threshold are configured for BaSe-AMy. The solutions were compared in terms of average throughput, packet loss, delay, fairness, Peak Signal-to-Noise Ratio (PSNR) and power consumption.

7.4.3 Results and Analysis

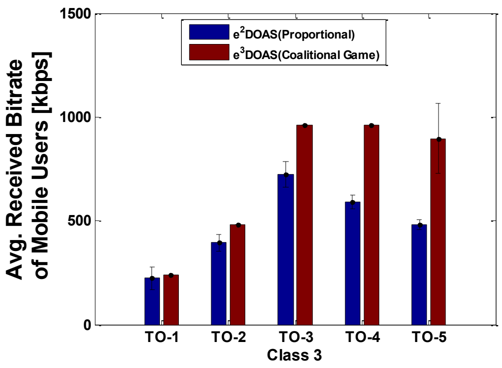
In this section, the network simulation results were generated from the two types of scenarios previously described.



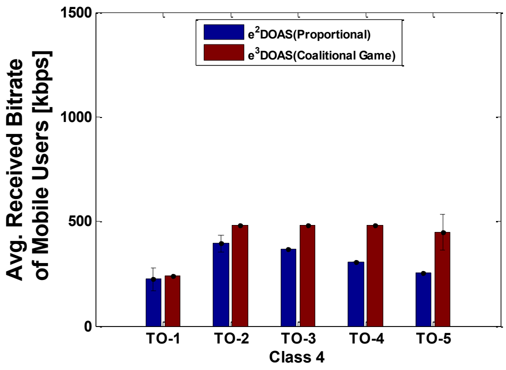
(a) Class 1



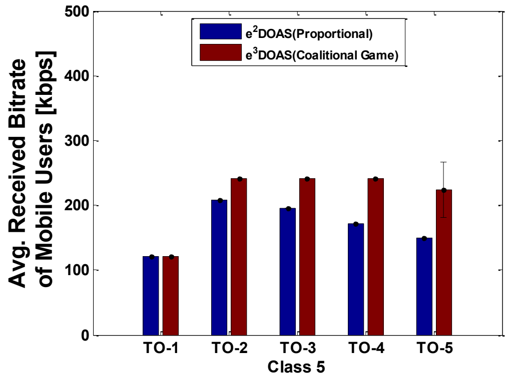
(b) Class 2



(c) Class 3

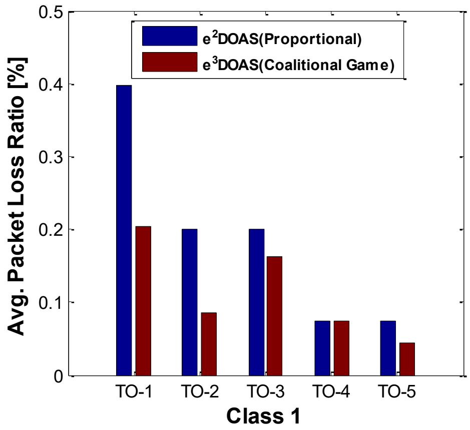


(d) Class 4

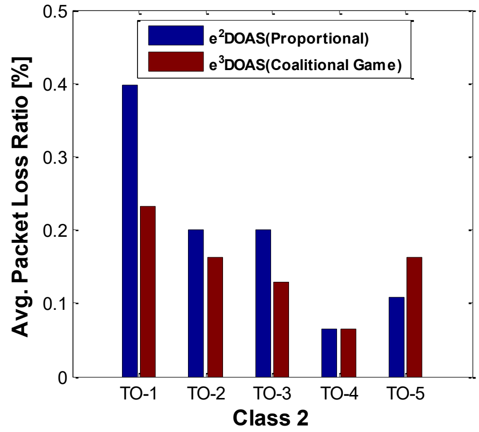


(e) Class 5

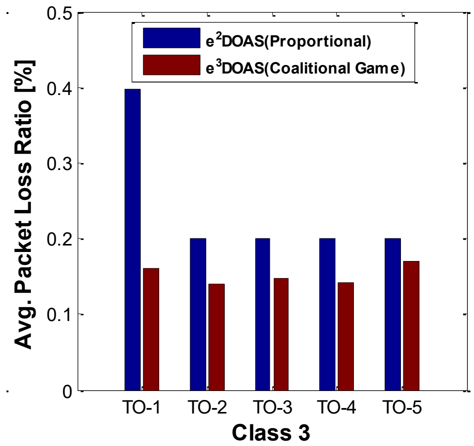
Figure 7.18: Average Received Throughput of Different Class Devices with the Different Utility Trade-offs



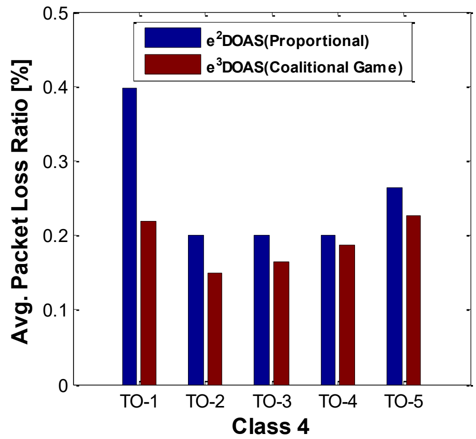
(a) Class 1



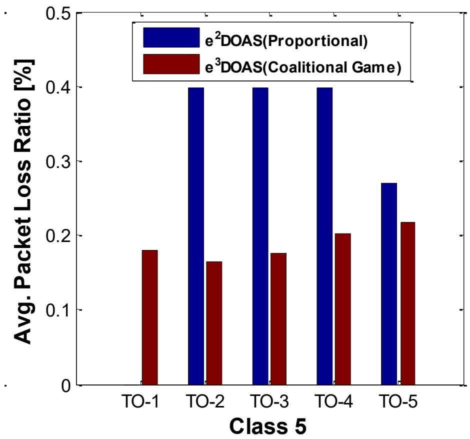
(b) Class 2



(c) Class 3



(d) Class 4



(e) Class 5

Figure 7.19: Average Packet Loss Ratio of Different Class Devices with the Different Utility Trade-offs

7.4.3.1 Impact of Different Utility Trade-offs on Coalition Game-based Rate Allocation

E^{3}DOAS makes use of the coalition game-based scheme in fair rate allocation for limited bandwidth resource. Whereas, E^{2}DOAS makes use of the simple proportional allocation scheme based on the channel conditions. Figure 7.18 illustrates the average received bitrates of different device classes. The TO-1 represents the users with the highest energy-saving requirements and TO-5 - users which require the highest QoE. Accordingly, the descending encoding bitrates adapt the video to the mobile users based on the TO-5 to TO-1 requirements.

The received bitrates of the mobile users under both of E^{3}DOAS and E^{2}DOAS decrease from TO-5 to TO-1. This is because the user with a higher QoE requirement (e.g., TO-5) will be allocated higher bitrate, whereas the users with higher energy-saving requirement (e.g., TO-1) will be allocated lower bitrate to conserve the battery lifetime of their mobile devices. Moreover, the results show that E^{3}DOAS using the proposed coalition game-based rate allocation mechanism is able to fit the available channel bandwidth more efficiently than E^{2}DOAS . Hence, on average, the received throughput under E^{3}DOAS are 34% higher than that under E^{2}DOAS .

