Chapter 28
QoE-Based Network and Application Management

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Abstract This chapter presents an overview of a set of recently proposed QoE-based management approaches that all try so resolve a central dilemma: maximizing user satisfaction while at the same time maximizing resource efficiency and economy. To this end, it first builds bridges between recent approaches towards QoE-based Network Management and standardized Network Management functions. This is contrasted by a discussion of recent approaches towards QoE-based Application Management. Further, it is shown how both Network Management and Application Management can work together in concert. Finally, open issues regarding a better integration of management and QoE are outlined.

28.1 Introduction

Proactive management of applications and networks has the potential to resolve the central dilemma of delivering applications to end users at maximum quality, while at the same time minimizing the costs of the other stakeholders involved in the delivery, including network, service and cloud providers. The so-far typical Internet control paradigms "best effort", "one size fits all" and "prevent performance problems by overprovisioning" have led to inadequate and uneconomical ways of providing sufficient levels of QoE. Indeed, users and providers may have different (and potentially

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S. Möller and A. Raake (eds.), *Quality of Experience*,
T-Labs Series in Telecommunication Services, DOI: 10.1007/978-3-319-02681-7_28,

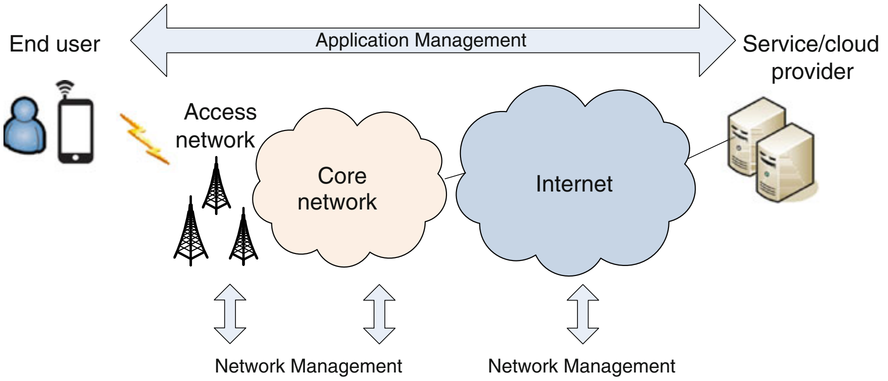

Fig. 28.1 Network management (NM) and application management (AM) constitute complementary approaches that utilize different monitoring and control points

conflicting) views, experiences and understandings of a service [48]. In this context, QoE is supposed to enable a broader, more holistic understanding of the impact of networked communication and content delivery systems on the end-user and thus to complement management perspectives on quality and performance that have traditionally excluded the user perspective.

This chapter presents an overview of a set of recently proposed QoE-based management approaches that are specifically related to *Network Management* (NM) and *Application Management* (AM). While NM is based on monitoring and exerting control on access, core network and Internet level, AM seeks to adapt quality and performance on end-user and application host/cloud level. The different, complementary perspectives applied by AM and NM are illustrated by Fig. 28.1. NM focuses on monitoring and control onto the network entities in order to keep the network up-and-running. Thus, it is not surprising that "Over-The-Top" (OTT) services running on top of Internet, such as YouTube, Skype and Netflix have implemented their own AM, i.e. QoE control schemes on application level such as forward-error coding or adaptation of video resolution, which aim at decreasing the risks of spatial (blocking etc.) or temporal (stalling etc.) artifacts, respectively. Naturally, this type of control that adapts the application to the conditions found in the network is situated much closer to the user than the network-level control. Thus, AM can act as a "mediator" between network and user interface, optimizing QoE under the given circumstances.

What is common to both categories of QoE-based management approaches (AM, NM) is that they are based on the results of various QoE research fields: QoE assessment, modeling, measurement and monitoring. Consequently, this chapter builds on the previous chapters in this book, illustrating how QoE management serves as a major crystallization point and catalyst for advancing this area of research.

The remainder of this chapter is structured as follows: Sect. 28.2 introduces a set of recent approaches towards QoE-based Network Management and relates them to the FCAPS classification. Likewise, Sect. 28.3 presents a set of recent approaches towards QoE-based Application Management. Section 28.4 then shows how both types of approaches are put together in a combined fashion using QoE management in walled-garden IPTV settings and YouTube video streaming as examples. Finally, Sect. 28.5 wraps up the chapter and points at some aspects that need further attention.

