FRADIS: A Machine Learning-based Multipath Solution for Differentiated Services in a Network Slicing-enhanced Delivery Environment

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Abstract*—The increase in number of devices per person driven by the latest wearable and IoT devices poses challenges for network support. Despite advancements like IEEE 802.11ax and 5G New Radio, no single technology or provider can handle the growing data surge and diverse service demands. To meet this demand, a programmable and flexible network infrastructure is essential, supporting various technologies and adopting a software-based architecture with open interfaces. A key concepts in achieving this is Network Slicing (NetSli). In this context, the FRAmework for performance-aware Differentiated Innovative Services (FRADIS) was designed as a comprehensive framework for the 5G and beyond heterogeneous network environment, aiming to facilitate the differentiated delivery of services with diverse requirements. FRADIS integrates machine learning to optimize service-specific approaches, choosing between infrastructure-dependent (traffic engineering) and protocol-based solutions. The framework targets a wide range of services, including smart city monitoring, e-health information, emergency messages, infotainment, targeted advertisements, IoT and sensor data, road traffic navigation, agriculture monitoring, and touristic virtual reality. This paper describes the architecture of FRADIS, aiming to achieve traffic control through NetSli at lower network layers, employing a dynamic traffic characteristics-oriented protocol at the transport layer, and using machine learning for adaptive content delivery at the application layer. Preliminary results indicate the benefits of the proposed framework and its flexibility to support multiple types of rich-media applications.

***Index Terms*—Network Slicing, MPTCP, Machine Learning**

I. INTRODUCTION

Globally, there is a significant rise in the generation and exchange of data. Cisco's projection [1] anticipated that global Internet traffic would surpass 350 Exabytes per month (4.8 Zettabytes per year) by the end of 2022. However, IDC reported that in 2020 alone, 64.2 Zettabytes of data were created or replicated, mostly transmitted over existing networks [2]. Cisco, IDC, and Ericsson observed a diversification of traffic types and an increase in traffic requirements, attributed to the growing number of high-end mobile devices and user consumption of bandwidth-intensive services like HD, 4K, UHD, and 360° videos. Ericsson estimates that video will constitute over 77% of traffic by 2026 [3].

The increase in the number of devices per person, from 2.4 to 3.6 in 2022, is also driven by the inclusion of wearable devices and IoT devices, expected to have reached 28 billion in 2023 [1]. Despite advancements such as IEEE 802.11ax for wireless broadband and 3GPP 5G New Radio for cellular networks, no single network technology or provider can handle the anticipated surge in data and support services with diverse characteristics. Relying solely on entirely new technologies for 5G networks is unrealistic. The proponents argue that achieving the vision of 5G networks and services requires a combination of innovative solutions and diverse technologies [4]. This places pressure on researchers to find solutions that can support the latest applications with diverse requirements, while balancing conflicting user demands for high-quality services and industry and societal needs for performance and energy efficiency.

Enabling applications with distinct service requirements necessitates a programmable and flexible network infrastructure that can be utilized by various network technologies. This shared infrastructure must adopt a software-based architecture with open interfaces, allowing different users access while accommodating their specific service needs. A critical concept introduced recently plays a key role in achieving this design: Network Slicing (NetSli).

NetSli involves partitioning a shared physical network infrastructure into multiple logical networks, known as slices. Slices are independently controlled and managed by the slice owners, such as Over-The-Top service providers or Virtual Mobile Network Operators, and can be utilized by one or multiple users. Each slice is assigned a specific set of network functionalities exclusive to that slice, ensuring isolation, and is tailored to meet particular usage requirements [5], [6].

This paper presents the FRAmework for performance-aware Differentiated Innovative Services (FRADIS) architecture. This architecture, illustrated in Fig. 1, was designed as part of the FRADIS project, which is supported by the Science Foundation Ireland Frontiers for the Future programme. FRADIS aims to enhance differentiated service delivery in the 5G and beyond heterogeneous network environment. It incorporates innovative algorithms and protocols for dynamic management of performance, energy consumption, and quality trade-offs based on specific service requirements. The project utilizes a groundbreaking machine learning solution to optimize service-specific approaches, choosing between infrastructure-dependent (traffic engineering) and protocol-based solutions. FRADIS targets a diverse range of services, including smart city monitoring, e-health, emergency messages, infotainment, targeted advertisements, IoT data, and more. The framework employs NetSli at lower layers for dynamic traffic control, introduces a novel protocol at the transport layer, and utilizes machine learning for adaptive content delivery at the application layer. The ultimate goal is to maintain high service quality levels in the future heterogeneous and dynamic network environment.