According to the device-oriented solution, the lower highest adaptive bitrates are assigned to the lower performance device classes (i.e. decreasing from Class 1 to Class 5), which causes the lower throughput allocation for the lower performance device classes, for example, the average received throughput of Class 5 are much lower than that of other classes. Moreover, E^{3}DOAS using the coalition game-based solution considers the fairness of resource allocation between the different classes and achieves better performance of the received throughput. In addition, according to the results shown in Figure 7.18 the higher standard deviations of E^{3}DOAS (i.e. the number of mobile users were randomly changed) indicate E^{3}DOAS senses the change of network status (i.e. the mobile users come and go to/from the network and remain in the network for the different durations) and is able to adapt the bitrate flexibly.

Figure 7.19 describes the results of Packet Loss Ratio (PLR), showing how E^{3}DOAS performs fairer rate allocation. E^{2}DOAS shares equally the bandwidth resource among the users. However, E^{3}DOAS includes fairness control using Shapely values and guarantees resource allocation for the users who have lower bandwidth requirements. This

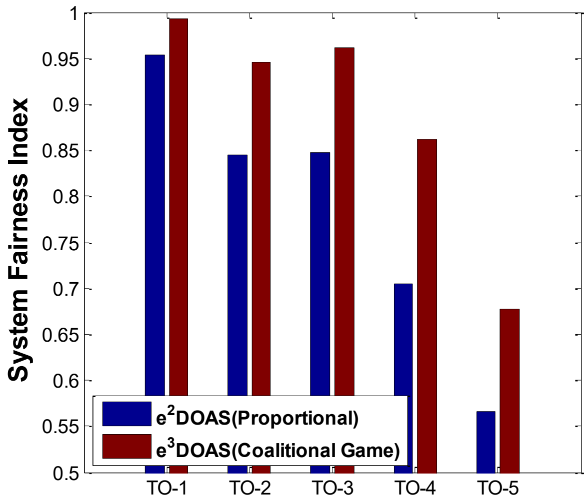


Figure 7.20: System Fairness Index

is why E^{3}DOAS achieves on average 0.17% lower PLR than when E^{2}DOAS employs.

The Jain's Fairness Index of the whole adaptive system shown in Figure 7.20, indicates that by using E^{3}DOAS with the proposed coalition game approach, the system fairness has increased considerably. When the mobile users are all set with TO-1 and request lower video quality levels, it is enough to allocate the bandwidth fairly with both adaptive solutions. However, the fairness decreases when the requested bitrates increase and the available channel resources are limited. However, E^{3}DOAS exhibits 24% higher fairness than when E^{2}DOAS is employed including for instance when the utility trade-offs of mobile users are all set to TO-5 and the encoding bitrate of the transmitted video is the highest.

Therefore, E^{3}DOAS using coalition game-based rate allocation improves the efficiency and the fairness of the system when compared to E^{2}DOAS which uses proportional rate allocation.

7.4.3.2 Performance Comparisons between Device-Oriented and non-Device-Oriented Solutions

This section compares the performance of the Device-Oriented solutions (E^{3}DOAS and E^{2}DOAS) against that of the non-Device-Oriented (BaSe_AMy and QOAS) in terms of QoS, QoE and power consumption metrics. 50 scenario simulation runs were considered with different number of mobile users (i.e. varying from 10 to 50 in a single cell) with

Table 7.15: Average Peak Signal-to-Noise Ratio and Power Consumption

	e³DOAS		e²DOAS		BaSe_AMy		QOAS	
	PSNR [dB]	Power Consumption [mW]	PSNR [dB]	Power Consumption [mW]	PSNR [dB]	Power Consumption [mW]	PSNR [dB]	Power Consumption [mW]
Class 1	49.42	1227.62	49.33	1095.84	10.92	1142.82	10.03	1192.98
Class 2	49.05	968.46	48.95	855.17	21.80	906.78	10.36	1035.30
Class 3	49.51	1146.86	48.85	1060.39	22.49	1053.56	9.81	1405.10
Class 4	47.60	750.83	47.61	690.41	50.52	760.78	10.55	1198.31
Class 5	47.60	627.68	47.60	621.26	12.48	703.31	10.17	795.88

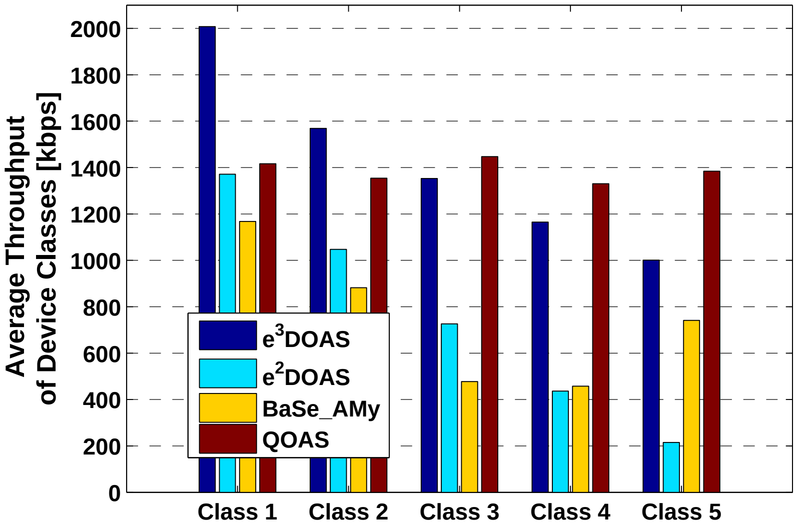


Figure 7.21: e^{3}DOAS Assessment: Average Throughput of Device Classes

the different device classes based on the configuration in Table 7.12. Different from the previous sub-section, all the mobile users were randomly assigned with different utility TOs to simulate the different personal QoE and Energy-saving profiles while testing E^{3}DOAS and E^{2}DOAS . The simulation results were averaged and listed in Figures 7.21-7.24 and Table 7.15.

