QoE Management for Future Networks

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Abstract. This chapter discusses prospects of QoE management for future networks and applications. After motivating QoE management, it first provides an introduction to the concept by discussing its origins, key terms and giving an overview of the most relevant existing theoretical frameworks. Then, recent research on promising technical approaches to QoE-driven management that operate across different layers of the networking stack is discussed. Finally, the chapter provides conclusions and an outlook on the future of QoE management with a focus on those key enablers (including cooperation, business models and key technologies) that are essential for ultimately turning QoE-aware network and application management into reality.

Keywords: Quality of Experience · QoE Management
QoE-driven Network and Application Management · SDN
NFV · MEC

1 Introduction to QoE Management

Understanding, monitoring and managing the provisioning of networked applications and services is a domain that receives growing interest by academia and industry. This development is mainly a consequence of increasing competition amongst stakeholders in the ICT, media, and entertainment markets, the proliferation of resource intensive services (such as online video and virtual reality movie streaming) and the ever-present risk of customer churn caused by inadequate service quality. Furthermore, the foreseen paradigm shift towards an Internet of Services (IoS)

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will lead to systems where new applications and services are based on flexibly configurable large-scale service chains, which depend on high levels of flexibility, quality, and reliability [20].

These trends create conflicting demands, particularly on the network operators and service providers involved. On the one hand, they need to offer sophisticated high-performance infrastructures and services that enable affordable high quality experiences that lead to customer satisfaction and loyalty [48]. On the other hand, they have to operate on a profitable basis in order to remain economically viable in the long run.

In this context, Network and Application Management (NAM) has the potential to resolve this central dilemma by enabling a better match between resource supply and demand on the basis of more informed trade-offs between quality, performance, and economy [66,73,84] based on validated ground truths. NAM is supposed to observe and react quickly to quality problems, at best before customers perceive them and decide to churn. It should ensure that sufficient quality and performance are provided while constraining the application (and its underlying service building blocks) to behave as resource-efficiently as possible in order to minimize operational costs.

Figure 1 provides a high-level overview of managing resources and quality in the context of networked multimedia and communication services, where the management of networks and applications constitute complementary approaches. Network management (NM) focuses on monitoring and controlling the network entities of the delivery infrastructure on access, core network, and Internet level. The goals of network management typically are efficient resource allocation, avoidance of Quality of Service (QoS) problems (like packet loss from congestion) and generally keep the network "up and running" without faults. In contrast, application management (AM) aims to adapt quality and performance on end-user as well as application host/cloud level.

In most cases nowadays, AM adapts the application to the conditions encountered in the network as it is situated much closer to the user than network-level controls. For example, in the context of HTTP Adaptive Streaming (HAS), where the quality of the media stream (and consequently, its bitrate) is dynamically adapted not only to the network bandwidth available on the path between client and server, but also application layer parameters (like video buffer level) and context (like battery status). AM thus often acts as a "mediator" between network and the end user, while taking other aspects (application, user preferences, context) into account. While AM is being widely used in todays consumer Internet where traffic is transmitted on a "best effort" basis without taking into account the diverse quality requirements of different applications and users, it is only when network and application management are being used in conjunction, that the full potential of NAM can be reached [66,84].

In addition, there is a growing awareness within the scientific community and industry that technology-centric concepts like *Quality of Service* (QoS) do not cover every relevant performance aspect of a given application or service (cf. [30,65]) and to understand the related value that people attribute to it as

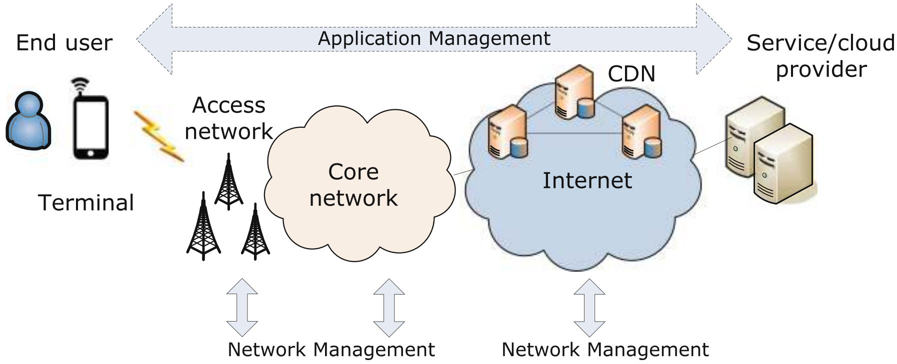

Fig. 1. Overview: Network- and Application Management operate at different control points along the delivery chain of services and applications (based on [66]).

a consequence [21,48]. For these reasons, the concept of *Quality of Experience* (QoE) has gained strong interest, both from academic research and industry stakeholders. Being linked very closely to the subjective perception of the end user, QoE is supposed to enable a broader, more holistic understanding of impact and performance of network communication and content delivery systems and thus to complement traditional perspectives on quality and performance.

While conceptualizations and definitions of QoE have dynamically evolved over time (cf. [67]), the most comprehensive and widely used definition of QoE today has emerged from the EU Qualinet community (COST Action IC1003: European Network on Quality of Experience in Multimedia Systems and Services): *"Quality of Experience (QoE) is the degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and/or enjoyment of the application or service in the light of the users personality and current state. In the context of communication services, QoE is influenced by service, content, device, application, and context of use." (Qualinet White Paper on Definitions of Quality of Experience (2012))* [61].

Thus in contrast to QoS, QoE not only depends on the technical performance of the transmission and delivery chain but also on a wide range of other factors, including content, application, user expectations and goals, and context of use. Understanding QoE thus demands for a multi-disciplinary research approach that goes beyond the network level. In particular, different applications have different QoE requirements (also including different QoS-dependencies), necessitating different QoE models, monitoring and eventually, different QoE management approaches. For example, while for securing the QoE of online video services, media playback quality (high resolution, no stalling, etc.) is of prime importance, the situation is different for online cloud gaming, where the reactiveness of the system is at least equally relevant.

For these reasons, the potential of extending QoS-focused traditional NAM towards QoE-based NAM[1] seems large. According to existing literature (cf. [6,66,70,73,84]) QoE-based NAM is supposed to yield the following main advantages:

- More efficient and effective utilization of resources (network bandwidth, radio resources, CPU, etc.) by performing informed trade-offs (e.g. low latency vs. less playback interruptions when increasing buffer sizes) and maximizing impact of resource allocation
- Increased satisfaction of users, plus the resulting economic benefits (increased loyalty, reduced churn, ability to upsell, etc.)
- Maximization/balancing of user satisfaction over the whole customer population (QoE Fairness)
- Ability to quickly detect/anticipate problems that really matter and solve them in real-time or even before the customer perceives them
- Ability to charge for value (i.e. high quality or reliability of the service) that has actually being delivered to the customer, enabling new business models

Given these potential improvements and benefits, the overarching key question of this chapter is: "How can QoE frameworks, tools, and methods be used to substantially improve the management of future applications and networks?" To this end, this chapter discusses the potential of QoE-driven NAM for future networks in the light of current research. In this context we aim to take into account challenges arising from current and future applications (like Virtual Reality, or VR, and Augmented Reality, or AR), as well as the ongoing transformation of communication networks by emerging technologies such as Network Functions Virtualization (NFV), Software-defined Networking (SDN), and Mobile Edge Computing (MEC). It first provides an overview of the most relevant theoretical frameworks related to QoE management in Sect. 2. Then selected concrete research on promising technical approaches to QoE-driven NAM that operate across different layers of the network stack presented. Finally, the chapter provides an outlook on the future of QoE management with a focus on those key enabling technology that will be essential for realizing the vision of truly effective QoE-aware network and application management.