This paper is organised as follows. Section II describes the technology-enablers of FRADIS, while Section III discusses its design and preliminary results. Conclusions and directions for future work end this paper in Section IV.

II. Background and Related Work

This section describes the protocols, approaches and tools employed in the design of the proposed FRADIS solution.

A. Network Slicing

NetSli, involving the partitioning of a shared physical network into logical slices, each independently managed by owners like Over-The-Top service providers or Virtual Mobile Network Operators, poses challenges. Orchestrating these slices, each allocated specific functionalities and serving targeted usage, requires careful management. Various proposed solutions address these challenges, such as a distributed autonomous slice management framework [7] and a mathematical model for efficient radio resource allocation in a two-level hierarchical network [8].

Numerous studies in the literature leverage NetSli to enhance network performance and provide QoS support for various services. Costanzo et al. [9] proposed a network slicing solution utilizing an efficient scheduling algorithm within a centralized architecture for real-time bandwidth allocation to different slices in a cloud Radio Access Network (RAN). Khan et al. [10] introduced a communication model based on network slicing to enhance low Signal-to-Interference-Plus-Noise-Ratio (SINR) video streaming among vehicles. Campolo et al. [11] suggested a slicing framework supporting autonomous driving services while meeting the requirements of various existing applications. González et al. [12] described a slice allocation algorithm for 5G networks based on network slicing to ensure optimal workload allocation, considering metrics such as throughput and energy consumption. Velasco et al. [13] discussed the advantages of an innovative solution for autonomic slice networking to maintain required network performance while reducing operating costs.

B. MultiPath Transmission Control Protocol

The Multipath Transport Control Protocol (MPTCP) is a transport layer protocol that enhances the traditional TCP by facilitating concurrent data transport over multiple paths, thereby improving throughput [14]. Operating in a connection-oriented manner and designed to be transparent to both applications and networks, MPTCP allows the establishment of multiple sub-flows for a single connection session between two hosts. In the context of mobile devices within a 5G heterogeneous network delivery environment, MPTCP can simultaneously utilize multiple interfaces and network