28.2 QoE-Based Network Management

Given the broad range of issues that may be considered under the umbrella term of Network Management (NM), we consider it beneficial to identify those areas that may in particular be exploited to optimize service quality as perceived by end users. In that sense, we draw links between QoE-driven NM approaches and the ISO-standardized FCAPS framework, which serves to classify NM objectives across five different levels, as elaborated on in the first subsection. We then present an overview of recent approaches to QoE-based NM, with focus on QoE-driven resource management and multi-operator scenarios.

28.2.1 The FCAPS Classification

The ISO-standardized minimal set of functional areas of NM are defined as FCAPS (Fault, Configuration, Accounting, Performance and Security Management) [31] and commonly referred to within NM [12, 21, 23, 48]. With regards to QoE, the following areas are of specific importance:

- Fault Management is aiming at isolating and fixing network failures as quickly as possible in order to minimise the time that the users are disconnected from network service(s). Thus, it provides a central lead in assuring QoE by limiting the impact of network problems on user annoyance.
- Performance Management potentially has the most obvious connection to QoE and user delight, although its monitoring and control facilities are rather limited [20, 21]. The performance aspect of NM focuses on monitoring network-related parameters such as byte counts and link loads (which may include the generation of alarm messages once pre-configured thresholds are crossed, and by subsequently allocating more resources (which is commonly referred to as "throwing bandwidth at the problems").

The relative high importance of Fault Management within NM as compared to Performance Management is motivated by the observation that users react much more to uncontrolled quality degradations (e.g., due to packet losses because of congestion) than to controlled degradations (e.g., congestion avoidance through throughput reduction) [15, 25]. Performance management that focuses on provisioning of QoE is recognised as a key topic for future NM [48]. From a user perspective, the other NM functional areas related to Configuration (monitoring and managing the system configuration), Accounting (focusing on billing and charging), and Security (managing network authentication, authorization, and auditing) may be considered as generally having a less prominent and more indirect link to QoE improvements. However, for certain service scenarios (e.g., e-commerce, e-banking, e-health), the latter functions may prove to be of high importance.

28.2.2 QoE-Driven Network Resource Management

With regards to QoE-driven network resource management approaches, a distinction has been made between user-centric and network-centric approaches, whereby the former explicitly take into account end-user QoE-related feedback, while the latter implicitly treat QoE while conducting QoE optimization based on network-collected data [57]. While resource allocation decisions are inherently made in the network, feedback collected from the client device or triggered by the end user can provide valuable input to the decision making process. Furthermore, certain information which may be relevant in making optimal resource allocation decisions may only be available in the network (e.g., operator policy, subscriber data, service priority, network resource availability). Resource management can actually take place in two different parts of the network: access and core network. Regarding the FCAPS classification, there are clear links with Performance Management (in terms of QoE-driven control of network resource allocation) and Fault Management (i.e., the collection of relevant data influencing QoE can serve to both identify and manage faults in both the network and at the client device).

Access network. While the access network can be wireline or wireless, it is in the domain of wireless networks that we find resources to be both more constrained and more variable over time, due to issues such as time-varying transmission channel conditions, user mobility, etc. [22], see also Chap. 27. As a result, the majority of research dealing with QoE-driven resource allocation targets this domain (as will be the focus of our review), with clear impacts on end user perceived service quality [11, 49].

Utility functions have been used to correlate user perceived value with QoS metrics such as delay, loss, error probability, and throughput [19, 40, 65]. In [65], the authors use utility functions to maximize utility across multiple users accessing different video contents in a wireless network by calculating the optimal radio resource allocation per user. They propose an enhanced objective function to avoid noticeable quality fluctuations (shown to have a negative impact on user perceived service quality). The maximization of aggregate utility across all users in a cell is also addressed in [9], where the mapping of service response time and user data rate (in the case of Web browsing) to MOS serves as input for a proposed radio resource allocation algorithm applicable in beyond 3G networks. Further solutions address QoE-driven traffic management in network access points by way of admission control, prioritized scheduling, and bandwidth management, relying on traffic differentiation and the customer subscription scheme [55].

A challenge with utility-based resource allocation mechanisms lies in the fact that certain applications have resource demands that may change over time (for example, the relationship between user perceived value and allocated bandwidth may change based on application state, such as a new media component added or removed from an ongoing session, or user behaviour such as pausing a video stream). In certain cases, dynamic feedback provided by the client can be used to drive network scheduling mechanisms, such as in the case of YouTube (to be discussed further in Sect. 28.4).