Figure 7.21 indicates the average achieved throughput of each mobile device class under the different adaptive solutions. QOAS achieves very high throughputs (average 29.9% higher than that of the other schemes) for all the mobile users because the adaptation is only based on the network conditions, at the cost of high packet loss ratio and high end-to-end packet delay. BaSe_AMy allocates the different level bitrates to the users based on the battery level and power consumption information of mobile devices. For example, according to Table 7.12, the mobile devices from Class 4 have the highest power consumption rate per unit data (i.e. $r_{d,m}$) which results in Class 4

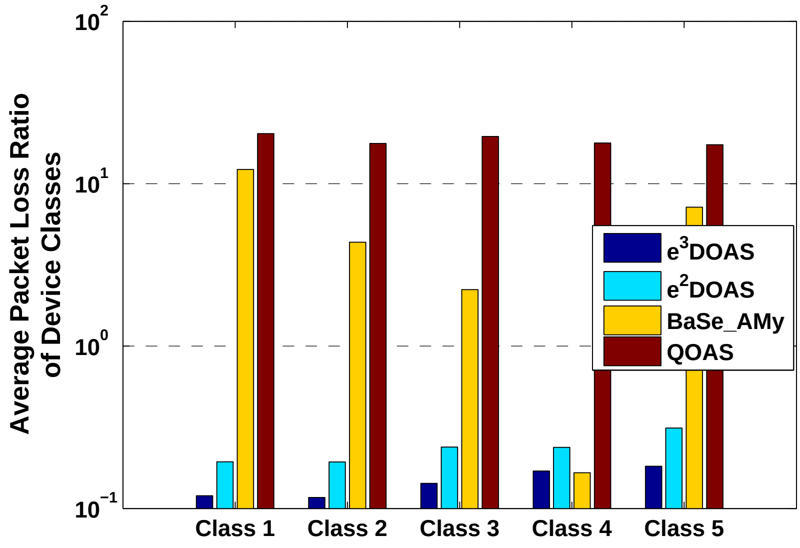


Figure 7.22: e^{3}DOAS Assessment: Average Packet Loss Ratio of Device Classes

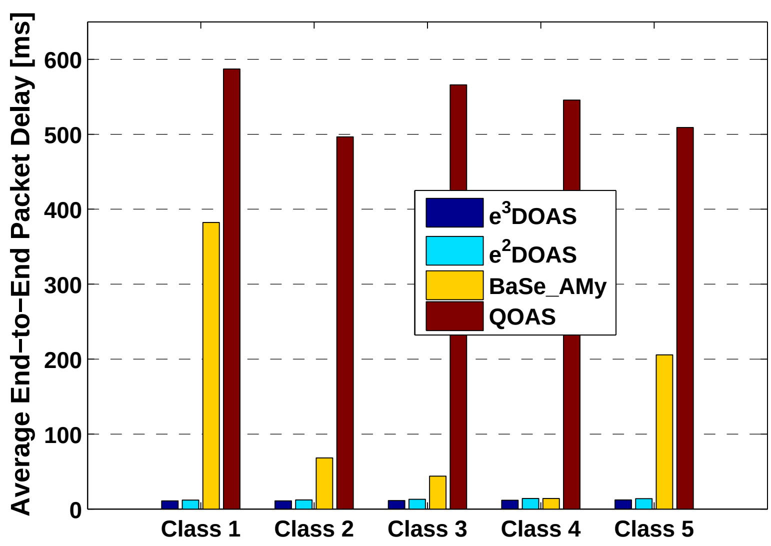


Figure 7.23: e^{3}DOAS Assessment: Average End-to-End Packet Delay of Device Classes

devices receiving the lowest adaptive bitrate. The Device-Oriented solutions, E^{3}DOAS and E^{2}DOAS , decreasingly assign the optimal quality level bitrates to the mobile devices from Class 1 to Class 5 based on the different device characteristics.

Due to the fairness controlled by the coalition game-based scheme, E^{3}DOAS results in 50.4% on average higher throughput than E^{2}DOAS . Moreover, by considering the heterogeneity of the mobile devices, it is more efficient to utilize channel resources. These solutions achieve lower PLRs and end-to-end delay, especially in case of E^{3}DOAS with a PLR as low as below 0.2% and the under $12ms$ delay when compared to other

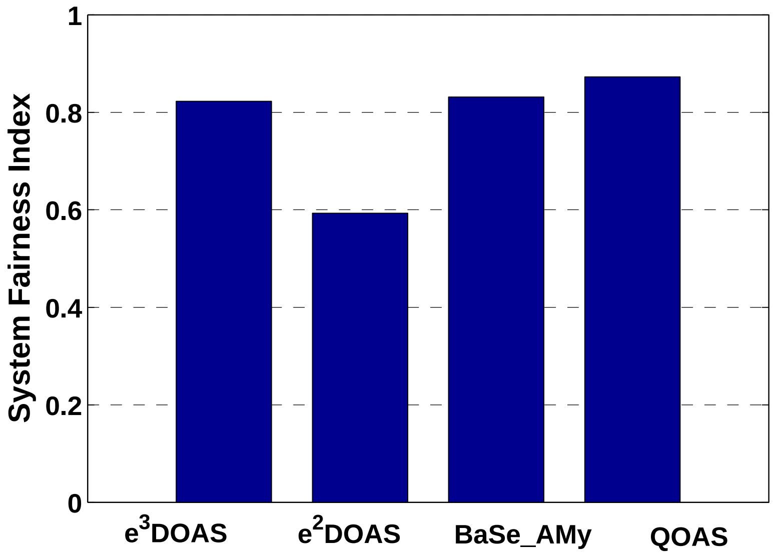


Figure 7.24: e^{3}DOAS Assessment: Average System Fairness of Device Classes

adaptive solutions, as listed in Figure 7.22 and Figure 7.23. Additionally, Figure 7.24 demonstrates that E^{3}DOAS provides over 0.80 Jain's fairness score (the full score is 1.0) for the mobile users as well, which is 25% better than when using E^{2}DOAS without coalition game based fairness controlling scheme. Even though QOAS and BaSe_AMy also achieve high fairness, they afford poor system throughput and higher packet loss ratio.

Based on eq.(4.12) and the PSNR estimation method from [94], the results of PSNR and average power consumption of each class were calculated and listed in Table 7.15. E^{3}DOAS improves on average with up to 24.99dB and 38.45dB of PSNR when compared against BaSe_AMy and QOAS, respectively. Moreover, E^{3}DOAS also achieves more power savings for the lower class devices (i.e. Class 4 and Class 5) than the non-device-oriented solutions.

To conclude, E^{3}DOAS provides better system fairness, higher bandwidth utilization, lower network latency and packet loss ration, offering a better trade-off among QoS, QoE and Energy savings when compared to the other schemes involved.

7.5 Chapter Summary

This chapter presents the performance evaluation of the proposed architecture and set of solutions for energy-quality trade-off when performing wireless multimedia streaming.

Evaluation was done using simulations, which involves the following proposed schemes:

- **UPS** - The performance evaluation presented the simulation results and analysis of Utility-based Priority Scheduling (UPS) mechanism for video delivery in LTE downlink systems. The proposed solution makes use of the device display resolution and energy consumption rate to efficiently allocate the resources for the transmission channel. The simulation results show how the proposed UPS algorithm accommodates an average 67% higher number of UEs while providing good quality levels within a single cell in comparison with other existing solutions such as M-LWDF and PF.

- **DOAS** - The performance evaluation presented the simulation environment, traffic modelling and result analysis of Device-Oriented Adaptive Multimedia Scheme (DOAS) that makes efficient use of the network resources and provides high QoE levels to multi-screen end-users. DOAS differentiates streaming service for mobile devices based on their screen resolution. DOAS jointly works with the existing scheduling mechanisms (e.g. PF and M-LWDF) for downlink transmissions in LTE systems. Simulation testing results show how DOAS outperforms a non-adaptive solution in heavy network traffic conditions in terms of average 87.2% reduced packet loss ratio and average 26dB improved PSNR, and how DOAS also finds a very good trade-off between throughput, packet loss, delay on one side and PSNR on the other.