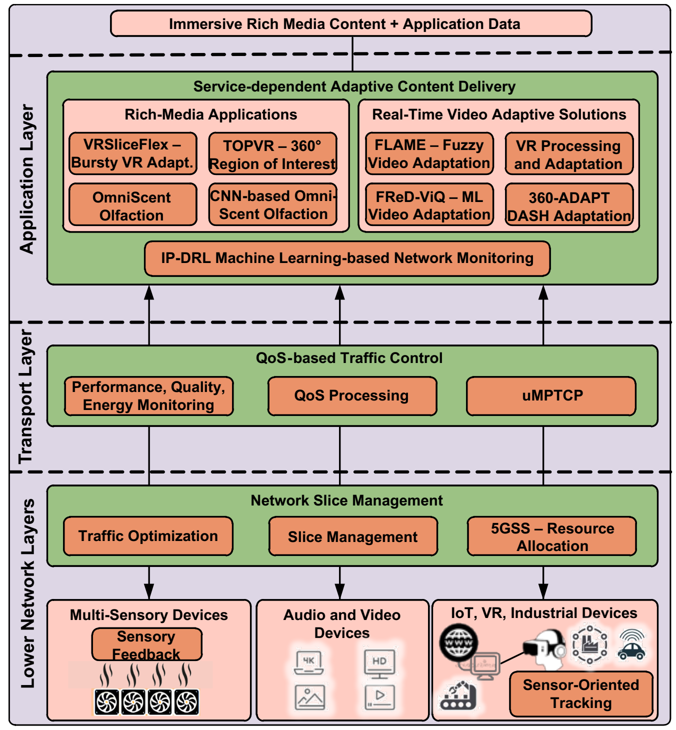

Fig. 1. FRADIS Architecture

access technologies, enhancing network delivery performance, robustness, and resource utilization [15]. MPTCP's support for multipath transmissions proves beneficial for load balancing, and it ensures continuous data transmission as long as at least one sub-flow is available [16]. Noteworthy is the work of Chen et al. [17], introducing an Energy-aware Multipath-TCP-based Content Delivery Scheme (eMTCP) that optimizes QoS and energy consumption by offloading the data stream between two network interfaces (LTE and WiFi) in a heterogeneous wireless environment.

However, a major limitation of MPTCP lies in its congestion control mechanism, which lacks consideration for different traffic characteristics. Proposed solutions aim to address this limitation, including an energy-aware MPTCP extension [18] and a performance-oriented solution [19]. These solutions focus on efficient network delivery based on either energy or performance goals, irrespective of traffic requirements. Other approaches concentrate on supporting specific traffic types or specific features, such as reliability. Given the diversity of traffic types, there is a need for a dynamic solution that can identify traffic types and distribute traffic to optimally meet their requirements.

C. Machine Learning

Numerous innovative services have emerged, propelled by recent societal challenges, technological advancements, and increased interest in formerly niche areas, which are now becoming mainstream. In the 5G heterogeneous network delivery environment, a service-oriented perspective aims to accommodate a broad spectrum of services with varying requirements and device types, extending beyond traditional human communications to include diverse forms of machine communications. These services encompass emergency communications for public safety, coordination of IoT devices and vehicular traffic, including unmanned aerial vehicles, and the exchange of rich media content such as AR, VR, digital twinning and 3D video [20]–[22].

Due to the highly diverse requirements and dynamic nature of these services, robust support is essential to ensure high QoS and user-perceived Quality of Experience (QoE). In this intricate context, machine learning (ML) approaches, particularly ML-enhanced networking solutions, have shown promise in areas like traffic prediction, routing optimization, QoS/QoE support, and security, operating at either the application or lower network layers [23], [24]. Despite their diversity, many proposed solutions often target a singular dimension, such as network conditions, necessitate extensive training, or focus on specific application areas [25].

Based on the reviewed works, it is possible to understand that the combination and enhancement of multiple technologies is needed in order to effectively support different traffic types and service differentiation. FRADIS aims to enhance the support for differentiated services by employing Network Slicing. The framework is designed to accommodate various applications with different traffic types, each with diverse and changing QoS requirements, enabling dynamic and flexible traffic delivery control. FRADIS also proposes the development of a novel Utility-based Multi-path Transport Control Protocol (uMPTCP) that considers performance, energy, and quality when transmitting data across different traffic flows. Additionally, the framework introduces an innovative edge-based machine learning approach to address a multi-objective problem, optimizing both QoS and user QoE along with overall system performance. This machine learning system learns the optimal selection of either traffic engineering or an end-to-end solution, depending on expected benefits, to effectively support service differentiation.

III. FRADIS Solution Design

The architecture of FRADIS, illustrated in Fig. 1, consists of three main components, in green: Network Slice Management, QoS-based Traffic Control and Service-dependent Adaptive Content Delivery.

A. Network Slice Management

1) Traffic Optimization: FRADIS employs a hierarchical architecture, enabling dynamic control of Key Performance Indicators (KPIs) for multiple flows with varying QoS demands. Additionally, a NetSli orchestrator ensures complete isolation between different service slices, applying forwarding rules to maintain QoS across the network. FRADIS also introduces a novel algorithm for slice management to compute the optimal paths between communicating nodes.