2 Towards a Generic Framework for QoE-Driven Network and Application Management

In this section, we first derive the key components and challenges of QoE management by surveying recent literature discussing QoE management and related frameworks. Then we present a generic framework for QoE-driven Network and Application Management (NAM).

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[1] QoE-based NAM refers to QoE management applied to the domains of telecommunications and multimedia.

2.1 Key Components and Key Challenges

Technical Frameworks and Challenges. Schatz et al. [66] provide a comprehensive overview of previous work in this area before 2014, distinguishing between network and application management. When it comes to network management, fault and performance management represent areas of specific importance. QoE-driven network resource management is the second main topic in this context. Several works on resource management targeting two different parts of the network (access and core network) are discussed as well as QoE-based network management in multi-operator settings. The part on QoE-based application management focuses on management schemes explicitly designed for UDP/RTP-based and HTTP Adaptive Multimedia Streaming. Finally, the authors demonstrate a usefulness of a joint network and application management on two very distinct application scenarios, i.e. QoE management for managed services and Over-The-Top (OTT) Video. Finally, the authors state that a key challenge to be addressed by the research community relates to clarification and ensuring a common understanding of the meaning of different concepts and notions (like quality and performance) as well as highlighting their importance for different stakeholders.

Furthermore, a survey published in [11] authored by Barakovic et al. presents an overview, key aspects and challenges of QoE management focusing in particular on the domain of wireless networks. The paper addresses three aspects: QoE modeling of the QoE management, i.e. monitoring and measurement, QoE adaptation and optimization. When it comes to the first aspect, i.e. monitoring and measurement, the authors have concluded that different actors involved in the service provisioning chain will monitor and measure QoE in different ways, focusing on those parameters over which a given actor has control (e.g., a network provider will monitor how QoS-related performance parameters will impact QoE, a device manufacturer will monitor device-related performance issues, while application developers will be interested in how the service design or usability will affect QoE). Moreover, the authors identify the following four monitoring challenges, which should be properly addressed by the research community: (1) Which data to collect?; (2) Where to collect?; (3) When to collect?; and (4) How to collect? On the other hand, a part dedicated to the last two aspects was concluded with a statement that in most situations the user perceived QoE will depend on the underlying network performance. However, network-oriented QoE optimization processes would clearly benefit from perceived quality feedback data collected at the users side, since QoE is inherently user-centric. Similarly as in the previous case, the authors identify the following four control challenges that arise in this context: (1) What to control?; (2) Where to control?; (3) When to control?; and (4) How to control?

On the other hand, when it comes to frameworks, Liotou et al. present in [53] a conceptual framework toward QoE support, described in terms of functionalities, interactions, and design challenges. The framework consists of three main building blocks, i.e., a QoE-controller, QoE-monitor, and QoE-manager, all part of a “central QoE management entity”. The QoE-controller plays a role of an interface between a central QoE management entity and underlying network, synchronizing communication exchange in both directions. It is in charge of configuring a data acquisition process, by requesting and collecting feedback from appropriate data sources. It also provides the collected data to both the QoE-monitor and QoE-manager. Finally, the QoE-controller applies the corresponding QoE-aware control decisions back to the network, during a final step of the QoE management loop. On the other hand, the QoE-monitor is responsible for estimating the QoE per flow, that is, per users session, and for reporting this to the QoE-manager. The QoE-manager is in charge of conducting any type of customer experience management or QoE-aware network management. Regarding the first building block, i.e. the QoE-monitor, and challenges in this context, it is of crucial importance to select and implement the most convenient QoE estimation model for an application scenario of interest as its accuracy and reliability can rapidly influence a precision and reliability of actions done by other building blocks of the framework and therefore also of all the QoE management process. When it comes to the QoE-controller and challenges in this case, it becomes even more complicated. Firstly, a selection of appropriate nodes to be used for an acquisition of QoE-related input is of a strategic importance. Secondly, an appropriate type of collected QoE-related input represents the other challenge. The authors also discuss some realization issues and challenges in the paper, e.g. a physical location and type of a QoE management framework's implementation as well as power requirements for collecting QoE data. Besides the technical challenges listed above, an operator interested in implementing this framework has to take some business and legal aspects, which are clearly highlighted and discussed in the paper, into account. Finally, the authors showcase usefulness and efficiency of the proposed framework via an LTE case study.

Another framework termed an autonomous QoE-driven network management framework designed by Seppanen et al. is described in [70]. The authors consider the proposed framework generic and applicable to a broad range of systems. The framework represents a part of a complete customer experience management system. It consists of three layers, i.e. a data acquisition, monitoring, and control layer. The data acquisition layer is in charge of collecting all raw data by probes or other means of data collection. On the monitoring layer, the raw data produced by the data acquisition layer is processed into knowledge about a state of the network, which is in turn passed to the control layer. The control layer performs actions upon the network based on this knowledge. The authors verify the performance and effectiveness of the proposed framework by several tests, where RTP video streams were subject to a quality-driven network control. In all the cases, the tests result in an improved quality for the relevant clients. More specifically, the tests show that it is possible to improve the quality perceived by premium users without sacrificing the quality of the streams belonging to normal users. Finally, the authors claim that the framework is not only able to make a good decision for a given time instant, but also to predict the outcome of different decisions and pick the most optimal one. In other words, the framework is not only able to improve the perceived quality of the selected streams, but also to be conservative with the available resources and identify when they are really needed.

Non-technical Frameworks and Challenges. Both [53,70] highlight the benefits of performing QoE-driven and application-aware network management. In general, information exchange and cooperation among players involved in service delivery has the potential to improve the effectiveness of QoE mangement schemes [35]. However in practice, involved players need incentives to engage in cooperative efforts (e.g., information exchange, content caching, etc.) due to conflicting goals and interests. For example, a cloud provider might aim to maximize end-customer QoE, while a network provider might aim for maximizing the efficient use of network resources. Thus, the overall goal of QoE-driven NAM depends on the actual stakeholder group(s) involved in its realization. Examples for such goals are: maximizing the QoE of a given customer (end user perspective), maximizing overall average QoE of multiple customers in a cell/segment while maintaining QoE fairness (ISP perspective), or maximizing the number of satisfied users while minimizing resource consumption (network/cloud provider perspective).

In this sense, the overall goals of QoE management strongly depend on the stakeholders or groups of stakeholders taken into account. As regards the latter, the challenge to address in this context is: to which extent can cooperative management schemes and underlying business models involving multiple players achieve efficient management of network/system resources, while enhancing customer QoE? ISPs employ various traffic engineering mechanisms to keep their infrastructures running efficiently. Insight into the network requirements and adaptation capabilities of OTT services could aid them in making more efficient traffic management decisions. For example, information such as service utility functions and service adaptation capabilities could be used to perform cross-layer QoE-driven resource allocation among multiple simultaneous and competing service flows [40]. Furthermore, insight into application-level KPIs could aid ISPs in identifying user perceived QoE degradations and determining root causes of degradations. Given that a large portion of customer complaints aimed at ISPs stem from service provider problems rather than network operation problems, insights into the root causes of QoE degradations could help ISPs determine whether or not resolving a given problem falls within their domain.

Offering application providers access to network-related performance information through APIs could provide the potential for enhanced network-aware adaptation decisions (e.g., adapt video streaming quality, or assign end users to servers such that end-to-end delays are minimized). Furthermore, insight into contextual information such as traffic load patterns can be used by service providers for optimizing service delivery. Similarly, offering network providers access to application-level requirements could provide the potential for application-aware and QoE-driven cross-layer resource management.

In general, as stated in [27], cooperation opportunities can act as enablers for ISPs as well as content delivery infrastructure and service providers to jointly launch new applications in a cost effective way. For example, traffic-intensive applications such as the delivery of high definition video on-demand, or real-time applications such as online games, could benefit from cooperative QoE management solutions.