As opposed to feedback automatically generated by the client, the approach in [10] proposes mechanisms for end users to dynamically and asynchronously express their subjectively perceived (dis)satisfaction with respect to the instantaneous experience of their service quality. Based on direct user actions indicating preferences regarding service performance and corresponding cost, user's service utility functions are adapted, consequently driving the utility maximization problem being solved at the wireless base station.

While the majority of existing research addressing QoE-driven radio resource allocation focuses on downlink transmission, the need for optimized uplink resource allocation has been recognized in light of end users increasingly upstreaming multimedia content. A distributed QoE optimization approach is proposed in [14], supporting both optimized allocation of uplink resources and media adaptation decisions at the source client (e.g., video rate adaptation and decision on which video layers to transmit).

Core network. In the context of converged core network evolution, the 3rd Generation Partnership Project (3GPP) has specified the Policy and Charging Control (PCC) architecture, supporting differentiated service quality based on the mapping of service flows to different bearers [4]. The decisions regarding bearer assignment may be driven by service requirements specified and negotiated at the application-level and passed on to underlying network mechanisms. In [58], the authors propose mechanisms for the E2E negotiation and calculation of both optimal and suboptimal multimedia service configurations and corresponding network resource allocations, given service utility functions and user preferences. Such calculations may further serve as input to PCC mechanisms responsible for performing domain-wide QoE-driven resource allocation decisions [34].

Related approaches have proposed the inclusion of a QoE estimation/control server as a novel application server in the 3GPP architecture, responsible for collecting relevant data (e.g., related to network performance, client device performance, subscriber profiles, service requirements, or operator policy), estimating QoE, and invoking QoE control mechanisms [19]. Examples of such mechanisms include prioritized network resource usage, modified service bandwidth limits, or notifications sent to subscribers informing them of potential actions to take to improve QoE.

28.2.3 Towards QoE Management in Multi-Operator Settings

Considering QoE from an end-to-end (E2E) perspective, it is clear that communications may span multiple types of networks (fixed or wireless) belonging in turn to multiple operators. While QoS assurance in independent transport networks has been well studied, challenges remain on how to secure E2E QoS and QoE across multiple network domains, relying on inter-domain signalling and inter-provider agreements [62].

Network convergence and quality assurance in multi-operator networks are fundamental issues addressed in the scope of Next Generation Network (NGN) standards. A high-level framework addressing E2E QoE assurance has been proposed in [70], relying on the assumption that client devices are capable of reporting QoE/QoS performance to network QoE management components along the E2E path. Given that in practice, different networks will generally manage and optimize QoE locally, in which case E2E QoE will depend on the traversed networks, QoE management in the network may be integrated or complemented with application-level QoE control mechanisms [63].

Seamless communications is a specific multi-operator setting that actually tries to exploit quality diversity by automatically choosing the best-fitting network to a set of decision criteria, typically involving quality, cost and security [30] and thus addressing the FCAPS dimensions Accounting and Security Management. While seamless communications were initially QoS-oriented, attention turned to QoE as a driving paradigm for making optimal network switching decisions [13, 29]. Switching decisions can be made in both proactive (in order to optimize starting conditions and load distribution) and reactive (to performance degradations and link losses) ways.

In addition, the commercialization of QoS in heterogenous networks with multiple operators (i.e., inter-operator/inter-domain QoS as a good) has recently received a strong impetus. For example, in the ETICS project [1] the user-centric understanding of demand, i.e., willingness-to-pay and QoE for network services, has been piggybacked on course-granular inter-domain end-to-end QoS Service Level Agreements (SLAs) used for efficiency reasons aggregating the required QoS guarantees for several users or whole domains. In this context, recently initiated studies are addressing the notion of evolved QoE-driven Service Level Agreements[1], incorporating measures of user-perceived service quality (and stemming from knowledge regarding correlations between QoS and QoE) [3]. Further considering business opportunities, the exchange of monitoring data collected at different points along the service delivery chain among different players involved (application/service providers, network operators, etc.) may provide valuable insight into the causes of QoE degradations and potential for QoE control, both from a network and an application perspective.

