Quality of Experience Characterization and Provisioning in Mobile Cellular Networks

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Abstract. Traditionally, mobile cellular networks have been designed with Quality of Service (QoS) criteria in mind. Quality of Experience (QoE) has, however, recently emerged as a concept, disrupting the design of future network generations. The emergence of the QoE concept has been a result of the inevitable strong transition that the mobile industry is experiencing from system-centric networks to more user-centric solutions. Motivated by this boost towards user-centricity, the objective of this dissertation is to explore the challenges and opportunities that arise in modern cellular networks when QoE is considered. In this direction, throughout this dissertation, QoE estimation models and metrics are explored and exploited in order to quantify QoE and improve existing network mechanisms. The core of this dissertation is the proposal of a QoE provisioning cycle that allows the control, monitoring (i.e., modeling) and management of QoE in a cellular network. In terms of modeling, QoE assessment methods and QoE-related performance indicators are described and classified, with an emphasis on parametric quality estimation. In terms of QoE management, novel QoE-aware mechanisms that demonstrate QoE improvements for the users are proposed, such as a radio scheduling algorithm that improves QoE by mitigating throughput fluctuations, and a context-aware HTTP Adaptive Streaming (HAS) mechanism that successfully mitigates stallings in bandwidth-challenging scenarios. Finally, a programmable QoE-SDN APP into the Software-Defined Networking (SDN) architecture is introduced, which enables network feedback exposure from Mobile Network Operators (MNOs) to Video Service Providers (VSPs), revealing QoE benefits for VSPs' customers and bandwidth savings for the MNOs.

Keywords: Quality of Experience (QoE), HTTP Adaptive Streaming (HAS), radio resource scheduling, Software-Defined Networking (SDN), mobile cellular networks.

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1 Dissertation Summary

1.1 Motivation and Scope

Over the last few years, there has been a tremendous increase in the network traffic generated by mobile users, a phenomenon which can be attributed to multiple factors. On the one hand, the emergence of smart phones and tablets along with the huge, recently emerged app market have changed the landscape in the telecommunications sector. In parallel, the charges even for intensive data usage are tolerable, as network operators offer very attractive subscription packets to attract customers. On the other hand, modern networks, such as the Long Term Evolution - Advanced (LTE-A) and emerging 5G networks, can offer very high bandwidth to their users, supporting a plethora of diverse, resource-hungry services, and further boosting the demand for data consumption. All these conditions make mobile users more and more demanding in terms of the quality they expect to achieve.

Recognizing this fact, there has lately been a momentum that pushes the epicenter of interest from the "network" to the "user". While network and service providers are trying to create or follow this "user-centric" trend, new terms have been coined that allow its more comprehensive description. The term "Quality of Experience" (QoE) is irrefutably the most dominant one, as it describes "*the overall acceptability of an application or service, as perceived subjectively by the end-user*". This means that older terms such as Quality of Service (QoS), traditionally used for years, are now considered only partial or incomplete. The reason behind that is that QoS can only record the technical characteristics of a service without giving a clear indication of the user's satisfaction when interacting with this service. In fact, the relationship between these two metrics (QoS and QoE) has been found to be non-linear.

The definition of QoE makes clear that it is a very broad and generic concept, and as such, it incorporates the complete end-to-end system effects (terminal, network, services, etc.) together with the human impressions of these effects. As vague as the concept of QoE may sound, reliable estimation methods have been developed with the assistance of subjective experiments with human evaluators. These experiments lead to reliable QoE assessment methods, which manage to automatically evaluate and rate the QoE of a user with respect to a specific application or service. This procedure is called "QoE modeling", and it is the most important first step towards QoE provisioning.

The awareness of an overall QoE score is very important for all involved stakeholders in the service communication chain. Once QoE is measured, this may be exploited in many aspects by network operators and service providers. First of all, the extraction of a QoE score of a service with respect to a user is the most attractive and absolute way to evaluate the performance of the offered services. Second, network problems such as bottlenecks or local failures may be identified by predefined QoE thresholds, and proactive or reactive actions may be triggered to correct them. A third important motive for QoE awareness is the possibility to incorporate QoE intelligence in the network mechanisms, and specifically in the network decision processes. This may lead to "QoE-driven" or otherwise called "QoE-aware" algorithms that can help the network function in a more efficient and effective way. For instance, QoE may become the

criterion or trigger mechanism of standard network algorithms (e.g., radio resource scheduling, mobility management, power control, etc.) replacing current QoS-based criteria, such as plain signal strength measurements. What is more, understanding and identifying the key factors that truly affect the user's experience creates the possibility to propose innovative algorithms that focus on targeted QoE performance indicators. Finally, QoE-awareness may drive a more resource-efficient network operation, by helping recognize moments and cases of operation when providing extra resources to the users would not improve their perceived QoE. In other words, "over-engineering" could be avoided.