From a business oriented point of view, when considering QoE management, a key question is how to exploit QoE-related knowledge in terms of increasing revenue, preventing customer churn, and ensuring efficient network operations. Given a multi-stakeholder environment, business models driven by the previously discussed incentives are needed to model the relationships between different actors involved in the service-delivery chain. Ahmad *et al.* [6] address both the technical aspects and the motivation in terms of revenue generation for OTT-ISP collaboration. Their simulation results show that based on a proposed collaboration approach, there is a potential for increased revenue for the OTTs and the ISPs, stemming from increased customer satisfaction due to improved QoE. This work was further extended in [7] covering different perspectives of ISP and OTT collaboration in terms of QoE management, i.e., quality delivery, technical realizations, and economic incentives. The authors propose and evaluate a QoE-aware collaboration approach between OTTs and ISPs based on profit maximization by considering the user churn of Most Profitable Customers classified in terms of Customer Lifetime Value.

Consequently, an important consideration are the economical and monetization aspects of QoE [77,85]. Examples of different business models may be foreseen exploiting the cooperation between ISPs and OTT providers as summarized by Liotou *et al.* [52]:

- token-based models: charge a user according to a certain level of QoS/QoE; this may be accompanied with the purchase of a particular application,
- contract-based models following a tiered approach with different bandwidths and quotas, and
- Pay-as-you-go service models, where users are charged for a QoS/QoE level in relation to a particular service.

Summary of Key Challenges. To summarize, the key challenges to be dealt with by the research community and practitioners in the near future, coming from the works surveyed above, can be divided into three main parts, i.e., challenges related to QoE management as a whole (covering high-level conceptual, overarching technical and non-technical aspects of the QoE management), challenges directly related to QoE monitoring and challenges directly related to QoE adaptation and optimization (i.e. control). The challenges are summarized in Table 1.

When it comes to the challenges related to QoE management as a whole, it is critical to ensure a common understanding of different concepts and notions deployed in this context and to highlight their importance for different communities involved in the QoE management. Moreover, the physical location of a QoE management framework and the type of its implementation represent pragmatic challenges in this case. As also previously noted, legal and business aspects related to the implementation of a QoE management framework need to be addressed. This includes the different optimization goals and interests of different stakeholders. In this context, the willingness and (financial) incentives of different players involved in service delivery to disclose information to each

Table 1. Summary of main QoE management challenges

QoE management as a whole	QoE monitoring	QoE adaptation and optimization
Different concepts and notions used in QoE management	Type and amount of data to be collected	What to control?
Physical location of QoE management framework instances Conflicting stakeholder goals and interests	Placement and selection of the collection point/points	Where to control?
Type of QoE management framework implementation	Periodicity of data collection and approach used	When to control?
Legal and business aspects related to practical implementation of QoE management	Power requirements for collecting QoE data	How to control?

other is a critical obstacle. Even though initial studies show promising results [6], until now the actual benefits have not been proven along the whole cost chain. Moreover, regulatory restrictions related to the network neutrality principle [33] may have a key impact on realizing possible cooperation scenarios linked with application-aware traffic management.

Regarding the technical aspects of QoE monitoring, the following issues are open: the type of data to be collected (e.g., related to the service usage and configuration, network performance, user preferences, and context of use), the placement and selection of the collection point(s), the periodicity of the data collection and its approach together with a selection of the most convenient QoE estimation model for an application scenario of interest and the power requirements for collecting QoE data. In the case of the QoE adaptation and optimization, the following four questions: (1) what to control?; (2) where to control?; (3) when to control?; and (4) how to control? should be properly answered by the community in the near future [11].

The following section brings together a number of the aforementioned challenges by means of a generic framework for QoE-driven Network and Application Management.

2.2 A Generic Framework for QoE-Driven NAM

Several QoE-driven NAM approaches are investigated in [69]. The presented solutions focus on different applications and differ with respect to their specific management target. For example, some of the approaches aim on video quality fairness among heterogeneous HAS clients [37,43], while other works reduce the control delay of Skype with respect to bandwidth variations [83], or reduce video stallings for HAS [60]. Based on those existing approaches, the authors define monitoring and controlling of QoE indicators on network- and application-level as key building blocks for a generic NAM framework. By focusing on the key functionalities, the framework can cope with a multitude of NAM approaches, despite the diverse objectives and applications that are covered. The presented framework is a first step towards addressing the QoE management challenges introduced in Subsect. 2.1, as it helps to achieve a common understanding of different concepts and can be used to compare different solutions, e.g. with respect to design choices like frequency or location of monitoring and control functionalities.

We note that the focus in this section is on the **technical realization aspects of NAM** and not on the business aspects and financial incentives of multi-stakeholder cooperation. The presented framework assumes that there are underlying business models as well as contractual mechanisms (like SLAs, ELAs[2]) supporting the necessary cooperation between multiple involved stakeholders, such as OTT/service providers and network providers.

Building Blocks. In order to supervise the state of running applications, *Application Monitoring (AppMon)* is performed, while *Network Monitoring (NetMon)* keeps track of network-related QoE influence factors (QoE-IFs). The collected information is communicated to a centralized instance, e.g. a *Policy Manager (PM)*, which has an up-to-date global view of the network and the applications running on top of it. Based on its knowledge, the PM is capable to compute appropriate control actions, which, on the one hand, can be performed on network-side. This is denoted as *Network Control (NetCon)*. On the other hand, control actions can be performed on application-level, forming the *Application Control (AppCon)*. Further, a joint optimization of application and network might be feasible for several use-cases. Repeatedly monitoring and controlling of application and network then form the control loop of those approaches. This is in line with two of the general steps for QoE management, as defined in [11], namely (1) QoE monitoring and measurements, and (2) QoE optimization and control.

Besides the implementation of NAM building blocks, the abstract framework considers three optimization types:

- Application-level Optimization (ALO)
- Network-level Optimization (NLO)
- Policy Manager Optimization (PMO)

The location, where monitoring information is used to decide control actions, determines the optimization type. We shortly describe the optimization types and illustrate their employment in NAM approaches by providing examples in the following paragraphs.

Application-level Optimization (ALO). The application collects significant information about network or application. Based on this knowledge, the application initiates adaptation or invokes network-level mechanisms.

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[2] The acronyms refer to service level agreements (SLAs) and experience level agreements (ELAs) respectively, cf. [77].

Zhu et al. [83] propose an ALO-based cross-layer framework for OTT services like Skype conferencing. Their applied methods are similar to existing network layer techniques, such as Explicit Congestion Notification (ECN) and Differentiated Services (DiffServ). They use the existing ECN and DiffServ IP packet header fields to exchange cross-layer information like for example congestion and packet priority. Their results show a speed up of Skypes's response to bandwidth variation by indicating congestion immediately. Further, the audio packets' delays can be reduced by intra-flow prioritization.

Adzic et al. [5] use a content aware method to determine whether the video quality gain (expressed in SSIM) when switching to a higher level justifies the additional bandwidth consumption. The researchers assume DASH streaming in a mobile environment, where high-speed bandwidth volume is mostly limited. DASH servers provide videos encoded in constant bitrate (CBR), that does not consider the video content. Thus, an increase in bitrate does not necessarily mean a remarkable increase in SSIM for each video sequence. This ALO-mechanism prevents the client from selecting a higher bitrate when video quality cannot be increased significantly.

Network-level Optimization (NLO). The network collects significant information about network or application. Using this information, the network parameter are adapted or instructions for adaptation are given to the application.

NLO-centric mechanisms are discussed in the works of Wamser et al. [41,79,80]. All of them implement an estimator of the YouTube client's buffer state by deep packet inspection performed in the network. Based on this information, different actions are performed in the network. The software-defined networking (SDN) approach [41] proposes a dynamical re-routing of traffic. Whereas, in [80] resources are flexibly aggregated from one or more access networks. A home network scenario was investigated in [79], as a network adaptation, YouTube flows are dynamically prioritized. The employment of these mechanisms supports clients that are at risk of an empty buffer. The methods applied in the network lead to a fast buffer re-fill of those clients and the video stream's smoothness can be enhanced.