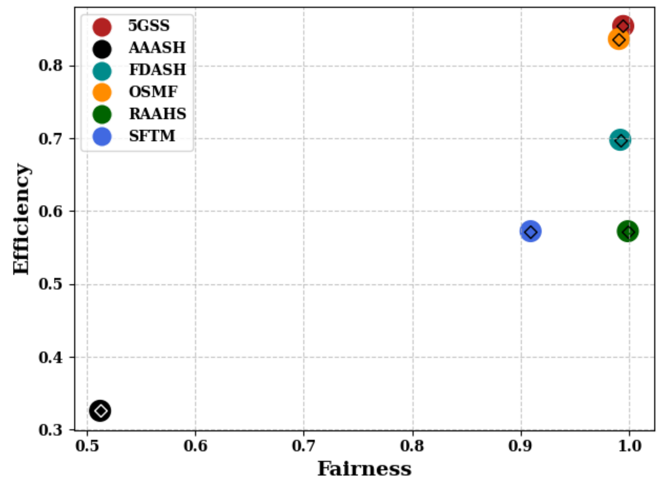

Fig. 2. Throughput efficiency and fairness achieved by 5GSS, AAASH, FDASH, OSMF, RAAHS, and SFTM Solutions in a 5G streaming environment. The reported results pertain to three slices, where slice 1 hosts five DASH users, while slices 2 and 3 each host five VR and Gaming clients.

2) Slice Management: For the purpose of managing network slices, FRADIS will incorporate a Network Slice Management component tailored to differentiated traffic exchange. This component is tasked with facilitating network slicing support for a variety of services and comprises two blocks: the Slice Support System (SSS) and the Domain Slice System (DSS). The SSS handles tasks such as network slice creation, decommissioning, and provisioning, while the DSS ensures quality assurance. The Cross Domain Slice Manager within the SSS gathers performance data from each individual domain, aggregating it to ensure overall requirements are met. This process aids in supporting management and resource provisioning across diverse administrative domains, involving different vendors.

3) Resource Allocation: The FRADIS Network Slice Management algorithm (FNSM) will be a two-stage process. In the initial stage, FNSM will function as a groundbreaking network slice broker, selecting the optimal network slice for a particular service based on available resources, the number of tenants utilizing the slice, and considerations of traffic and price. This facilitates real-time resource allocation, utilizing traffic monitoring and forecasting, while also accounting for potential mobility factors. In this context, 5G Slice Stream (5GSS) is an innovative resource allocation solution, specifically tailored to elevate streaming performance and address the unique requirements of three distinct slices with different streaming types—DASH, VR, and Gaming. With a primary focus on video streaming and considering it as one of the pivotal slices, the 5GSS solution simultaneously considers multiple parameters such as buffer impact factor, download impact factor, throughput proximity, and quality switch factor, and applies Pareto optimization to identify optimal bitrate selection in a 5G RAN slicing environment. The comprehensive NS3 experimental setup involves 5G NR and DASH modules.

Within this setup, three RAN slices are employed, each accommodating five users with distinct streaming preferences, i.e., DASH, VR, and Gaming. These slices are efficiently created and managed, leveraging the advanced features of 5G NR. Features such as Bandwidth Parts (BWPs) and numerology not only enhance spectrum sharing efficiency but also reduce latency, offering a valuable opportunity to address the dynamic requirements of streaming services and network slices. Fig. 2 results validate the superior performance of 5GSS demonstrating noticeable improvements in throughput efficiency and fairness in comparison to AAASH [26], FDASH [27], OSMF [28], RAAHS [29], and SFTM [30] approaches.

The second stage of FNSM will focus on dynamic resource provisioning, integrating an innovative Pareto optimal technique to dynamically scale network slice resources for optimal traffic delivery. It will also address conflict resolution with a focus on computational efficiency. This pioneering approach, addressing the lack of existing solutions for dynamic resource scaling based on specific service requirements, is expected to significantly advance the state of the art and result in notable improvements compared to existing solutions.

B. QoS-based Traffic Control

FRADIS performs QoS-based traffic control at its transport layer, with sub-flows for different service types and dynamic traffic characteristics-oriented data transport.

1) Performance, Quality and Energy Monitoring: Diverse parameters such as network performance, device energy consumption, and monetary cost are collected and monitored in order to compose a QoS utility function.

2) QoS Processing: QoS utility functions enables controlled content delivery while considering diverse QoS parameters. These functions trigger a QoS aware-algorithm for content classification.