- **eDOAS** -The performance evaluation of eDOAS was conducted with three main goals: (1) to study the impact of device heterogeneity on energy consumption, (2) to study the impact of different quality levels on energy consumption, and (3) to compute the energy consumption rate for data/received stream and the energy consumption per unit of time for each device class, which were then used for the mathematical energy model in the simulation environment. The evaluation results show the benefits of eDOAS in comparison with other two schemes in terms of: saving at least 5% of energy consumption, average lower 18% of outage probability, good throughput, much lower packet loss rate and average 15dB improvement of PSNR.

- **e^{3}DOAS** - Based on the real energy consumption and QoE models, the evaluation of E^{3}DOAS makes use of the coalition-game theory and information on heterogeneous mobile devices to find the best trade-off between QoE and energy savings in a multi-device wireless multimedia environment. The results show how E^{3}DOAS to 20% increase in system fairness when compared to other device-oriented adaptive solution. In addition, the network simulation results also show that E^{3}DOAS finds the better trade-off between QoE and energy-savings, outperforming the other non-device-oriented schemes considered from the literature, in terms of average throughput, packet loss ratio, end-to-end delay, PSNR and energy consumption rate.

Chapter 8

Conclusions and Future Works

This chapter presents this thesis conclusions summarized according to its main contributions and lists several potential future works.

8.1 Conclusions

The purpose of this research is to find a way towards "Always Best Experience" for multimedia streaming services in future wireless networks (e.g. 5G) that would be beneficial for both mobile users and network operators. It is noteworthy that existing solutions are faced with great challenges due to high content demand which increases network traffic, current network bottlenecks, technological evolution cost and user perceptual quality requirement of multimedia services. Most of the related works include complex and expensive solutions, have poor performance, or do not consider the quality of user experience. This thesis proposes a suite of novel multimedia adaptive delivery solutions for heterogeneous wireless networks, which considers mobile device heterogeneity, energy consumption, user QoE and network conditions, in order to increase mobile users' experience anywhere at any time.

The solution suite proposed in this thesis consists of four major schemes: 1) a **Utility-based Priority Scheduling scheme (UPS)** for multimedia streaming in LTE downlink system; 2) a **Device-Oriented Adaptive scheme (DOAS)** for multimedia delivery in LTE networks; 3) an **Energy-aware Device-Oriented Adaptive scheme (eDOAS)** for video transmission in WiFi offloading environment; 4) an **Evolved Energy-saving QoE-aware Device-Oriented Adaptive scheme (e^{3}DOAS)** for multimedia streaming in an OFDMA-based wireless network.

This thesis presents the principles, mechanisms, algorithms, experimental energy and subjective tests, network performance evaluations, and result analysis for the four major proposed schemes, UPS, DOAS, eDOAS and e^{3}DOAS, which are summarized as follows:

1. Unlike most existing packet scheduling schemes that only consider network conditions (e.g. packet loss, latency and jitter), **UPS** also takes into account device characteristics (i.e. screen resolutions) and energy consumption rates. The scheduling priority used to allocate bandwidth resource to each served mobile user is computed based on the utilities of *device screen resolutions*, *packet loss rates* and *energy consumption rates*. The highest priority is given to the mobile user which has the highest product value of the utilities and the highest average received instantaneous rate. The rest of mobile users will be assigned after next utility calculation until all the users are served. Additionally, the modified UPS-upgraded QOAS server adapts different bitrate streams to different class devices with different display resolutions. In order to prioritize the users with high resolution devices and serve them with high quality video streams, both device classification-based adaptation and display utility-based scheduling are necessary to be considered.

   Network performance evaluation of UPS is done with LTE-Sim in a single cell LTE network compared against two well-known scheduling schemes: *M-LWDF* and *PF*. The experimental results show that UPS outperforms the other two compared schemes in terms of average video throughput, packet loss ratio and PSNR: 1) UPS achieves 18% average increase in the throughput in comparison with those of M-LWDF and PF with the same network conditions and numbers of users; 2) UPS also reduces 60% average packet loss compared to the other two schemes with the same scenarios; 3) Compared to the other two schemes, UPS serves alomost fourfold number of users by providing the same video quality for the users.

2. **DOAS** is a cost-efficient and easily deployed adaptive scheme built on the top of the current LTE downlink scheduling systems, which considers mobile device heterogeneity and network conditions. Mobile devices with different screen reso-

lutions (i.e. from high to low) are classified into different device classes (i.e. from high to low). Different numbers of video quality levels are allocated to different device classes. Depending on actual network conditions, DOAS adapts down video quality levels step by step to these device classes. Notably, DOAS does not require modifications of the MAC layer of the scheduling schemes.

DOAS deployed in conjunction with two well-known scheduling schemes (i.e. M-LWDF and PF) are tested in a single cell LTE network scenario with heavy load background traffic, respectively. The results of simulation experiments perform the comparison between two schemes using DOAS and those without using DOAS in terms of video throughput, packet loss, delay and PSNR: 1) When using DOAS, the higher device classes are allocated with higher bandwidth share resulting in higher video throughput, which saves more channel resource with respect to the scheduling scheme without using DOAS; 2) When jointly working with DOAS, the two scheduling schemes reduce with 60%, 65%, 67%, 65% and 65% average packet loss ratio in device class 1, class 2, class 3, class 4 and class 5, respectively, which are compared against those without DOAS; 3) Similarly, the experimental results also show that when using DOAS the delay is significantly reduced when compared with the non-adaptive solutions; 4) The video quality is estimated by PSNR values. The results show that when using DOAS there are improvements of average 25.5 dB, 50 dB, 53.5 dB, 41 dB and 36 dB in device class 1, class 2, class 3, class 4 and class 5, respectively, which are compared with the scheduling schemes without using DOAS.

3. **eDOAS** is an enhanced version of DOAS, which also considers the energy consumption rate and device battery life. Similar to DOAS, eDOAS divides the served mobile device into different classes based on their screen resolutions, and adapts down different video quality levels step by step according to the network conditions. Moreover, eDOAS predicts available video play duration based on the energy consumption parameters of the mobile device and checks whether the mobile device has enough battery to play the whole video or not before video streaming. If the battery life is enough eDOAS adjusts the quality level to match network conditions. If there is not enough battery or the mobile user wants to save more energy, eDOAS will adapt down the quality level until reaching a specific

battery threshold.

Simulation-based tests demonstrate how better results are obtained when employing eDOAS than when either non-energy-aware DOAS or non-device-oriented BaSe_AMy schemes are used, in terms of energy consumption, video play outage probability, video throughput, packet loss and PSNR: 1) Compared with using the other two schemes, around 5%, 7.3%, 4.0%, 12.1% and 10.1% of average energy consumption in device class 1, class 2, class 3, class 4 and class 5 are saved by using eDOAS, respectively. 2) eDOAS saves more bandwidth resource and reduces network congestion with respect to the other two schemes; 3) During the video streaming, when employing eDOAS, 12.5%, 12.1%, 1.2%, 10% and 0.1% of packet loss ratios on average are reduced in device class 1, class 2, class 3, class 4 and class 5, respectively, in comparison with those of the other two schemes; 4) eDOAS also provides good streaming quality by getting the conclusions from the results of estimated PSNR.