Policy Manager Optimization (PMO). A centralized instance (PM) has knowledge about both, network and application state. Based on its global system view, it can orchestrate control actions for applications or network.

A PMO approach called NOVA, short for *Network Optimization for Video Adaptation*, is developed by Joseph et al. [43]. The network regularly sends state updates to a so called base station. The client sent signal to the base station in case the video is in risk of a re-buffering event. An algorithm implemented in the base station computes the necessary bandwidth slices for each DASH client so that several QoE-IFs are optimized. The network controller performs the bandwidth slice allocation, the rate adaption is performed by the clients independently.

The model for NAM approaches, including the different building blocks, optimization types, and monitoring/control information flow, is illustrated in Fig. 2.

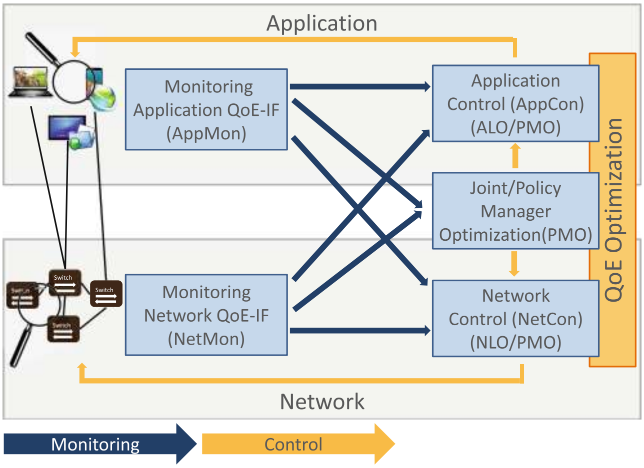

Fig. 2. Abstract NAM model with its building blocks and optimization types. Blue arrows indicate monitoring information, yellow arrows represent control information. (Color figure online)

It is very generic and omits details on the specific realization of the building blocks, e.g. distributed vs. centralized realization, or the monitoring layer, e.g. packet inspection vs. flow-based monitoring in the network. Frequency, location, and accuracy of monitoring dictate the level how fine-grained control actions can be performed and influence the potential of optimizing QoE. For instance, large time intervals between bandwidth probes restrict to a rough estimation that cannot consider short-time fluctuations. In turn, this leads to periods in which resources are under- or overestimated, resulting in non-optimal QoE due to the missing possibility to appropriately adapt to current network conditions. Nevertheless, the authors intend this generality in order to allow a simple classification NAM solutions with respect to monitoring and control capabilities. Based on the proposed framework, we classify several QoE-driven NAM approaches (Table 2). Besides building blocks and optimization type, we also provide the monitored QoE-IFs and the considered applications of the presented NAM approaches. As video streaming represents the majority of today's Internet traffic [23], it is largely discussed in current research. Accordingly, video streaming, is the dominant application among the approaches presented in the table. In particular, HAS is considered prevalently. To be able to adapt video quality, it already implements a control loop that monitors the network throughput or the client's buffer filling level. However, there is variety of applications running on top of future networks, e.g. VR applications or 3D and 360° video streaming. The QoE requirements of those applications need to be evaluated in order to facilitate QoE optimization. [32] proposes a QoE management approach for Cloud gaming, which can be seen as one representative in that direction. Furthermore, it shows that the generic functions of the NAM model also suit for applications

Table 2. Classification of different NAM approaches w.r.t. optimization type and frequency of control and monitoring actions. (I = Initial, T = Triggered, P = Periodical, ALO = Application-level optimization, NMO = Network-level optimization, PMO = Policy Manager optimization)

	Opt type	Net-Mon	Net-Con	App-Mon	App-Con	Monitored QoE-IFs	Considered Applications
[83]	ALO	P	T	P	P	Media encoding bitrate, network congestion	Skype
[54]	ALO	P	P	P	P	Media encoding and encoding bitrate, network bandwidth	HAS
[5]	ALO	-	-	P	P	Media encoding and spatial/temporal characteristics, network bandwidth	HAS
[79]	NLO	P	T	P	-	Video buffer, network bandwidth	YouTube
[41]	NLO	P	P	P	-	Packets in the network (DPI), network bandwidth	YouTube, HAS
[24]	NLO	I	P	I	P	Active DASH streams, network resources, client properties, network bandwidth	HAS
[25]	NLO	P	T	I	-	Packet loss, transmission delay	IPTV, Audio
[57, 58]	NLO	P	P	I	-	Not specified	Mobile applications
[22]	NLO	P	-	P	P	Encoding bitrate, user subscription, operator cost, network bandwidth	HAS
[37]	NLO	P	T	-	-	Network bandwidth	HAS
[80]	NLO	P	P	P	-	Video buffer, network bandwidth	YouTube
[29]	PMO	P	-	I	P	Media encoding and encoding bitrate, device resolution, network bandwidth	HAS
[32]	PMO	P	-	P	T	Available bandwidth, active gamers, client setup information, available games	Cloud gaming
[60]	PMO	P	T	P	P	Media encoding and encoding bitrate, video buffer, network bandwidth	HAS
[56]	PMO	P	T	P	-	Video encoding and encoding bitrate, buffering status, network throughput, packet loss	HAS
[43]	PMO	P	P	T	-	Media encoding and encoding bitrate, video buffer, network bandwidth	HAS
[19]	PMO	P	T	P	P	Required throughput per client, available bandwidth, network latency, end device properties, video buffer, video quality	HAS
[63]	PMO	P	P	P	P	Metadata of video content, video buffer, device resolution	HAS
[44]	PMO	P	T	I	T	User preferences, device capabilities, service features, network resource availability	Audio/video call

other than video streaming. The classification of NAM approaches reveals that the solutions differ with respect to capability, location, and frequency of control and monitoring functionalities, and that various QoE indicators are considered. This highlights that the challenges concerning QoE monitoring and QoE adaptation still need to be discussed by the community, as outlined in Sect. 2.1. In order to compare different NAM solutions and to investigate the impact of different monitoring and control capabilities on QoE-IFs, the authors set up a measurement environment that implements the key building blocks and facilitates the interaction between the involved entities. Initial testbed-driven results and a quantitative analyses of two NAM approaches are presented in [68].

3 Specific QoE Management Approaches

This section presents the results of selected QoE management related research conducted in the context of COST Action IC1304, serving as examples illustrating how some of the aforementioned challenges related to QoE-driven NAM can be effectively addressed. To this end, we present work on multidimensional QoE modeling, QoE management by differentiated handling of signaling traffic as well as QoE management with SDN.

3.1 Multidimensional Modeling as a Prerequisite for Effective QoE Management

What is often neglected in the process of QoE management (described in Sect. 2) is that an essential prerequisite for success is a deep and comprehensive understanding of the influence factors and multiple dimensions of human quality perception and how they may impact QoE in future networks and services, given

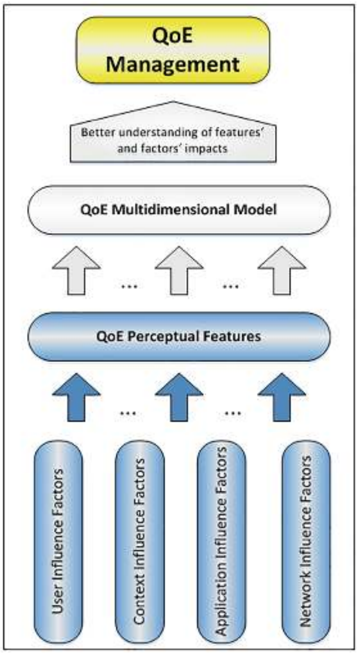

Fig. 3. Multidimensional modelling of QoE.

that humans are quality meters [49]. With the advent of 5G, the range of offered services, application domains, and the context in which they shall be used in will increase significantly. Consequently, factors such as explosive growth of data traffic volume, number of connected devices, continuous emergence of new services and applications, etc., will all contribute to the complexity of managing QoE [82]. The challenge is even greater, given that all above mentioned targets should be addressed in a multidimensional fashion (multiple factors and features) and from the point of various actors in the service provisioning chain. In this respect, multidimensional QoE modeling aims to quantify the relationship between different measurable QoE influence factors, quantifiable QoE features (or dimensions), and QoE for a given service provided by future environment (as given in Fig. 3).