28.3 QoE-Based Application Management

The management approaches described in the previous section have focused primarily on controlling quality on access and core network level. In contrast, QoE-based application management targets the application server at the head-end as well as the

[1] For a more extensive discussion on user-centric SLAs please refer to Chap. 7 in this book.

client terminal as the main control points. This section discusses QoE-based application management with a focus on non-interactive media streaming for services like online video and IPTV. With respect to such (typically passively consumed) video streaming services, a clear distinction can be made between more traditional streaming techniques based on push-based paradigms and server-side decisions as opposed to newer pull-based paradigms involving intelligent clients and HTTP adaptive streaming [52]. In addition to media-related metrics (e.g., frame rate, encoding, content type), in the former case, QoE management solutions for UDP/RTP media streaming are driven by intrinsic network metrics such as packet loss ratio and transfer delay, while the latter case generally focuses on HTTP/TCP-related metrics such as re-buffering rate and duration [7].

28.3.1 UDP/RTP-Based Multimedia Streaming

Several studies have addressed QoE-driven adaptation schemes for video delivery via UDP/RTP over different types of networks, aiming at alleviating the impact of packet loss and media distortion on the user experience. The adaptation of video sender bitrate to meet end user QoE requirements (derived based on application and network parameters, and taking into account content type) is addressed in [39]. In their subsequent work [38], the authors apply a newly proposed video quality prediction model for the purpose of QoE control via sender bitrate adaptation targeting UMTS networks. Feedback regarding network QoS information is collected via transmitted RTCP reports. In a similar fashion, but with a focus on voice scenarios, [35] propose a QoE-driven VoIP adaptation scheme based on different network conditions and available bandwidth. In a more generic approach targeting multimedia access networks, [41] proposes an autonomic QoE management architecture that monitors network problems, determines QoE optimization actions (using an approach based on neural networks), and executes necessary actions (e.g. activating Forward Error Correction packets or selecting the delivery bit rate).

What is common to the above QoE-centric Application Management approaches is that they focus on bitrate adaptation, with most of the intelligence residing at the server side. However, with the growing popularity of TCP (and HTTP) based media streaming, the research focus has shifted accordingly towards more client-centric approaches, as discussed in the next subsection.

28.3.2 HTTP Adaptive Streaming

Adaptive streaming over HTTP [52, 64] is becoming an increasingly popular way of delivering videos over IP networks using the TCP protocol. It is typically implemented as a combination of streaming servers and intelligent clients that make adaptation decisions based on local observations. Nonetheless, providing high QoE remains a challenge particularly in mobile networks featuring bandwidth fluctuations and outages that ultimately cause buffer starvation and frequent picture quality changes. These issues necessitate the development of intelligent QoE-aware adaptation mechanisms (i.e., a quality scheduler) on the application level.

In this context, [54] benchmarked the quality adaptation strategies of several commercially available solutions. Their results confirm the large QoE impact of the quality scheduler, highlighting the inherent tradeoffs between high average quality, stable quality, protection against buffer underruns and bandwidth utilization as well as the need for more sophisticated solutions. Further, evaluating commercial bitrate-adaptive players in the context of competing for shared resources, the authors in [36] constitute that they lack to satisfy fairness, efficiency, and stability goals. To this end, they developed a suite of techniques for improved chunk scheduling and bitrate selection that can systematically guide the tradeoffs between reaching the aforementioned goals.

While DASH (Dynamic Adaptive Streaming over HTTP) is typically used in the context of single-layer codecs (H.264/AVC), recent studies have addressed streaming adaptation algorithms for scalable video coding based on H.264/SVC [51, 56]. In [56], the authors propose an adaptation algorithm which they present as outperforming other DASH mechanisms in terms of video quality, low switching frequency and usage of the available resources in a realistic mobile network scenario. A general analysis of the impact and trade-offs of SVC-based quality adaptation algorithms is given in [5], with a focus on Peer-to-Peer (P2P) Video on Demand (VoD) provisioning systems that feature dynamic optimization of what the authors term 'session quality' (rebufferings, playback delay, etc.).

While client-side bitrate adaptation is the de-facto approach today, the authors in [46] argue that CDN (Content Delivery Network) performance variability is difficult to detect when relying simply on such approaches. Consequently, they present a coordinated Internet video control plane that can use a global view of client and network conditions to dynamically optimize video delivery via control over two parameters: suitable choice of bitrate, and choice of CDN/server. The goal is to provide a high quality viewing experience despite an unreliable delivery infrastructure, supporting bitrate adaptation at both the start and during a session. Their analysis shows that such a control plane can potentially improve the rebuffering ratio by up to 100 % in the average case and by more than one order of magnitude under stress.