3) uMPTCP: The Utility-based Multi-path Transport Control Protocol (uMPTCP) proposed in FRADIS extends MPTCP, in order to facilitate the transparent mapping of various services to infrastructure. It is a novel dynamic traffic characteristics-oriented performance, energy and quality-aware data transport protocol to improve the transmission efficiency and resource utilization. This protocol enhances the MPTCP transport layer to enable controlled content delivery while considering diverse parameters such as network performance, device energy consumption, and monetary cost. Unlike existing research that typically focuses on a single congestion control algorithm for MPTCP, uMPTCP incorporates a utility function-based coupled congestion control mechanism. This dynamic mechanism adjusts the protocol behavior to transport different services based on *QoS Monitoring*. uMPTCP dynamically selects appropriate sub-flows for each service type, pushing the boundaries of the current state of the art by addressing dynamic traffic characteristics-oriented data transport protocols. The dynamic selection of sub-flows by uMPTCP is expected to significantly enhance QoS parameters for all service types, particularly in highly loaded network conditions where no such protocol currently exists. This involves data scheduling and congestion control based not only on traffic requirements and network conditions, but also on energy efficiency. As seen on Fig. 3, it is already possible to outperform the base MPTCP protocol solely considering latency, significantly improving the average round-trip time of packets. Integration with 5G network slices for dynamic traffic control in order to provide support for distribution of traffic with diverse requirements.

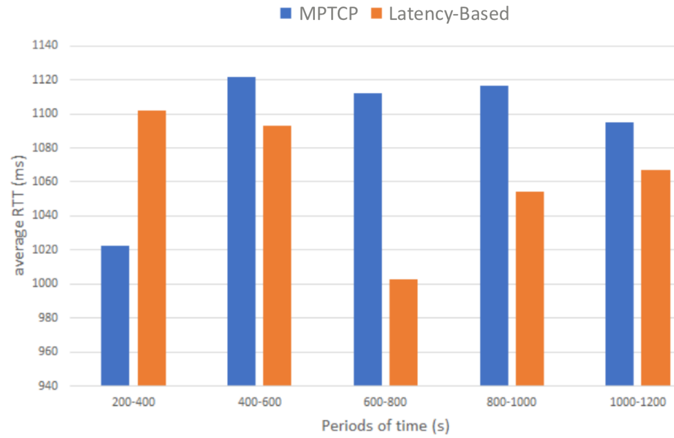

Fig. 3. Latency-based MPTCP solution

C. Service-dependent Adaptive Content Delivery

FRADIS supports diverse types of applications in its application layer. Rich-media solutions for the delivery of VR, eXtended Reality (XR), and multi-sensory content, and immersive adaptive 360° video experiences make use of the underlying FRADIS architecture with machine learning-based network monitoring and the benefits of the transport and lower layers solutions for adaptive and optimized delivery.

1) Rich-Media Applications: FRADIS provides interactive support for rich-media applications. In this context, TOPVR [31] is a collaborative trajectory-oriented viewport prediction solution for both on-demand and live 360° VR video streaming. TOPVR integrates a user management system that identifies potential users with comparable preferences and trajectory changes closest to the current user over time. Moreover, its collaborative viewport prediction method forecasts future viewing positions for each user based on recent viewing data, along with similar trajectories and trend changes observed in other users watching the same VR content. TOPVR solution can be readily deployed in VRSliceFlex solution that will focus on processing large bursts of packets for 360° video (30 FPS, 60 FPS), VR (Google Earth VR - Tour and Google Earth VR - Cities) and Gaming (Minecraft and Viruspopper) applications in the context of active RAN slicing within the 5G network architecture. VRSliceFlex will allow to uniquely address the unique demands and the efficient sharing of RAN resources for diverse applications with distinct requirements.

Multi-sensory effects, such as scent dispensing, are also supported in FRADIS. OmniScent [32] integrates 360° videos to multiple olfaction dispensers, mirroring the directions of immersive scenes and their related scents. The underlying FRADIS architecture provisions and controls the networked scent devices according to application and user needs. OmniScent-CNN is an extended version of the multi-sensory solution to automatically generate scent effects based on convolutional neural networks (CNNs). The CNNs perform image recognition on 360° video frames and trigger appropriate scents automatically.