4. **e^{3}DOAS** balances user perceptual quality and mobile device energy consumption and performs a trade-off of quality levels to mobile users within a small-scale wireless network by using a coalition game theory based fairness control mechanism. The server side of E^{3}DOAS involves several innovative components: *Data Cloud (DC)*, *Crowdsourcing Qualitative Test Scheme (CQTS)* and *Energy-saving Device-Oriented Adaptation Scheme (ESDOAS)*. DC stores device characteristic information, parameters of energy consumption models and QoE models and pre-encoding multimedia clips. CQTS collects perceptual quality scores and updates QoE modelling information periodically. ESDOAS optimizes the quality level selection to fit both requirements of device energy-saving and user perceptual quality, then fairly adapts the quality level to users depending on network conditions.

   Based on the simulation tests, the following conclusions have been reached: 1) By using the coalition game theory based fairness control mechanism, e^{3}DOAS achieves improvements on average of 14.4% and 11.2% in system bandwidth utilization and system fairness, respectively, in comparison with using e^{3}DOAS without this fairness control mechanism (i.e. e^{2}DOAS); 2) e^{3}DOAS contributes to alleviating network congestion in terms of average throughput, and reduces 22%

and 4.04% of packet loss ratio on average compared with BaSe_AMy and QOAS, respectively; 3) e^{3}DOAS achieves lower packet latency (i.e. under 13 ms) in different device classes; 4) e^3 provides on average 22 dB higher PSNR than employing QOAS and BaSe_AMy with the similar energy consumption in the same network conditions.

All the contributions discussed above play equal important roles in the future **"Always Best Experience"** multimedia streaming in the heterogeneous network environment. UPS is a MAC layer scheduling solution for LTE downlink. DOAS is an application layer adaptive streaming scheme which is working on top of current LTE downlink system or other wireless technologies. eDOAS is an enhanced extension of DOAS which prolong the battery life of the served mobile devices. Different from the former, e^{3}DOAS balances QoE and energy-saving, and fairly adapts streaming to the mobile devices with different characteristics (e.g. display resolution). e^{3}DOAS has higher computational complexity, which is suitable for small scale deployments, unlike DOAS and eDOAS which could be employed in a large scale environment. In conclusion, all the contributions provide different solutions for video streaming satisfying different user requirements and deployment approaches.

Additionally, this thesis presents a real energy measurement test-bed and real experimental subjective tests which are used for energy consumption rate measurement of mobile device models and QoE parameter modelling for user perceptual quality, respectively.

In conclusion, the proposed solutions in this thesis provide differentiated services in terms of device heterogeneity and better trade off between user QoE and energy consumption when adaptively streaming multimedia content over heterogeneous wireless networks.

8.2 Future Works

This thesis presents an important contribution towards "Always Best Experience" multimedia streaming in the future wireless network environment, which provides better energy consumption-user QoE trade off for mobile users using heterogeneous devices. Following this research, the following future works could be considered:

- **Enhanced CQTS System Implementation and Deployment** - In order to obtain a more accurate non-reference QoE model during video transmission, an enhanced CQTS system is required to be implemented and deployed in a campus like environment that collects and analyzes more relevant parameters, such as video frame rate, packet loss, delay and user behaviour information (e.g. frequency of pausing/aborting playing video, frequency of failing to open/watch video and frequency of watching a whole video).

- **MPEG-DASH integrated with Device-Oriented Mechanism** - MPEG-DASH has been used in some new multimedia streaming services. A MPEG-DASH based adaptive delivery built with HTML5 will be considered to provide service differentiation based on device characteristics.

- **Network Management and Optimization for LTE-WiFi offloading** - The bottleneck of wireless networks is a great challenge for network operators until 5G technologies are widely deployed. Mobile data offloading is a very good alternative and cost-efficient. A novel network management and optimization solution for multimedia streaming over LTE-WiFi will be studied, and a game theory based solution will be proposed.

- **Future AR/VR-based Multimedia Streaming** - Digi-Capital forecasts that Augmented/Virtual Reality (AR/VR) could bring 150 billion dollars in revenue by 2020 [213]. It is expected that the fast growing AR/VR technologies will lead to the next evolution of multimedia content delivery in the immediate future. There are many challenges for researchers to propose an efficient solution for multimedia streaming over AR/VR with respect to ultra high quality 3D video traffic, very low transmission latency for sensor and control signalling, faster interaction among AR/VR users and so on.

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Appendix A

Energy Measurement Results

Table A.1: List of **Local Playback Energy** Measurement Results for Class 1, 2, 3, 4 and 5

Devices	**Quality Levels**	**Avg. Power Consumption [mW]**	**Avg. Energy [Joule]**	**Battery Lifetime [hours]**	**Energy STD**	**Coefficient of Variation [%]**
Class 1	**QL 1**	1151.15	686.08	6.93	3.31	0.48
	QL 2	925.58	551.65	8.62	0.65	0.12
	QL 3	692.39	412.66	11.53	2.91	0.71
	QL 4	678.55	404.42	11.76	2.79	0.69
	QL 5	626.41	373.34	12.74	2.58	0.69
	QL 6	675.21	402.43	11.82	2.65	0.66
Class 2	**QL 2**	4294.88[1] 1074.05[2]	2559.75[1] 640.14[2]	6.75[1] 6.72[2]	64.39[1] 61.58[2]	2.52[1] 0.85[2]
	QL 3	3513.88[1] 583.27[2]	2094.27[1] 347.63[2]	8.26[1] 12.38[2]	26.54[1] 56.94[2]	1.27[1] 5.92[2]
	QL 4	3015.04[1] 392.13[2]	1796.96[1] 233.71[2]	9.62[1] 18.41[2]	47.88[1] 52.34[2]	2.66[1] 1.65[2]
	QL 5	2586.78[1] 355.40[2]	1541.72[1] 211.82[2]	11.21[1] 20.31[2]	56.02[1] 55.51[22]	3.63[1] 2.09[2]
	QL 6	2406.93[1] 373.72[2]	1434.53[1] 222.74[2]	12.05[1] 19.32[2]	50.25[1] 57.07[2]	3.50[1] 3.81[2]
Class 3	**QL 3**	724.37	431.72	8.43	5.12	1.19
	QL 4	505.55	301.31	12.08	9.73	3.23
	QL 5	413.84	246.65	14.75	8.46	3.23
	QL 6	433.68	258.48	14.08	8.44	3.26
Class 4	**QL 4**	354.95	211.55	14.59	5.88	2.78
	QL 5	302.58	18.34	17.12	1.21	0.67
	QL 6	315.30	187.92	16.43	3.62	1.93
Class 5	**QL 5**	235.07	140.10	18.89	4.23	3.02
	QL 6	226.71	135.12	19.58	0.64	0.40