QoE modeling and management in mobile cellular networks are fundamental components, part of a wider framework that enforces the end-to-end QoE provisioning. This framework also includes wider challenges such as the collection of appropriate input data that will lead to the awareness of QoE (i.e., QoE monitoring), the realistic implementation of such a framework in real networks, and the possible interaction between network providers and service providers, aiming at the holistic delivery of optimal QoE to the end-users, among others.

This dissertation focuses on exploring the challenges and opportunities that arise in modern mobile cellular networks in terms of QoE provisioning to end-users. Specifically, it aims to characterize and exploit QoE models and metrics in order to improve existing mechanisms in mobile cellular networks standardized by 3GPP (3rd Generation Partnership Project), but also towards the 5G horizon, such as radio resource allocation, Device-to-Device (D2D) communication setup, adaptive video streaming, etc.

1.2 Dissertation Contributions

In this dissertation, the reader will delve into details regarding the topic of QoE management in mobile cellular communication networks. The main contributions of the research conducted in this dissertation are the following:

- Proposal of a conceptual framework for achieving end-to-end QoE provisioning in mobile cellular networks. This framework is analyzed in terms of its design, its constituents and their interactions, as well as key implementation challenges, while its proof-of-concept in an LTE network is assessed.
- The identification and analysis of parametric QoE formulas and Key Performance Indicators (KPIs) that can be used for real-time QoE assessment of popular service types in communication networks (i.e., VoIP, online video, video streaming, web browsing, Skype, IPTV and file download services).
- A network management framework that exploits QoE awareness for controlling the operational mode of mobile users in LTE-A networks with D2D support. Simulation studies have revealed the twofold benefits of this mechanism, i.e., both for the users (increase in QoE) and the operators (increase in offered throughput).
- Proposal of a new radio scheduling logic, which takes into account the impact of throughput fluctuations on the QoE of interactive applications. By quantifying how traditional radio scheduling decisions influence the user-perceived QoE, a novel "consistent" resource allocation process is proposed, which further improves users' QoE by moderating these fluctuations.

- Analytical investigation of the video quality degradation problem as it is experienced by mobile users in vehicles, and proposal of a proactive context-aware HTTP Adaptive Streaming (HAS) strategy, which helps prevent stallings in light of bandwidth-challenging situations.
- Proposal of a Software-Defined Networking (SDN)-based architecture that promotes and enables a technologically feasible realization of a collaboration paradigm between Video Service Providers (VSPs) and Mobile Network Operators (MNOs). The potential of this architecture is highlighted through the proposal and evaluation of three use cases that are unlocked by this architecture, in the context of HAS. In this paradigm, feedback about the network throughput is provided to a VSP so that he can be in a stronger position to redefine encoding, caching, and per-user video segment selection.
- Identification of the essential attributes that can shape QoE-centric networks towards the 5G era, and introduction of the "experience package" concept. Experience packages can lead to a more personalized service provisioning to users, considering not only technical parameters, but also the user profile and the context of the communication.

Below, results concerning the most important contributions are presented.

2 Results and Discussion

2.1 A Conceptual Framework towards QoE Management in Mobile Cellular Networks

The first main study conducted in this dissertation provides insights on the issue of network-level QoE management, identifying the open issues and prerequisites towards acquiring QoE awareness and enabling QoE support in mobile cellular networks. A conceptual framework for achieving end-to-end QoE provisioning is proposed (Fig. 1), and described in detail in terms of its design, its constituents and their interactions, as well as the key implementation challenges. The main components of this framework are three building blocks, namely the QoE-Controller, QoE-Monitor and QoE-Manager. Apart from proposing and describing a high-level architecture for QoE management in mobile cellular networks, we use the LTE-A network as a case study to demonstrate the feasibility, performance issues and potential benefits of the proposed QoE management framework, using simulation.