Approaches and Results. In search for multidimensional modeling approaches to QoE in terms of multimedia services, one may note that most studies, addressing different factors and features that impact and describe the user experience or quality thereof (referring also to studies of user satisfaction or preferences), focus on a limited set of factors and features. Hence they offer an incomplete view of the user experience and QoE. For example, as summarized in [75], we have, models for file transfer [74], Voice over IP [38], video streaming [34,36,45,71], online video [39], etc. which are based on weighted impacts of system influence factors (that is Quality of Service technical parameters). What is generally missing, is a multidimensional approach to QoE modeling, i.e., the quantification and deeper understanding of multiple influence factors affecting QoE and features describing it, together with their mutual interplay [12,13].

Following the idea, authors in [72] give a generic framework for QoE in a multidimensional fashion by offering an ARCU (Application-Resource-Context-User) model which categorizes influence factors into four multidimensional spaces and further maps points from these spaces to a multidimensional QoE space, representing both qualitative and quantitative QoE metrics. What this study lacks is the concrete implementation on given multidimensional services and consequently the results.

However, studies that have started to address QoE modeling as an important part of QoE management in a multidimensional fashion, operated in a Web environment. In a stationary/desktop Web context, authors in [76] used a multidimensional approach to investigate Web QoE by focusing on evaluation of three key dimensions that contribute to overall Web QoE: perceived performance, aesthetics, and ease-of-use. Key results have shown that page loading time and visual appeal have a significant effect on overall user QoE and that both, higher perceived aesthetics and ease-of-use, result in an increased user tolerance to delay. Also, the research proved that there exists strong correlation between overall QoE and perceived aesthetics, ease-of-use, and network performance.

In the mobile Web browsing context (browsing information, thematic, and e-mail portals via both a smartphone and tablet), authors in [12,13] have proposed multidimensional models that represent and quantify mutual relations of QoE and key features, i.e., perceived Web site loading time, perceived aesthetics of Web site, perceived usability of Web sites, and perceived quality of Web site information, as well as key IFs and QoE features. These studies follow the principle given in Fig. 3 and their contribution is three-fold. Firstly, QoE in a mobile Web browsing context is addressed as a multidimensional concept. Then, the authors have shown that the impact of page loading time, aesthetics, usability, and quality of information provided by Web sites on mobile Web QoE exists. Finally, mutual relations between QoE and its features, as well as QoE IFs and features are quantified, and based on the obtained models, one is able to identify the importance (impact degree) of distinct dimensions in terms of considered perceptions and overall QoE. Therefore, the perception of Web site usability, aesthetics, loading time, and quality of information respectively in that order differ in the degree to which they impact the overall QoE (going from most to least influential) regardless of performed task or used device in a mobile Web browsing context [12]. In other words, the multidimensional models for mobile Web browsing QoE show that the most important perceptual dimensions were found to be perceived Web site usability and aesthetics, respectively, and that they impact QoE in a mobile environment more than the perception of Web site loading time, which was previously found to be the most influential in a desktop environment. The extension study given in [13] shows that in case of perception of Web site loading time, Web site loading time and number of taps respectively in that order differ in the degree to which they impact this QoE feature (going from most to least influential) in all considered cases (information, thematic, and e-mail portal). The number of taps, aesthetics of Web site, Web site loading time, and quality of Web site information respectively in that order differ in the degree to which they impact perceived usability (going from most to least influential) in all considered cases except when browsing the thematic portal (regardless of used device). Namely, when browsing the thematic portal via mobile device, Web site loading time and quality of Web site information switch places, i.e., the resulting order of impacts is: number of taps, aesthetics of Web site, quality of Web site information, and Web site loading time. The aesthetics of a Web site, number of taps, and quality of Web site information respectively in that order differ in the degree to which they impact the perception of aesthetics (going from most to least influential) in all considered cases except in the case of browsing the thematic portal via a smartphone, where the number of taps and quality of information switch places. The quality of Web site information, aesthetics of Web site, and number of taps to reach desired Web content respectively in that order differ in the degree to which they impact the perception of quality of Web site information (going from most to least influential) in all considered cases.

Conclusion. It is clear that not all factors can be addressed together in a single study. Therefore, the focus should be on exploring the impact of a chosen key set of influence factors and their perceptions (QoE features) on the user rating of overall perceived QoE for a given multimedia service in future network environment in a multidimensional fashion [14]. Based on that, one would be able to identify the importance of distinct dimensions in terms of overall user perceived QoE and consequently contribute to better QoE management, which represents an ultimate goal.

3.2 QoE Management by Differentiated Handling of Session-Control Signaling

As previously discussed in Sect. 2.2, the applications are responsible for collecting important information about the network or the applications runing on top of it, which are used for application-level adaptation or invocation of network-level mechanisms. These tasks concern the application-level signaling as being the main source of network intelligence, analysis, and user experience monitoring. The cooperation between the application- and network-level mechanisms may be realized by using different application-level signaling protocols, such as Session Initiation Protocol (SIP) or Hypertext Transfer Protocol (HTTP) [15]. While the new versions HTTP (i.e., HTTP/2) and HTTP alternatives (e.g., Stream Control Transport Protocol (SCTP) or Quick UDP Internet Connections (QUIC)) are the dominant signaling protocols in the Internet domain, the SIP is more used in the telecoms domain in the context of real-time communication services. The increasing usage of these services requires the real-time processing of growing amount of SIP signaling. In order to cope with the explosion of SIP signaling, the mechanism for differentiated handling of SIP messages is needed to increase the service quality, while decreasing the load of session-control resources [15].

In order to ensure high availability and reliability of SIP servers, different overload protection mechanisms have been previously discussed in the signaling performance context [31]. Many research activities have been performed to provide the SIP overload control by considering various parameters such as call rejection [10,51,81], session aware [42], and response time [55]. Moreover, the increasing usage of SIP signaling has resulted in the need for creating a methodology for SIP server performance measuring [78]. Different SIP performance metrics have been evaluated for that purpose in various environments, such as Internet Protocol (IP) multimedia subsystem (IMS) [16], Asterisk IP private branch exchange (PBX) [47], long term evolution mission critical systems (LTE-MCS) [8,9], content-aware network (CAN) and content-centric network (CCN) [62]. Considering the related work, it can be noticed that most of the research activities have been focused on analyzing the impact of session-control signaling on Quality of Service (QoS). However, acceptable QoS does not guarantee that end user will experience acceptable QoE.

Approaches and Results. In this regard, an algorithm for SIP message classification and priorization [18] (which is implemented in an NS-2 simulation environment [17] and on an Kamailio SIP server) has been investigated in terms of QoE impact. Serving as a mechanism for QoE management at the application layer shown in Fig. 4, this algorithm allows the optimization of SIP signaling procedures especially under high-load or overload conditions through improving

SIP performance metrics, i.e. registration request delay (RRD), session request delay (SRD), and session disconnection delay (SDD). This is a consequence of preferential handling of SIP messages used for session termination in comparison with the SIP messages used for session establishment, which allows the faster release of allocated resources and thereby improves the billing user experience. Moreover, this prevents the setup of new sessions under overload conditions until sufficient resources are available. This may lead to user experience improvement since users do not accept a service degradation or interruption once they have started a session. They would rather have the session to be blocked whenever the resources are not able to carry it with the appropriate quality.