[1]Viliv 70X EX [2]Samsung Galaxy S4 Mini LTE

Table A.2: List of **TCP Energy** Measurement Results over **WLAN** for Class 1, 2, 3, 4 and 5

Devices	**Quality Levels**	**Avg. Power Consumption [mW]**	**Avg. Energy [Joule]**	**Battery Lifetime [hours]**	**Energy STD**	**Coefficient of Variation [%]**
Class 1	**QL1**	1504.84	896.89	5.3	6.08	0.68
	QL2	1216.34	724.94	6.56	3.36	0.46
	QL3	983.07	585.91	8.12	6.09	1.04
	QL4	953.17	568.09	8.37	2.33	0.41
	QL5	910.22	542.49	8.77	2.45	0.45
	QL6	959.2	571.68	8.32	10.35	1.81
Class 2	**QL2**	5113.61[1] 1357.88[2]	3047.71[1] 809.30[2]	5.67[1] 5.32[2]	59.06[1] 1.49[2]	1.94[1] 0.18[2]
	QL3	4336.31[1] 920.01[2]	2584.44[1] 548.33[2]	6.69[1] 7.85[2]	38.01[1] 4.45[2]	1.47[1] 0.81[2]
	QL4	3632.11[1] 741.85[2]	2164.74[1] 442.14[2]	7.99[1] 9.73[2]	60.16[1] 9.44[2]	2.78[1] 2.14[2]
	QL5	3170.36[1] 668.89[2]	1889.53[1] 398.66[2]	9.15[1] 10.79[2]	97.33[1] 6.75[2]	5.15[1] 1.69[2]
	QL6	3015.84[1] 696.89[2]	1797.44[1] 415.35[2]	9.62[1] 10.36[2]	32.08[1] 4.22[2]	1.78[1] 1.02[2]
Class 3	**QL3**	1223.93	729.46	4.99	10.28	1.41
	QL4	992.88	591.76	6.15	9.07	1.53
	QL5	865.31	515.72	7.06	11.07	2.15
	QL6	862.49	514.04	7.08	6.75	1.31
Class 4	**QL4**	637.61	380.01	8.12	5.69	1.5
	QL5	604.56	360.32	8.57	9.24	2.57
	QL6	603.99	359.98	8.58	5.53	1.54
Class 5	**QL5**	607.1	361.83	7.31	2.86	0.79
	QL6	600.65	357.99	7.39	2.77	0.77

[1]Viliv 70X EX
[2]Samsung Galaxy S4 Mini LTE

Table A.3: List of **UDP Energy** Measurement Results over **WLAN** for Class 1, 2, 3, 4 and 5

Devices	**Quality Levels**	**Avg. Power Consumption [mW]**	**Avg. Energy [Joule]**	**Battery Lifetime [hours]**	**Energy STD**	**Coefficient of Variation [%]**
Class 1	**QL 1**	1682.10	1002.53	4.74	19.28	1.92
	QL 2	1386.23	826.20	5.76	26.68	3.23
	QL 3	1057.20	630.09	7.55	17.57	2.79
	QL 4	1015.21	605.06	7.86	14.54	2.40
	QL 5	955.71	569.60	8.35	15.18	2.67
	QL 6	988.77	589.31	8.07	15.21	2.58
Class 2	**QL 2**	4628.85[1] 1372.96[2]	2758.79[1] 818.28[2]	6.27[1] 5.26[2]	31.65[1] 106.76[2]	1.15[1] 3.86[2]
	QL 3	3930.26[1] 944.29[2]	2342.43[1] 562.80[2]	7.38[1] 7.65[2]	88.25[1] 58.12[2]	3.77[1] 0.95[2]
	QL 4	3328.66[1] 750.23[2]	1983.88[1] 447.14[2]	8.71[1] 9.62[2]	57.85[1] 53.88[2]	2.92[1] 0.59[2]
	QL 5	3088.05[1] 670.40[2]	1840.48[1] 399.56[2]	9.39[1] 10.77[2]	192.85[1] 58.69[2]	10.48[1] 2.90[2]
	QL 6	2631.69[1] 693.76[2]	1568.48[1] 413.48[2]	11.02[1] 10.41[2]	312.77[1] 49.26[2]	19.94[1] 1.02[2]
Class 3	**QL 3**	1228.47	732.17	4.97	16.62	2.27
	QL 4	1028.49	612.98	5.94	9.76	1.59
	QL 5	967.54	576.66	6.31	11.82	2.05
	QL 6	961.37	572.98	6.35	10.84	1.89
Class 4	**QL 4**	772.18	395.78	6.69	34.94	8.83
	QL 5	651.91	376.17	7.03	12.62	3.36
	QL 6	650.36	365.87	7.23	9.23	2.52
Class5	**QL 5**	631.15	376.17	7.03	12.62	3.36
	QL 6	613.87	365.87	7.23	9.23	2.52

[1]Viliv 70X EX
[2]Samsung Galaxy S4 Mini LTE

Table A.4: List of **TCP Energy** Measurement Results over **LTE** for Class 1, 2, 3, 4 and 5

Devices	Quality Levels	Avg. Power Consumption [mW]	Avg. Energy [Joule]	Battery Lifetime [hours]	Energy STD	Coefficient of Variation [%]
Class 2: Galaxy S4 Mini LTE	**QL 2**	2308.87	1376.09	3.13	152.91	1.26
	QL 3	1853.31	1104.57	3.90	134.04	1.97
	QL 4	1579.00	941.09	4.57	175.09	1.25
	QL 5	1516.90	904.07	4.76	204.92	4.20
	QL 6	1442.50	859.73	5.01	244.03	5.60

Table A.5: List of **TCP Traffic** Statistic over **WLAN** for Class 1, 2, 3, 4 and 5

Devices	Quality Levels	Avg. Through-put [Mbps]	Rx Packets	Rx Bytes	Avg. Packet Length
Class 1	**QL 1**	4.09	205402	308768174	1503.24
	QL 2	2.07	105329	157235341	1492.80
	QL 3	1.05	54114	79737056	1473.50
	QL 4	0.54	28511	41013022	1438.50
	QL 5	0.29	15862	21848004	1377.38
	QL 6	0.16	9403	12135314	1290.58
Class 2	**QL 2**	2.07[1] 2.09[2]	105430[1] 106092[2]	157220041[1] 158419413[2]	1491.23[1] 1493.23[2]
	QL 3	1.05[1] 1.07[2]	54283[1] 54617[2]	80243522[1] 80549078[2]	1478.24[1] 1474.80[2]
	QL 4	0.55[1] 0.56[2]	28436[1] 29403[2]	41724204[1] 80549078[2]	1467.30[1] 1441.24[2]
	QL 5	0.29[1] 0.29[2]	15170[1] 15875[2]	22255380[1] 21899826[2]	1467.07[1] 1379.52[2]
	QL 6	0.16[1] 0.21[2]	8621[1] 24960[2]	12440795[1] 33550696[2]	1443.08[1] 1344.18[2]
Class 3	**QL 3**	1.06	54576	80471348	1474.48
	QL 4	0.55	28854	41538804	1439.62
	QL 5	0.29	15869	21843818	1376.51
	QL 6	0.16	9365	12105338	1292.61
Class 4	**QL 4**	0.55	28875	41522894	1438.02
	QL 5	0.29	15850	21830156	1377.30
	QL 6	0.16	9325	12073766	1294.77
Class 5	**QL 5**	0.29	15928	21918588	1376.10
	QL 6	0.16	9432	12193628	1292.79