Specifically, we describe how this high-level architecture may be customized and applied for the purposes of implementing a real-time QoE-aware admission controller in LTE-A. We study a scenario where the user density in an outdoors small cell is gradually increasing, representing for instance scenarios where this small cell is used to serve a stadium during a concert or a football game. We evaluate the proposed QoE management framework and compare it with the conventional case where no QoE management framework is present, and therefore, users are admitted based on their positions or on received signal strengths from the surrounding base stations. (Fig. 2). It is observed, that the QoE management framework surpasses the QoE achieved via

conventional admission control schemes, due to using the actual quality experienced by the users as the decisive criterion for admission.

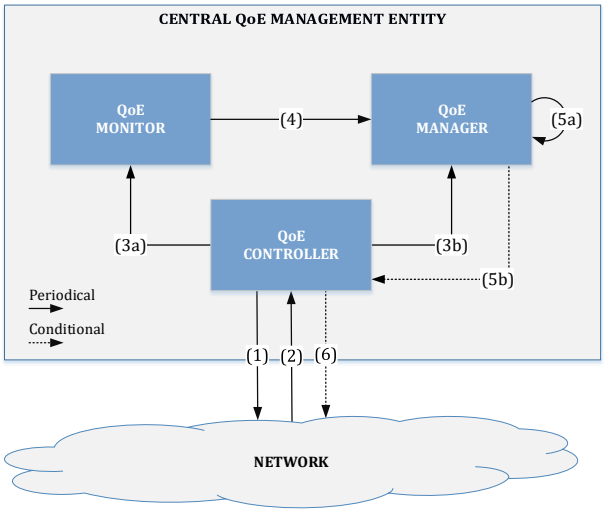

Fig. 1. The proposed QoE management framework.

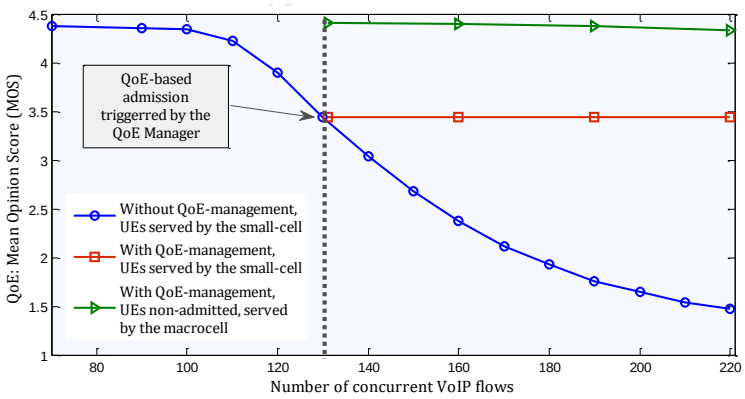

Fig. 2. QoE management framework evaluation for a QoE-driven admission control scenario.

2.2 Parametric QoE Estimation for Popular Services

As we are moving closer and closer to future network generations, the human factor is becoming the epicenter of attention and the driving force for the network design. Thus, the comprehension and, in extension, the control of the provisioned QoE to the users has become a necessity for network operators. Parametric QoE estimation models, i.e., formula-based QoE models, are a prerequisite for this purpose. They constitute the ideal tools towards live network quality monitoring and, hence, QoE management.

Nevertheless, despite the increased interest from academia and industry to push towards a QoE service provisioning model, a clear/comprehensive manual on the available parametric models and the critical QoE performance parameters per service type is currently missing. Identifying this gap, a second study conducted in this dissertation provides a thorough and handy "manual", currently absent from the literature, that identifies and describes appropriate parametric models for popular services nowadays, such as YouTube, Skype and IPTV, as well as summarizes standardized ones (Table 1).

Table 1. Parametric QoE estimation per service type.

Service Type	QoE Estimation Model	KPIs
File transfer	Data rate-based formula	Data rate, expected upper and lower data rate
Web browsing	Response time-based formula	Response time
Skype	Skype-specific formula	Frame rate, image quality, resolution
VoIP	ITU-T Rec. G.107, E-model	Packet loss ratio, delay, codec, coding rate
Video streaming	IPTV model	Data rate, frame rate
	YouTube (conventional) model	Number of stalling events, duration of stalling events, video duration
	YouTube with adaptive streaming model	Time on highest layer, amplitude, frequency of quality switches
Online video	ITU-T Rec. G.1070, E-model	Packet loss ratio for audio and video packets, relative delay between video and audio packets, data rate, frame rate, monitor size