On the basis of the foregoing considerations, there was a need for analysis of the interaction between session-control signaling, QoE and user perceptions of signaling performance metrics. With the aim of verifying the proposed algorithm for SIP message classification and priorization in user-oriented context, a research study has been conducted in order to obtain data for explaining the overall user satisfaction and satisfaction with SIP signaling procedures, i.e. register, session establishment, and session termination procedures, under different

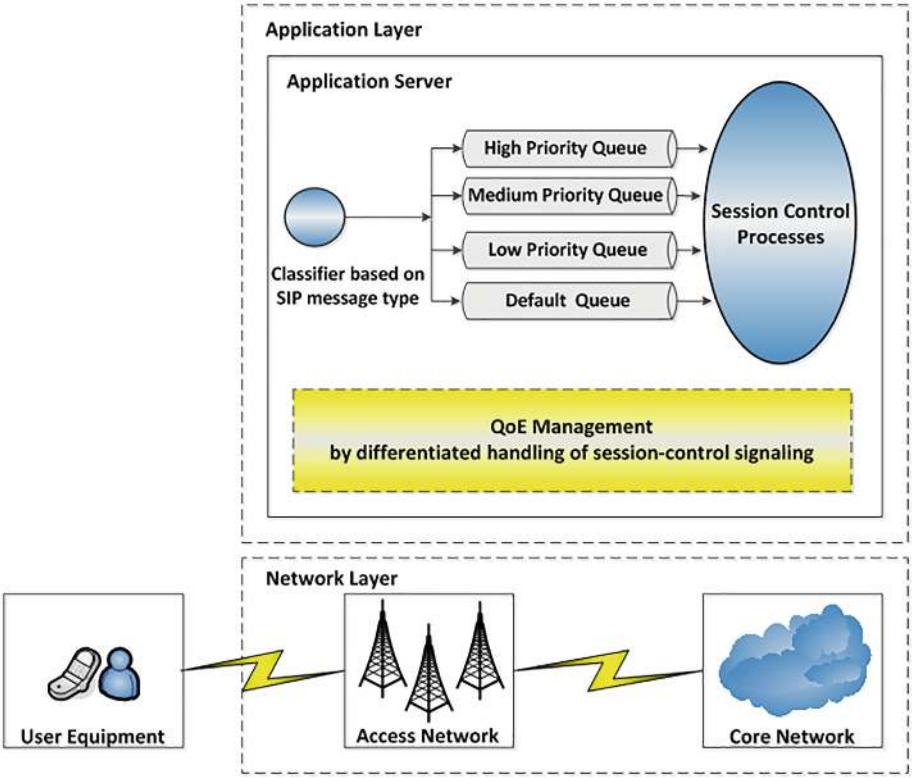

Fig. 4. QoE management by differentiated handling of session-control signaling.

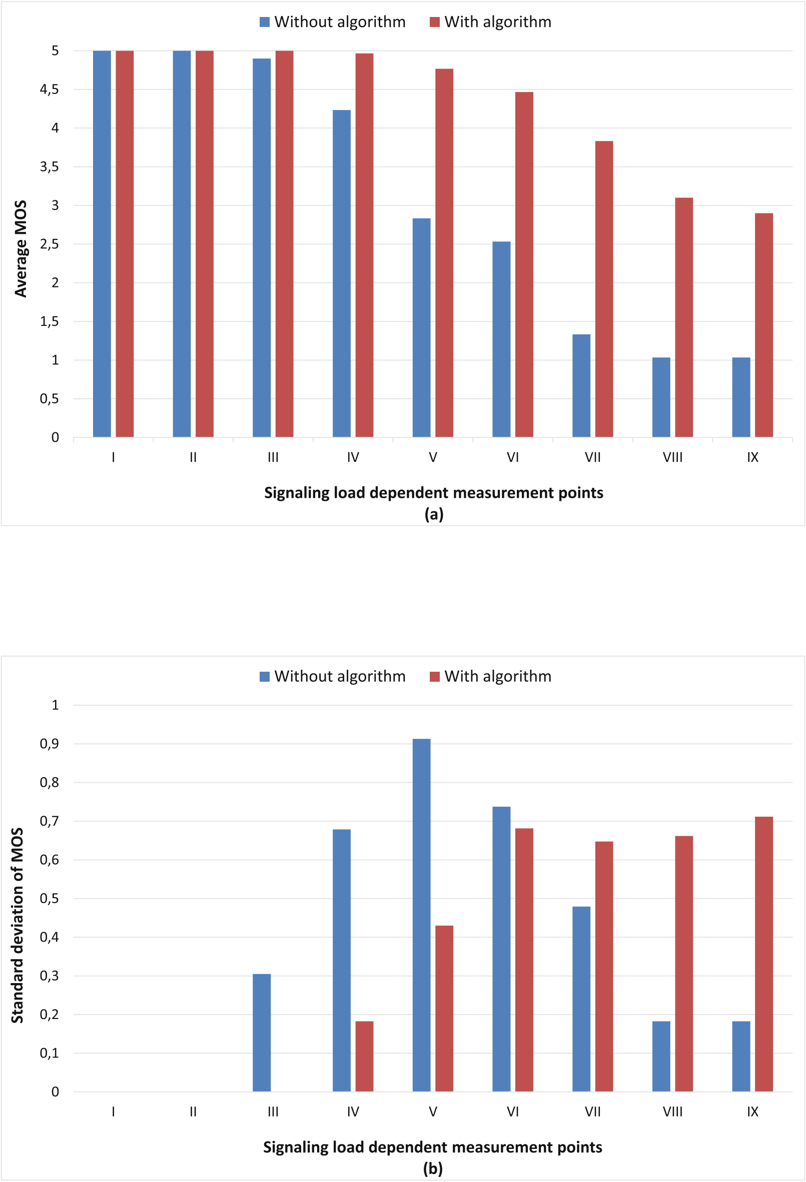

Fig. 5. The dependence of user perception of overall QoE in terms of MOS on the signaling load and algorithm implementation: (a) Average MOS; (b) Standard deviation of MOS.

load conditions. It has been found that session-control signaling plays its part in affecting the user QoE with Voice over Internet Protocol (VoIP) services. More precisely, a strong and negative impact of session-control signaling load on user perception of SIP performance metrics (i.e., RRD, SRD, SDD) and overall QoE has been determined. Fig. 5 shows the user perception of overall QoE expressed in terms of mean opinion score (MOS) in dependence on the session-control signaling load and algorithm implementation. Furthermore, the linear model is proposed to describe the relation between user perception of SIP performance metrics and overall QoE with VoIP.

In addition, it has been shown that the proposed algorithm for SIP message classification and priorization affects user perception of SIP performance metrics and overall QoE with VoIP by decreasing the strong impact of session-control signaling load on considered SIP performance metrics. Therefore, the additional model has been provided to evaluate the mutual relations of user perception of distinct SIP performance metrics and QoE. This has allowed us to determine the importance of various SIP signaling metrics according to the listed order, going from most to least influential: user perception of SRD, user perception of SDD, and user perception of RRD.

Moreover, since the algorithm for SIP message classification and priorization may be used for service differentiation, it has been investigated whether differentiated handling of SIP messages affects the quality of unified communication (UC) service components (i.e., QoS for voice/video calls, instant messaging (IM)/presence status) or not. It has been preliminary found that there is no statistically significant impact of SIP message differentiation on the QoS for the voice/video calls, IM/presence status. Nevertheless, the future work will address the impact of the differentiation of UC service components on QoE in different contexts.