2) Real-Time Video Adaptation: The core adaptation concept in FRADIS framework revolves around real-time video adaptation. In this regard, Fuzzy Logic-based Adaptive Multimedia StrEaming (FLAME) solution [33] based on advanced fuzzy logic theory ensures a seamless and optimal streaming experience. FLAME is adaptable to diverse video client settings and QoE goals. Its two variants, FLAME7 and FLAME5, utilize interactive membership functions and fuzzy rules, leading to reduced model complexities and training overheads. Experimental results demonstrate that FLAME significantly enhances uninterrupted streaming experiences for diverse users, surpassing alternative solutions such as PENSIEVE, BOLA, FESTIVE, BBA, and ELASTIC, with a notable 11.7% improvement in QoE.

Taking a stride beyond, the Fuzzy Reinforcement Learning Driven Improved Video QoE (FRED-ViQ) approach leverages both the fuzzy and Deep Reinforcement Learning (DRL) techniques for enhanced streaming experiences. FRED-ViQ stands out as a sophisticated and advanced adaptive streaming solution, employing efficient membership function modeling, a set of decision-making fuzzy rules, and an innovative DRL algorithm based on Dueling Double Deep Q-Network (D3QN), noisy networks, and prioritized experience replay (PER) techniques. This combination aims to enhance the QoE across linear, log, and HD settings.

MPEG Dynamic Adaptive Streaming over HTTP (MPEG-DASH) standard is one of the main video adaptation techniques for streaming on-demand content over the Internet [34]. DASH can enhance multimedia content delivery by dynamically adjusting network parameters in real-time. 360° video content also benefit from DASH-based adaptation [35]. 360-ADAPT works within FRADIS leveraging DASH to dynamically adjust streamed 360° media content with the goal to increase the quality of immersive viewer experience, while maintaining high quality audio. A real-life testbed demonstrated that 360-ADAPT significantly enhances immersive streaming experiences for users, outperforming other DASH solutions in terms of QoS (up to approx. 5% and 26% higher bitrates than BOLA and THROUGHPUT) and perceived user QoE (perceived audio quality approx. 7%, 19%, and 7% higher than BOLA, THROUGHPUT, and DYNAMIC, respectively).

3) IP-DRL ML-based Network Monitoring: FRADIS provides the capability to dynamically select between the traffic engineering approach, utilizing the proposed NetSli solutions, and the end-to-end approach, employing the proposed uMPTCP, for delivering differentiated content based on its specific requirements. This dynamic selection occurs at the Edge through an innovative machine learning approach. Formulating an optimization problem that considers the performance of both users and the system, an inventive solution is proposed using the Deep Reinforcement Learning (DRL) framework, the Innovative Performance-aware DRL (IP-DRL). IP-DRL utilizes a neural network, allowing a learning agent to make decisions without an initial dataset by interacting with the environment, such as a multi-user 5G and beyond network. Through IP-DRL, the Edge can make close-to-optimal decisions in a learning process, achieving optimization in both user and system performance. This machine learning solution dynamically selects the optimum approach, surpassing existing solutions that offer a single static approach and are constrained by its limitations. Unlike transport layer protocol solutions, which struggle to deliver high-quality services in highly loaded network conditions, and traffic engineering solutions, which may not be the most cost-effective option, the proposed approach is designed for adaptability and optimization.

IV. Conclusions and Future Work

This paper presented the architecture of FRADIS, its main components (i.e. Slice-based Dynamic Traffic Control, QoS-based Traffic Control and Service-dependent Adaptive Delivery) and preliminary results in terms of slicing optimization and QoS-aware multi-path transmission.

FRADIS aims to further improve slice resources of the network, dynamic scaling them based on specific service requirements. It will also employ the novel uMPTCP protocol to enable controlled content delivery, such as to improve network performance and decrease device energy consumption and monetary cost. Future work will focus on designing an innovative ML-based solution, which selects between the traffic engineering approach (which involves the proposed NetSli solution) and the end-to-end approach (which uses the proposed uMPTCP) in order to deliver the differentiated content according to its requirements in given network performance conditions.

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