[1]Viliv 70X EX
[2]Samsung Galaxy S4 Mini LTE

Table A.6: List of **UDP Traffic** Statistic over **WLAN** for Class 1, 2, 3, 4 and 5

Devices	Quality Levels	Avg. Throughput [Mbps]	Rx Packets	Rx Bytes	Avg. Packet Length
Class 1	**QL 1**	4.13	224514	307584180	1370
	QL 2	2.09	113706	155777220	1370
	QL 3	1.06	57879	79294230	1370
	QL 4	0.55	29824	40858880	1370
	QL 5	0.29	15857	21724090	1370
	QL 6	0.16	8773	12019010	1370
Class 2	**QL 2**	2.09[1] 2.12[2]	113535[1] 115273[2]	155542950[1] 157924010[2]	1370[1] 1370[2]
	QL 3	1.06[1] 1.08[2]	57933[1] 58787[2]	79368210[1] 80538190[2]	1370[1] 1370[2]
	QL 4	0.55[1] 0.51[2]	30054[1] 92321[2]	41173980[1] 126479770[2]	1370[1] 1370[2]
	QL 5	0.30[1] 0.29[2]	16032[1] 15934[2]	21963840[1] 21829580[2]	1370[1] 1370[2]
	QL 6	0.16[1] 0.15[2]	8928[1] 8431[2]	12231360[1] 11550470[2]	1370[1] 1370[2]
Class 3	**QL 3**	1.08	58510	80158700	1370
	QL 4	0.56	30103	41241110	1370
	QL 5	0.29	15830	21687100	1370
	QL 6	0.16	8729	11958730	1370
Class 4	**QL 4**	0.56	30203	41378110	1370
	QL 5	0.29	15847	21710390	1370
	QL 6	0.16	8735	11966950	1370
Class 5	**QL 5**	0.29	15879	21753450	1369.95
	QL 6	0.16	8785	12035450	1370

[1]Viliv 70X EX
[2]Samsung Galaxy S4 Mini LTE

Appendix B

Subjective Test Questionnaire Form

Subjective Test

Welcome Message
Welcome to the subjective testing session organized by the Performance Engineering Lab at Dublin City University.

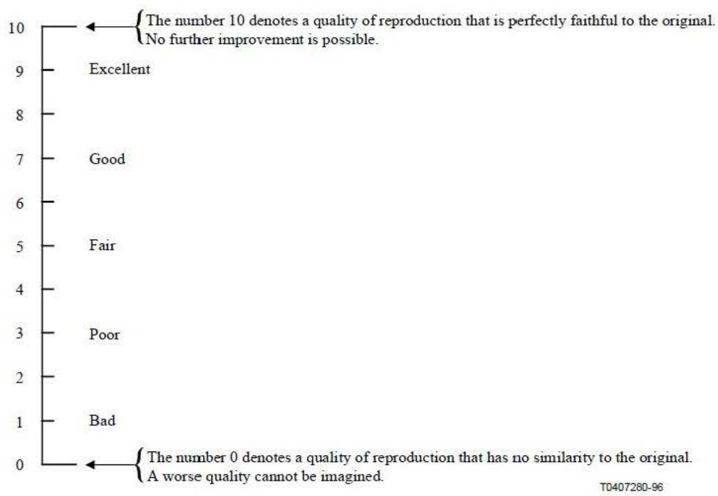
Test Objectives
We are trying to assess the quality of a number of multimedia clips.

Disclaimer
Please fill in the personal information page. The information collected will be utilized as reference for analysing the perceptual test results and will never be made public in any form.

Test Directions
The test consists of 120 phases. In each phase you will be shown a short multimedia clip and you will be asked to grade the overall quality on the indicated 0-10 scale. The instruction of the scale is shown as below:

* Required

Scale Example [b-ITU-T Handbook]



Personal Information Page

1. **Record No: ***
   Please ask coordinator first

   ____

2. **Gender ***
Mark only one oval.

- ( ) Male
- ( ) Female

3. **Age ***

____

4. **Do you use glasses or contact lenses ? ***
Mark only one oval.

- ( ) YES
- ( ) NO

5. **Do you have other visual conditions that may affect your perception of movies (e.g. colour blindness)? ***
Mark only one oval.

- ( ) YES
- ( ) NO

6. **How familiar are you with subjective video quality evaluation? ***
Mark only one oval.

- ( ) YES
- ( ) NO

Mobile Devices Related Questions

7. **Are you using any electronic devices with display (e.g. PCs, Laptops, Smartphones or Tablets) ***
Mark only one oval.

- ( ) YES
- ( ) NO *After the last question in this section, stop filling out this form.*

8. **How often do you watch Movies, Video Clips or any other types of video media? ***
Mark only one oval.

- ( ) Every Day
- ( ) Once a week
- ( ) Once a month
- ( ) Never

9. **Do you watch videos on the Internet using mobile devices (e.g. Smartphone, Tablet)? ***
Mark only one oval.

- Every day
- Once a week
- Once a month
- Never

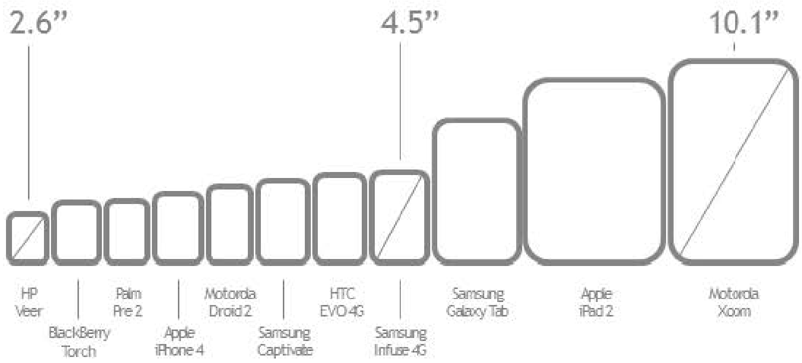
10. **How much time do you spend in the front of the screens every day (e.g. PCs, Laptops, Smartphones, or Tablets)? ***
Mark only one oval.

- < 1 hour
- 1 to 3 hour
- 3 to 5 hour
- 5 to 8 hour
- > 8 hour

11. **What is the resolution of the mobile device you are using daily? ***
If you don't know its resolution, please type the name the device model (e.g. iPhone 6, iPhone 6 plus, Nexus 5...)
Mark only one oval.

- Greater than or equal to 1024 X 768
- From 1024 X 768 to 768 X 480
- From 768 X 480 to 480 X 360
- From 480 X 360 to 320 X 240
- Smaller than 320 X 240
- Other: ____________________

Size of screens: Examples



12. **What is the screen size of your mobile device that you are using to watch video content? ***
If you do not know the size, please type the name of the device model (e.g. iPhone 6, iPhone 6 plus, Nexus 5...)
Mark only one oval.