Conclusion. Although the importance of session-control signaling has been already emphasized in the field of QoS, it has been considered to a limited extent in terms of the QoE. The performed research study has focused on the interaction between session-control signaling, QoE and user perception of SIP signaling performance metrics. The research findings indicate that session-control signaling load negatively affects the user perception of SIP signaling performance metrics and overall QoE with the VoIP service. On the other hand, it is shown that differentiated handling of session-control signaling does not affect the QoS of UC service, whereas its impact on QoE in this context is planned for the future work. Therefore, one may conclude that further investigation of this application-level mechanism for QoE management is needed not to draw the misleading conclusion.

3.3 QoE Management with SDN

Motivation. Subsection 2.2 provides an overview of several QoE-driven NAM approaches, while this one expands on that overview so as to present the approaches that exploit the relatively new Software-Defined Networking (SDN) paradigm [46] in particular. Communication networks are already undergoing an immense transformation in light of this paradigm. SDN commonly refers to the separation of the network control and data planes, allowing a network infrastructure to be configured from a central point, an SDN controller (SDNC), by the means of software. This configuration flexibility is facilitated by open *Northbound* and *Southbound* interfaces of the SDN architecture, which enable exchange of information among different functional entities of that architecture in a well-defined manner. QoE management is not left unaffected from the advancements of SDN technologies, since they bring in new potentials in terms of a) identifying novel use cases for QoE control beyond the pre-SDN era, and b) proposing new architectures and frameworks to achieve that. From the QoE standpoint and the related basic functions of monitoring, reporting and management, SDN architecture provides several benefits which are illustrated in Fig. 6.

Network-level *QoE monitoring* by an SDN infrastructure operator is simplified, since SDNC autonomously builds a "global view" on the network with respect to its topology and performance indicators (such as throughput and packet loss statistics). This enables the network operator to apply different QoE-centric optimization strategies and enforce optimal, network-wide decisions. Then, SDN architecture envisages the open interfaces that would ease *QoE reporting* by end-user clients and application servers on monitored application-level QoE influence factors (IFs). These interfaces would provide a basis to realize cooperative QoE management between end-user applications and the underlying network. For presentation simplicity, Fig. 6 only outlines QoE reporting on application-level IFs. The latter QoE IFs are passed on to an SDN application called "QoE mediator", which runs on top of an SDNC and is responsible for,

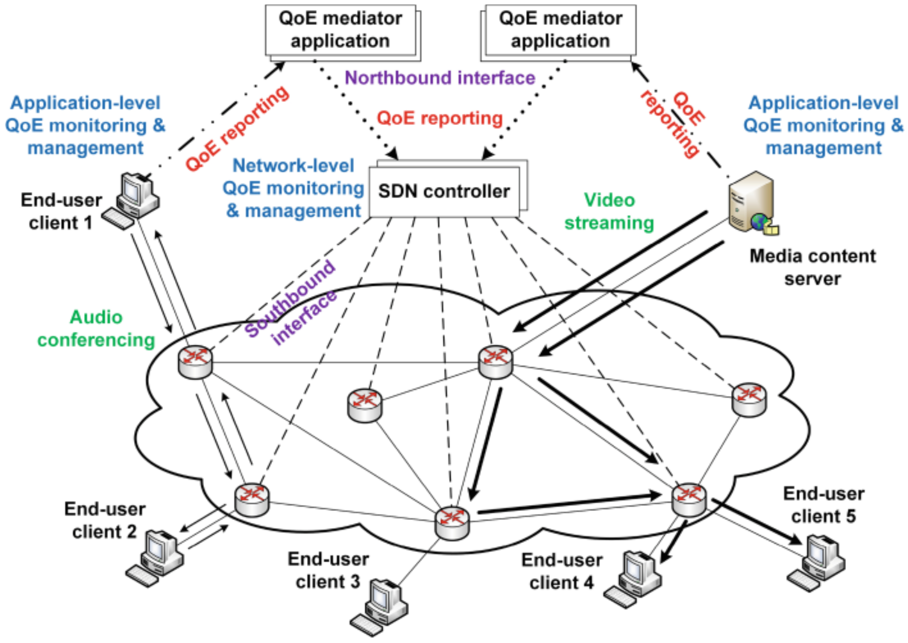

Fig. 6. QoE functions in the SDN scope.

e.g., generating aggregated QoE reports from multiple end users/applications. Aggregated QoE reports are delivered to the SDNC over a Northbound interface that it exposes. For a realization of the cooperative management, QoE mediators may also serve as, e.g., PMOs and instruct end-user clients or application servers which management actions to enforce. The latter role would require QoE mediators to employ an interface that supports conveying application-level management instructions as well. With regards to network-level *QoE management*, SDN facilitates per-flow network forwarding decisions and differentiated traffic treatment (e.g., video streaming vs. audio conferencing) on various levels of granularity, thus adding to overall QoE management flexibility.

Approaches and Results. Recent research papers show that this potential has already been acknowledged and taken advantage of. So far, most attention has been paid on how SDN's Southbound interface and, one of its main realizations, the OpenFlow (OF) specification [2] can be used to program network switches in compliance with operator policies, which enforce *automated flow manipulation*. This way, different traffic management schemes can be applied, such as to recalculate and adjust traffic routes, prioritize traffic handling in the switches, or employ network admission control. A high-level view of an SDN-based system that would maximize user QoE by optimizing path selection process is described by Kassler *et al.* [44]. The authors present general requirements of such a system that would consider demands and parameters of various multimedia flows, in terms of media codecs, flow bitrates, end-to-end (E2E) delay, etc. To achieve it, an SDNC would be used to collect information on multimedia applications, build a global network view, and install optimal routing decisions. QoE Fairness Framework (QoE-FF) for adaptive video streaming is presented by Georgopoulos *et al.* in [29]. The goal of QoE-FF is to find an optimal point of video quality requests among heterogeneous end-user clients competing for the same network resources. To realize such a goal, QoE-FF relies on a PMO entity that collects client device characteristics influencing QoE (e.g., screen resolution) and video service features (such as supported content bitrates) via a Northbound interface, as well as network bandwidth status, and then impose the respective bitrate demand on each client. Jarschel *et al.* [41] describe an SDN-based approach that investigates route selection strategies in order to improve QoE for YouTube users. For the application-aware strategy, an SDNC exploits the estimated playout buffer status and traffic demand on network bandwidth to choose a less congested network path.

Nam *et al.* jointly optimize the selection of video delivery nodes in a Content Distribution Network (CDN) and network routes in the base SDN infrastructure [56]. Their approach is built on monitoring application-level QoE IFs, such as initial reproduction delay and buffering rate, and calculating a new path in response to QoE degradations. An approach to dynamic network bandwidth reservation that optimizes QoE among multiple competing video clients is outlined by Ramakrishnan *et al.* in [63]. This approach employs the scheme of allocating bandwidth to each client that considers QoE IFs in terms of, for example, specific content type (e.g., dynamic vs. static video scenes), media codec used, as well as client's playout buffer level. Implementation-wise, an SDN-centric architecture is proposed that revolves around the QoE optimization application on top of PMO-like SDNC. This SDN application obtains information on client's device type and its buffer status, requested video sequence(s) and base network topology, and then tailors the bandwidth reservation in cases of congested network. M. Eckert and T. M. Knoll present the Internet Service quality Assessment and Automatic Reaction (ISAAR) framework [26], which encompasses QoE management functions for an SDN-enabled mobile network, namely network-level QoE monitoring and control. ISAAR exploits the SDN capabilities for (a) flow-based QoE estimation, which is realized by OF flow detection and selective packet capturing, and (b) QoE control enforcement via OF traffic prioritization and other traffic engineering (TE) techniques. Ramakrishnan *et al.* in [64] describe an SDN-based architecture that allows the generation of QoE metrics (e.g., PSNR) and QoE analytics. To achieve that, a "Video Quality Application" (VQA) queries information from an SDNC regarding video content, user devices, and network performance.