2.3 QoE-Inspired Consistency in Radio-Scheduling

Radio scheduling is a well-studied problem that has challenged researchers throughout the last decades. However, recent findings that stem from the QoE domain come to give a new perspective to traditional radio scheduling approaches. In this study, we take advantage of recent subjective results regarding the impact of throughput fluctuations on the QoE of interactive applications and revisit well-known scheduling algorithms. By quantifying the impact of traditional radio schedulers on user-perceived QoE, we manage to draw new conclusions regarding the radio scheduling problem, such as the importance and impact of consistency of the resource allocation decisions on the users' QoE. As main result, fair algorithms inherently seem to be more consistent than greedy ones, providing less throughput fluctuations and, thus, better QoE. Based on this outcome, we propose a new scheduling approach, which further improves users' QoE by moderating throughput fluctuations. Such fluctuations' effect may be moderated, i.e., smoothed out, by introducing a new scheduling metric ($\boldsymbol{m_{i,k-fluct}}$) that tries to capture and mitigate the magnitude and occurrence of throughput fluctuations.

For evaluation purposes of the herein proposed scheduler, we compare the CDF of this scheduler with state of the art schedulers, for the case of 20 users uniformly

distributed in a cell. The results are presented in Fig. 3. We can observe that the proposed scheduler: a) is very fair, as shown by the steepness of the CDF, b) that the achieved minimum Mean Opinion Score (MOS) values are higher than for the other schedulers (CDF shifted to the right), while c) the larger MOS values are comparable to the other schedulers. This behavior is explained by the fact that the resource allocation procedure of the proposed scheduler is greedy in some sense. Trying to minimize the gap between the average throughput values and the potentially achieved data rates jointly for all the users, eventually this scheduler manages to first satisfy the low-throughput users. However, the low-throughput users do not necessarily take the "best" Resource Blocks, and therefore higher-throughput users are also served well.

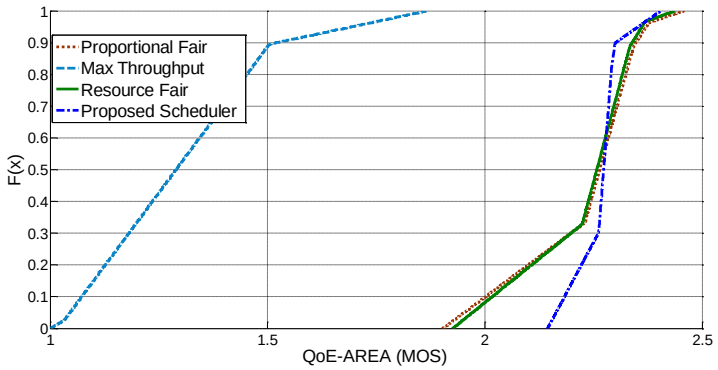

Fig. 3. MOS CDF for standard schedulers and the $m_{i,k-fluct}$ metric.

2.4 Enriching HTTP Adaptive Streaming (HAS) with Context Awareness

Video streaming has become an indispensable technology in people's lives, while its usage keeps constantly increasing. The variability, instability and unpredictability of network conditions poses one of the biggest challenges to video streaming. In this study, we analyze HAS, a technology that relieves these issues by adapting the video reproduction to the current network conditions. Particularly, we study how context awareness can be combined with the adaptive streaming logic to design a proactive client-based video streaming strategy. Our results show that such a context-aware strategy manages to successfully mitigate stallings in light of network connectivity problems, such as an outage. Moreover, we analyze the performance of this strategy by comparing it to the optimal case in terms of QoE-related KPIs for video streaming. The collected evaluation results encourage further research on how context-awareness can be exploited to further enhance video service provisioning by service providers.

In Fig. 5 we present: a) the conventional case, where no context awareness about an imminent outage event is available, and consequently, a standard HAS strategy is continuously executed, b) the case where context awareness about the starting point and duration of this outage event is available, which automatically leads to the selection of a proactive HAS strategy after a minimum required "advance time", and c) the optimal strategy in terms of maximizing the selected video quality layers and minimizing the

quality switches. Looking at Fig. 5 we can see that a stalling of around 80 sec is completely avoided when context awareness is deployed, or when optimal knowledge is assumed. The explanation behind the prevention of the stalling lies in Fig. 5: In the "without context" case higher HAS layers are selected as compared to the "with context" case. Having downloaded lower HAS layers in the "with context" case, the buffer of the client is fuller in terms of playtime than it would have been if higher HAS layers had been downloaded instead.