Hoßfeld et al. [28] discusses technical challenges emerging from shifting services to the cloud as well as how this shift impacts QoE and QoE management, with a focus on multimedia cloud applications such as video streaming. Discussing the different ways how to address these challenges, the authors show how different players in the ecosystem (including network, service, and cloud providers) have to interact and exchange information in order to realize QoE-based management for cloud-based multimedia services. This QoE management proposed in [28] clearly goes beyond pure Application Management, a topic addressed in the next section.

28.4 Bringing Application and Network Management Together

As a synthesis of the previous two sections, we are now going to discuss how network and application management can work together in a complementary fashion. This is illustrated in the context of two different scenarios, with the first one being more telco operator-centric and the second one being more Internet/OTT-centric.

28.4.1 QoE Management for Managed Services: Walled-Garden IPTV

As defined by ITU standards, IPTV refers to the delivery of multimedia services (e.g., television, video, audio, graphics, data) over managed IP networks that provide required levels of QoS/QoE, security, interactivity, and reliability [32]. The phrase *walled-garden* IPTV has been used to refer to proprietary operator solutions offering full control of the service delivery chain, from acquiring and managing content, to delivery via broadband networks to set-top boxes in customer homes. Given full control, operators are able to employ both NM and AM approaches to provide a certain level of quality assurance to end users. An example QoE management approach applicable in such a traditional IPTV environment is presented in [47]. The authors propose a QoE estimation process (per IPTV channel) based on measured network QoS parameters, zapping time (channel switching time), audio/video quality, and media synchronization. The resulting estimations are used to invoke various NM or AM QoE optimization actions, such as modification of traffic flow prioritization, selection of other routing paths, or media transcoding at the server side.

Considering architectural solutions for IPTV, proprietary, walled solutions have been noted as being faced with issues related to interoperability, multi-vendor environments, and third-party provisioning [42]. Different solutions have involved the integration of IPTV services within NGN environments, for example based on a fully NGN-integrated quality-assured IPTV provisioning model [67]. Standardization efforts that have been made by organizations such as the ITU and ETSI/TISPAN have proposed different architectural options, focusing on those based on the NGN architecture [2, 33]. Considering the concrete case of NGN-based IPTV, service control functions corresponding to a *service layer* (e.g., session control and management, media control and processing) are inherently linked to resource and admission control functions in the *network layer*. Given that the network resource allocations requested are based on media requirements that are negotiated and established at the service layer, AM outcomes (e.g., choice of different content or encoding schemes) provide input for making NM decisions (e.g., resource reservation). On the other hand, data collected along different monitoring points in the network can be used to make AM decisions. Consequently, with the QoE-oriented service control and application functionalities intertwined with the transport layer QoS control mechanisms, it becomes evident that in the context of NGNs, application and network management schemes are conceptualized to work together in assuring end-user QoE. Given such functionalities, QoE management approaches such as the one presented in [47] could be considered, but in a standardized, multi-service, open environment rather than in a proprietary IPTV network.

28.4.2 QoE Management for OTT Video: The Case of YouTube

The previous scenario has outlined how the combined, complementary use of NM and AM is being addressed in an operator-controlled IPTV setting. In contrast, this complementary use can also be driven by the need to manage the QoE of a concrete resource-intensive video service delivered over the Internet: YouTube.

YouTube accounts for more than 30 % of the overall Internet's traffic [17], with over 4 billion videos viewed every day in 2012 [69]. This outstanding success also creates serious challenges for network operators and service providers, who need to engineer their systems to correctly handle the resulting huge volume of OTT video traffic and the large number of users in efficient ways. For these reasons YouTube has become a primary target not only for the networking community at large [6, 8, 16, 66], but also for QoE research, resulting in a growing amount of work on YouTube QoE management, e.g. [59, 61, 68].

From a technical perspective, YouTube is an online video platform that utilizes non-adaptive HTTP streaming to deliver multimedia content to clients via an inherently unreliable best-effort Internet in the form of a progressive download[2] [16]. Due to this technology choice, the smooth playback of the video (i.e., fast startup, no rebufferings) rather than visual image quality is the main QoE management challenge [27, 50]. In this respect, YouTube already features some performance improvement measures that have direct QoE impact: on the application level, YouTube streaming utilizes custom application flow control techniques referred to as 'block sending' as well as dual-threshold buffer management (cf. [8, 18]). The main purposes are throughput smoothing via rate control (however, not without side-effects due to interactions with the already present TCP flow-control [8]) and the prevention of stalling effects caused by buffer starvation. On the CDN-level, YouTube employs a three tier caching infrastructure distributed over four continents with two goals: enhanced streaming performance by selecting a nearby cache as well as load balancing among cache clusters [6].