This emerging interest of tackling QoE management with SDN is also visible from recent European research projects. The CASPER project (http://casper-h2020.eu/) exploits SDN and NFV advancements towards improving end-user QoE in wireless networks, focusing on voice, data and traditional video applications. A novel framework is proposed, targeting its integration by mobile operators. Moreover, the INPUT project (http://input-project.eu/) aims to extend SDN and NFV paradigms, in order to pave the way for personal cloud services and functionalities with the goal to optimize QoE. Also, 5G NORMA (https://5gnorma.5g-ppp.eu/) envisions a flexible architecture that enables the multi-service- and context-aware adaptation of network functions to support a variety of services and corresponding QoE/QoS requirements. Finally, project CROSSFIRE (http://mitn-crossfire.eu/) has investigated the sharing of the same physical infrastructure by multiple network operators with the objective to optimize network operation and enforce QoE management by the means of SDN/NFV.

Conclusion. To summarize, most of the SDN-based solutions and frameworks for QoE management focus on a single end-user application, such as video streaming, and on network-level management mechanisms, but without providing specific details on technical SDN realization and important architectural aspects. In the latter, some of the key parts missing relate to: (1) a coordinated approach in distributed QoE monitoring, and (2) common interfaces for reporting on QoE IFs, which regard applications and the underlying network, but also end-users and general context information. Furthermore, the outlined approaches are often use-case-specific and do not discuss general guidelines on how to extend them so as to achieve more comprehensive QoE management solutions.

4 Outlook: Future Evolution of Software-Based QoE Management

As discussed in the previous sections, QoE provisioning within the current networked communication paradigm is a very challenging task, since the service delivery chain involves multiple stakeholders typically with competing interests (OTT service providers, traditional Mobile Network Operators (MNO), and Internet Service Providers (ISPs)). As a result, true E2E QoE management of a service is currently impossible, since data traffic produced by an OTT is subject to the network quality provided by an MNO, before it reaches the end-user. However, new technological advancements bring hope towards overcoming this isolation and truly enabling a holistic, E2E, cross-layer (i.e. network-level and application-level) QoE management. These identified technologies are SDN, NFV and MEC. Although MEC and NFV are driven by the same motives and follow similar design principles, according to [4], they are "complementary concepts that can exist independently"; therefore, they are examined separately below.

4.1 Software-Defined Networking (SDN)

First of all, SDN is a promising technology towards the direction of software-based QoE management (see Sect. 3.3). SDN, as of today, is mainly a tool used by operators of the network infrastructure to enforce traffic management policies within their domain, leaving the potential of a joint orchestration at the network and application levels unexploited. Nevertheless, SDN enables an abstraction of the network infrastructure, which, combined with the necessary SDN interfaces, can facilitate a closer collaboration between MNOs/ISPs and OTTs, respecting in parallel privacy concerns of each stakeholder. This visionary approach has been acknowledged by strategic white papers [3], as well as research papers, such as [6] and [52].

To achieve the full potential of QoE management with SDN, well-defined interfaces capable of realizing QoE reporting for different multimedia services are needed. Such interfaces would allow the SDN architectural elements, namely end-user clients, application servers, SDN applications, SDNCs and infrastructure devices, to convey information on all relevant QoE IFs. These interfaces can be scenario-specific and open, introducing great flexibility to 3rd parties who can program proprietary applications that use these interfaces. In this way, not only a comprehensive view on QoE could be formed, but also a more rapid design and implementation of QoE management frameworks would be enforced. Another important technological aspect that should be addressed is the identification of how generic QoE management blocks (see Sect. 2.2) are "mapped" to concrete SDN architectures and combined to create an efficient management cycle. The latter calls for the specification of different management strategies with regards to SDN monitoring and network-level traffic treatment as well.

4.2 Network Functions Virtualization (NFV)

The NFV paradigm enables the implementation of network functions in software that can then run on common hardware, but that can also be moved or instantiated at various network locations on demand. In order to achieve that, the available network, processing, and storage resources are to be configured based on policies from a central NFV orchestration system. One NFV topic closely related to QoE management that requires research attention deals with designing network-level QoE monitoring as a virtual function, which could be started "on-the-fly" on a commodity server. Other NFV aspects that need inspection relate to the orchestration process, which combines the operation of virtualized network functions. Here, one of the challenges is to efficiently merge different virtualized network-level functions so as to achieve a specific QoE management objective.

4.3 Multi-access Edge Computing (MEC)

MEC is another promising technology that fosters the closer collaboration of network operators and OTT parties, such as cloud, content and application providers, with the goal of efficiently maximizing QoE. MEC differs from NFV in terms of applications' location (i.e. at the network edge), type (i.e. interfacing with the access network), and scope (i.e. mobility applications). Specifically, MEC represents a technological paradigm, where network operators open up the Radio Access Network (RAN) edge of their networks to 3rd parties so that the latter can flexibly implement and offer novel services to their mobile customers, such as video analytics and optimized local content distribution [1]. The ETSI body sees MEC as "the convergence of IT and telecommunications networking". Similarly to SDN, MEC schemes will foster the joint, cross-layer QoE management for mobile subscribers, through authorizing the OTT players to exploit assets that exclusively belong to MNOs. An early example of this potential is found in [50], where a MEC server runs a novel adaptation algorithm enriched by the knowledge on wireless network congestion, which is provided by the MNO. This algorithm changes on the fly the HAS manifest files in response to the current network congestion, which drives end-user clients to select appropriate video segment representations that will diminish stallings and, thus, improve QoE. Similarly, Ge *et al.* in [28] guide the segment selection for video streaming users by locally caching the most popular content at the qualities that current network throughput can support. A reference architecture for the QoE-oriented management of services in the MEC ecosystem, exploiting Channel State Information (CSI), is discussed in [59].

5 Conclusion

In this chapter we have discussed the current state of the art in QoE management as well as the main challenges faced in this field. We presented a comprehensive framework for QoE-driven Network and Application Management (NAM) as well as specific approaches and discussed future prospects of selected technologies in this field.

In general, our survey shows that there are many promising sophisticated approaches towards QoE-driven NAM. However, we also observe that research in this field tends to be rather patchy (i.e. addressing just parts of the overall system or optimizing just for a specific service) or tends to remain on a high level of abstraction (i.e. being far away from practical implementability). Thus the main overarching challenges in realizing the vision of QoE-driven NAM are less related to singular components, but rather to putting all components (and the related stakeholders) together in a coordinated and sustainable fashion. In fact, a number of works have shown that the most promising solutions require cooperation between stakeholders typically facing conflicting business interests (see Sect. 2.1). Thus, we hope to see more future work addressing these non-technical, yet critical challenges by pointing out collaboration opportunities and value creation in the context of QoE-driven NAM. Furthermore, monitoring and managing QoE comes at the cost of increased overhead and complexity (data gathering, coordination and control, etc.), which is further catalyzed by the emerging SDN and NFV technologies. Such costs tend to be neglected in existing research, yet they represent a major barrier to adoption in practice. Therefore we encourage the community to stronger integrate these aspects (and complexity in particular) in the design and evaluation of QoE management approaches. This especially refers to a holistic exploitation of SDN, NFV and MEC that would unleash the potenital of a coordinated QoE management between the application and network levels.

Finally, bringing QoE, AM and NM closely together also raises the need for aligned views and mindsets. Besides clarifying and synchronizing the meaning of different concepts and notions (like “quality”, “acceptability” or “performance”), their importance for the different academic and industrial communities needs to be assessed and aligned in order to make the vision of truly QoE-driven Network and Application Management a reality.

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