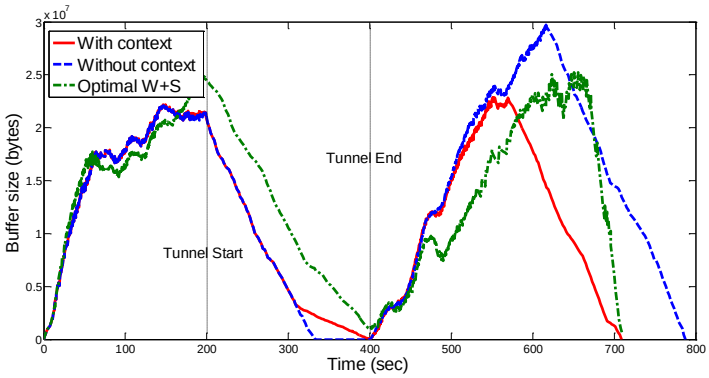

Fig. 4. Comparison of buffer size for different HAS strategies.

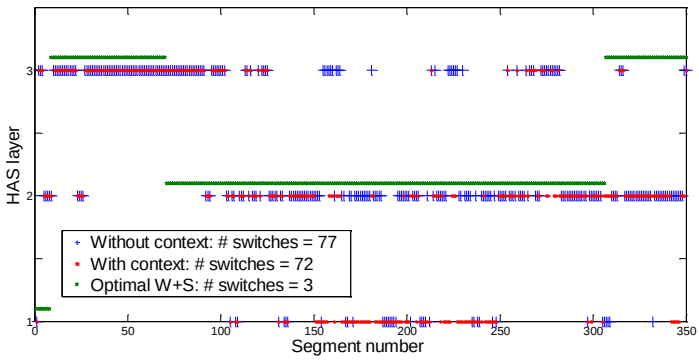

Fig. 5. Comparison of selected HAS layers for different HAS strategies.

2.5 QoE-SDN APP: A Rate-Guided QoE-Aware SDN-APP for HTTP Adaptive Video Streaming

While video streaming has dominated the Internet traffic, VSPs compete on how to assure the best QoE to their customers. HAS has become the de facto way that helps VSPs work-around potential network bottlenecks that inevitably cause stallings. However, HAS-alone cannot guarantee a seamless viewing experience, since this highly relies on the MNOs' infrastructure and evolving network conditions. SDN has brought new perspectives to this traditional paradigm where VSPs and MNOs are isolated,

allowing the latter to open their network for more flexible, service-oriented programmability. This study takes advantage of recent standardization trends in SDN and proposes a programmable QoE-SDN APP, enabling network exposure feedback from MNOs to VSPs towards network-aware video segment selection and caching, in the context of HAS. A number of use cases, enabled by the QoE-SDN APP, are designed to evaluate the proposed scheme, revealing QoE benefits for VSPs and bandwidth savings for MNOs.

The proposed QoE-SDN APP (Fig. 6) relies on the SDN architecture allowing the SDN controller to maintain a corresponding APP template. Such template offers VSPs the opportunity to program their QoE requirements and QoE assessment logic once subscribed. VSPs can then use the QoE-SDN APP to enhance their video segment encoding and distribution procedures by getting network feedback exposed by the MNOs.

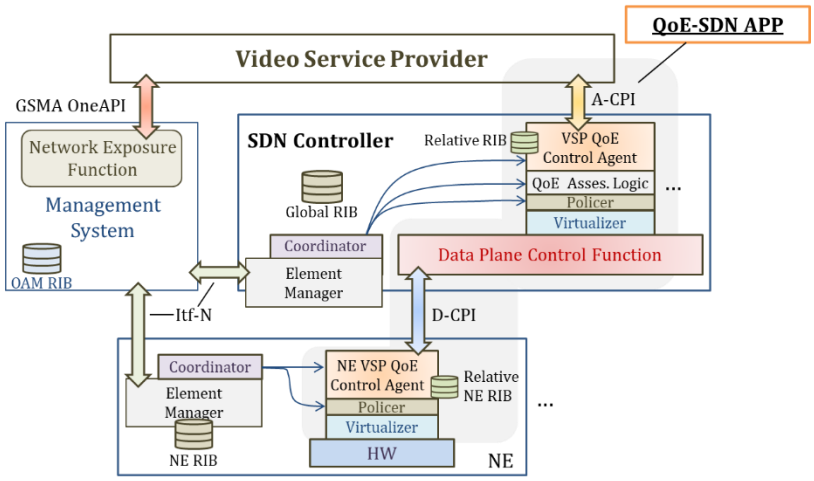

Fig. 6. QoE-SDN APP functions and architecture.