Albeit these measures were introduced for the purpose of improving the overall performance of the service (including other aspects such as fairness, efficiency and robustness), they do not represent full-fledged proactive QoE management, thus leaving room for further optimization [26]. This issue has been addressed by recent work on QoE-based AM and NM for YouTube that concentrates on two different network environments: (1) a local wireless mesh network access network environment that

[2] This refers to the implementation of YouTube as of end of 2012.

foresees central resource management; and (2) a global Internet environment where resource management can only happen decentrally.

As regards the former, approaches for local mesh networks have been addressing various network resource management options for QoE management based on application-level client feedback (generated by a custom application observing buffer levels at the client side): QoS differentation via traffic shaping [59], routing [61], and physical reconfiguration of nodes [60]. However, these options are not directly applicable to the global Internet environment with its inherent requirements for scaleability and decentralization. Thus as regards the Internet scenario, [26] suggests a controlled exploitation of selected tradeoffs in order to manage and improve YouTube QoE by means of combined AM and NM. For example, recent user studies on YouTube have found that increasing initial buffering delay before playback has less negative QoE impact than increasing the amount of stalling during playback [24]. Thus, if the QoS properties of the network transmission path as well as the properties of the video clip being requested are known, one can compute the optimal initial delay that minimizes the likelihood of stalling without annoying the user with unduly startup waiting times [26].

The key challenge that remains is that exploitation of such QoE-related tradeoffs requires a level of information exchange between network and application that cannot be passed to the network stack with today's APIs. Furthermore, the network stack must be able to react to these requirements dynamically. To this end, new APIs like the GAPI [43] and forwarding concepts such as Forwarding on Gates [44, 45] are currently being investigated to enable network-application interaction on a large scale.

Both examples in this section have shown that QoE-based network and application management should not be understood as separate, mutually exclusive paths towards QoE improvement. Indeed, as also suggested by [37, 71], the QoE management becomes most effective when NM and AM are allowed to work together in terms of a combined complementary approach.

28.5 Conclusion

This chapter has identified relationships between Network Management (NM), Application Management (AM), and QoE. While AM has a direct connection to QoE through the application's presentation layer and user interface, in practice there have been developed rather few ties between NM and QoE so far. This may make it hard for network managers to precisely locate the reason for specific user annoyance, or to create specific conditions for user delight.The latter is not surprising, as the control points within NM are much farther away from the users' points of perception than the control points within AM. Today, AM typically acts as mediator between network(s) and user(s) and aims at leveling off non-optimal network behaviour.We observed both pro-active and re-active management approaches that try to follow the different dynamics in the networked system in order to level out the QoE to the desired level(s), eventually determined by the user.

When applying the (within NM well-known) FCAPS classification to both QoE-based NM and AM, it becomes obvious that most of the proposed QoE-based management approaches fall into the domain of Performance Management. The presented examples are dominated by resource and access control, which even touches upon Accounting Management in particular if billing plans correlate with perceived utility [10, 53, 57]. However, within NM, Fault Management is seen at the number-one duty, followed by Configuration, Accounting and Security management, while Performance Management is often considered to be freestyle. We observe Fault Management functionality related to resource (re-)allocation and re-active routing of traffic, amongst others in the context of mobility and seamless communications. Furthermore, we observe that many contributions are rather patchy (i.e., they address just parts of the networked system) or found on high levels of abstraction (i.e., rather far away from practical implementability), and that NM and AM are typically not coordinated. Indeed, AM performed by "Over-The-Top" (OTT) services (such as YouTube, Skype, etc.) is not necessarily in line with network operator preferences. On the other hand, service differentiation on Internet level might violate the network neutrality principle if users are not notified about such measures by the corresponding operator.

Tying QoE, AM and NM closely together puts forward the need for aligned views and mindsets. For instance, the understanding of a fault can be completely different for a network provider (broken link) or for a user (missed goal in live soccer streaming due to a single freeze in the wrong moment). Besides clarifying and synchronizing the meaning of different concepts and notions (like "quality" or "performance"), their importance for the different communities need to be assessed and aligned in order to make the vision of truly user- and QoE-centric Network and Application Management a reality.

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