- < 4 inches
- 4 to 5 inches
- 5 to 7 inches
- > 7 inches
- Other: ____________________

13. **Which mobile device resolution would you prefer to use to watch videos? ***
Mark only one oval.

- Greater than or equal to 1024 X 768
- From 1024 X 768 to 768 X 480
- From 768 X 480 to 480 X 360
- From 480 X 360 to 320 X 240
- Smaller than 320 X 240
- Other: ____________________

14. **Indicate your preferences towards the video quality when watching the videos on your mobile devices? ***
Mark only one oval.

- Excellent Quality
- Good Quality
- Fair Quality
- Poor Quality
- Bad Quality

15. **Please rate your interest in prolonging the battery lifetime (energy saving) of your mobile devices? ***
Mark only one oval.

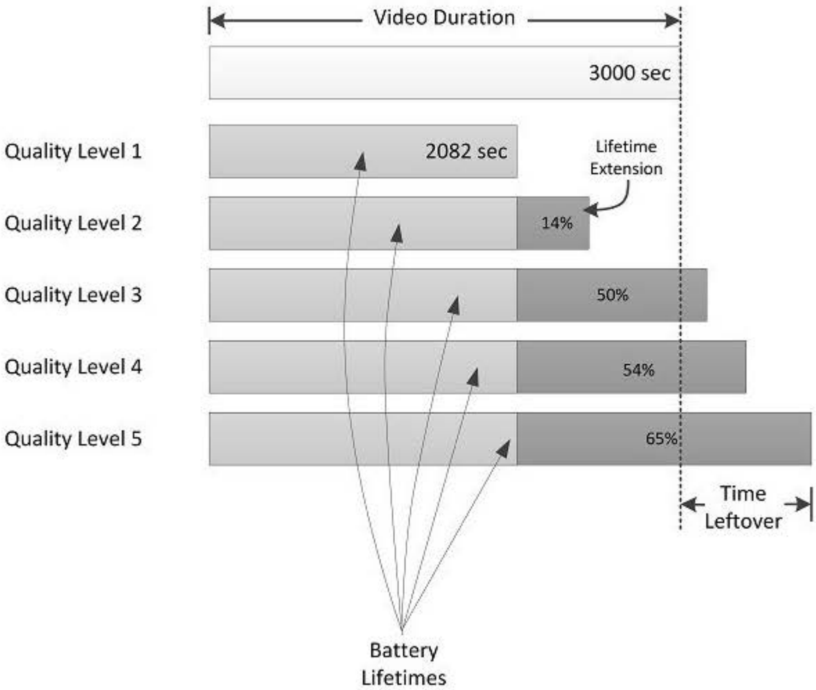
- Highly Interested
- Very Interested
- Interested
- Fairly Interested
- Not Interested

16. **When watching a video on your mobile device, please rate your preference if you have to consider the video quality or energy saving? ***

Mark only one oval.

- ( ) Video Quality
- ( ) Both
- ( ) Energy Saving

Before The Tests



17. **Please rate your preference in the following situation. Suppose you want to watch a 5 min long high-quality Internet video on your mobile device but you have limited battery level too see the full video clip at high quality. You have the option to select between different video quality levels at the risk of running out of battery, but with the possibility of watching the video later on. Please indicate which option you prefer. ***

Mark only one oval.

- ( ) High quality, no battery left and delay watching the video
- ( ) Good quality, no battery left and delay watching the video
- ( ) Fair Quality and 10% battery left
- ( ) Poor Quality and 22% battery left
- ( ) Watch the video later

Class X - (Name of Mobile Device)

Please watch 24 clips and rate your scores one by one

18. **Phase 1 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

19. **Phase 2 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

20. **Phase 3 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

21. **Phase 4 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

22. **Phase 5 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

23. **Phase 6 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

24. **Phase 7 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellant

25. **Phase 8 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellant

26. **Phase 9 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellent

27. **Phase 10 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellant

28. **Phase 11 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellant

29. **Phase 12 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Excellant

30. **Phase 13 ***

Please rate the overall quality of the multimedia clip
Mark only one oval.

1	2	3	4	5	6	7	8	9

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

31. **Phase 14 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

32. **Phase 15 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellent

33. **Phase 16 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

34. **Phase 17 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

35. **Phase 18 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

36. **Phase 19 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

37. **Phase 20 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

38. **Phase 21 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellent

39. **Phase 22 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

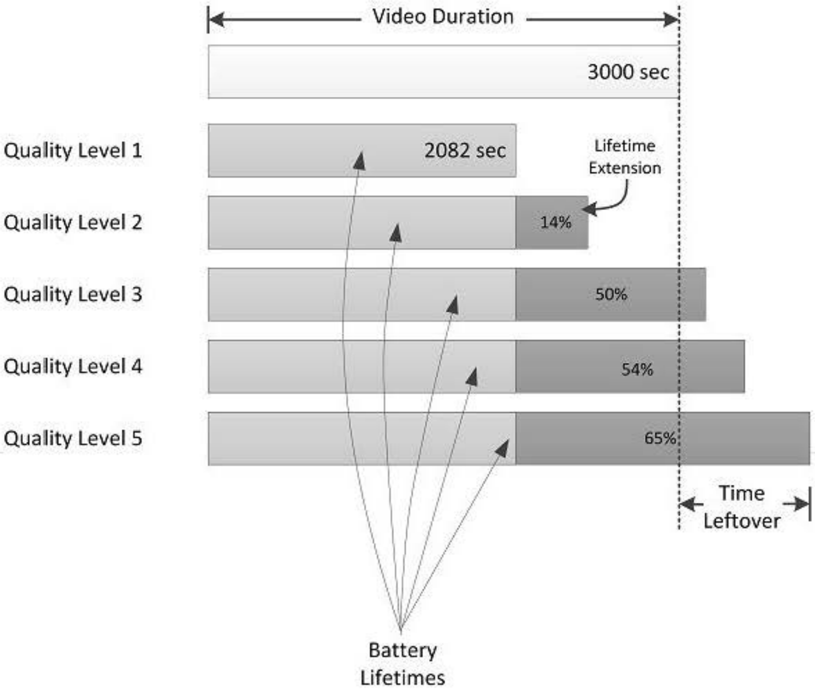
40. **Phase 23 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

41. **Phase 24 ***
Please rate the overall quality of the multimedia clip
Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Bad	◯	◯	◯	◯	◯	◯	◯	◯	◯	Excellant

After The Tests



42. **Please rate your preference in the following situation. Suppose you want to watch a 5 min long high-quality Internet video on your mobile device but you have limited battery level too see the full video clip at high quality. You have the option to select between different video quality levels at the risk of running out of battery, but with the possibility of watching the video later on. Please indicate which option you prefer.** *

Mark only one oval.

- High quality, no battery left and delay watching the video
- Good quality, no battery left and delay watching the video
- Fair Quality and 10% battery left
- Poor Quality and 22% battery left
- Watch the video later

The End

Thank you so much!

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