For our evaluation analysis, we adopted three use cases, considering first a HAS segment selection enforcement problem, then a segment encoding and placement (i.e., caching) problem, and finally a proactive segment selection and placement problem. Simulations were conducted comparing the aforementioned use cases with a standard, i.e., state of the art, version of HAS and with a conservative HAS variation that introduces minimum stalling events. In Fig. 7 we present the results with respect to the segment selection enforcement use case considering the aforementioned different HAS variations.

As shown in this figure, the experienced video bit rate in the system is higher for the standard case, followed by the rate-guided HAS (with the QoE-SDN APP) and the minimum stallings HAS. This is due to the fact that the standard HAS case allows users to select segments with a higher quality layer in contrast with the proposed rate-guided HAS, which takes a more conservative approach, guiding users to select segments with a lower quality. However, the proposed rate-guided HAS as well as the minimum stallings HAS allow more segments (i.e., more playtime) to be buffered, preparing the

video player better for imminent congestion and worse channel conditions. Therefore, such higher quality layer selection for standard HAS is the result of overestimated subjective bandwidth calculations that mislead users to request segments with a higher quality layer, and thus, eventually experience stalling events. This effect is illustrated in Fig. 7, where the QoE model for YouTube gives an estimation of the MOS as a function of the number and duration of stalling events, showing the benefits in terms of QoE for the proposed rate-guided HAS. Since stalling is the most important QoE shaping factor, such an improvement is highly desirable for the users and VSPs.

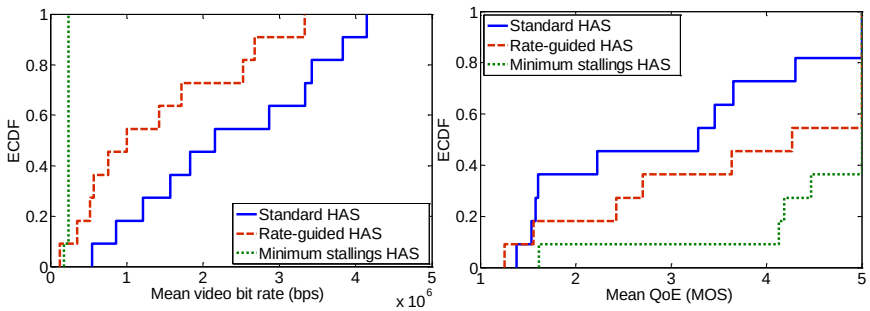

Fig. 7. ECDF of the mean video bit rate for all users (left), ECDF of MOS for all users (right).

3 Conclusions

The introduction of QoE intelligence and QoE-aware capabilities in mobile cellular networks changes the network management approach. Future network management implements a QoE management cycle, where a) QoE-related intelligence is gathered, b) QoE modeling and monitoring reveals the user satisfaction level or warns about imminent problems, and finally, c) a QoE control (i.e., management) procedure triggers proactive or reactive actions to appropriate network elements and functions.

This dissertation has dealt with the challenges arising from the need to integrate QoE intelligence in a mobile cellular network, which mainly concern the real-time evaluation of QoE, the improvement of existing network mechanisms, and the proposal of new QoE-inspired algorithms, stemming from the inherent characteristics of QoE and the non-linear impact of conventional QoS parameters on the user perception.

As a general comment, the research conducted in this dissertation has focused on the integration of QoE to research topics that are currently under intense research interest from academia and industry, such as D2D, HAS, radio scheduling and SDN. However, this is just a subset of potential solutions that may be proposed, when QoE intelligence is integrated into the real-time operation of a future network. Nevertheless, this dissertation provides valuable insights and useful findings in this direction, further encouraging research in the area of QoE characterization and provisioning in mobile cellular networks.

Overall, this thesis promotes the uniting of the domain of QoE with the domain of mobile communications, as well as the collaboration of mutual-interest between MNOs

(network layer) with service providers (application layer), presenting the high potential from such approaches for all involved stakeholders.

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