Approaches for Utility-Based QoE-Driven Optimization of Network Resource Allocation for Multimedia Services

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Abstract. Taking jointly into account end-user QoE and network resource allocation optimization provides new opportunities for network and service providers in improving user perceived service performance. In this chapter, we discuss state-of-the-art with regards to QoE-driven utility-based optimization of network resource allocation, in particular related to multimedia services. We present two general types of approaches: those which are primarily user-centric and those which are primarily network-centric. Finally, we provide a comparison of the analyzed approaches and present open issues for future research.

Keywords: resource allocation, quality of experience, utility functions, multimedia services, optimization

1 Introduction

With new and emerging multimedia services imposing increasing resource demands on the network (e.g., video on demand, VoIP, IPTV, interactive networked environments, etc.), a key issue for operators is efficient resource allocation and management (in particular related to wireless networks). Furthermore, the increasing competition in the telecom market powers the everlasting endeavor of both service and network providers to meet end users' requirements in terms of overall perceived service quality and expectations, commonly referred to as the user's Quality of Experience (QoE). Although QoE metrics involve aspects related to subjective user perception and context (e.g., subjective multimedia quality, user expectations based on cost, user environment), also an appropriate mapping to system related characteristics and quantitative network performance parameters such as delay, jitter, loss, and data rate, forming the notion of Quality of Service (QoS), is required.

Consequently, a joint consideration of network resource allocation optimization and QoE provisioning is an upcoming challenge for network providers. In order to devise a QoE-driven resource allocation framework, a two step approach is necessary, providing a clear mapping (quantitative and/or qualitative) of user defined/perceived quality metrics to application parameters (e.g., encoding, frame rate, resolution, content type) and eventually to different network QoS conditions (e.g., delay, packet loss, jitter, bit rate) [30]. Previous work has studied QoE as a mapping to QoS parameters [11], [13], while a cross-layer approach aiming at network resource allocation optimization focuses on the joint consideration of information collected along different layers, (e.g., application level data, channel quality conditions, etc. [5]).

In order to formalize the correlation between network performance and user perceived quality, utility functions have been defined as a formal mathematical vehicle for expressing user's degree of satisfaction with respect to corresponding multi-criteria service performance [14]. In brief, the concept of utility functions, adopted from economics, provides the means for reflecting in a normalized and transparent way various services' performance prerequisites, users' degree of satisfaction, different types of networks' diverse resources and dissimilar QoS provisioning mechanisms and capabilities, as well as cross-layering information, under common utility-based optimization problems. The goal of QoE provisioning via network QoS-aware resource allocation may thus be restated as to maximize users' aggregated sum of utilities, exploiting Network Utility Maximization (NUM) methods and mechanisms [12].

In this chapter, emphasis is placed on the notion of QoE-driven utility-based optimization of network resource allocation, in particular dealing with multimedia services. We give a comprehensive review and analysis of state-of-the-art solutions applying this concept in different network scenarios and assuming decision-making functionality from different points of view (user-centric, network-centric). Emphasis is placed on recent methodologies that differ and deviate from the traditional point of view of treating Quality of Service (QoS) requirements at the various levels in Internet engineering (application, networking, etc.) creating the need for a more dynamic, interdisciplinary, cross-layer approach to formalize the correlation and impact QoE to QoS that can be engineered and provided within the network. Such approaches escape from the strict bounds of network engineering when studying QoS/QoE, by establishing foundations (e.g., using elements such as dynamic/adaptive network/user utility functions and optimizations) towards creating a framework for interrelating components arising from different points of view (user, provider, operator, engineer).

Following this path, the chapter is organized as follows. Section 2 provides readers with an overview and background on utility-based QoE optimization, including the identification of challenges related to QoE-based resource management. To demonstrate the applicability of the aforementioned methodologies, this chapter will further provide a description of two types of approaches:

- Section 3 will focus on utility-based QoE provisioning in wireless access networks, offering a user-centric approach involving autonomic mobile nodes with enhanced decision-making capabilities towards reacting to mobility and QoS performance related events [6], [4], [3]. Such approaches take explicitly into account user experience and end-user QoE related feedback, while focusing on maximizing users' utility in a real-time manner.
- Section 4 will discuss end-to-end QoE provisioning in the converged NGN, providing a more network-centric decision-making approach with domain-wide QoE optimization being provided in the core network [1], [2], [8], [9], [10], while consid-

ering also operator costs and profit. In such approaches, triggers/events driving resource (re)allocation decision-making are commonly detected by network mechanisms.

Finally, the approaches will be compared in more detail and conclusions will be drawn in Section 5, while important open issues for future research will be identified in Section 6.

2 Background on Utility-Based QoE Optimization: Mechanisms and Challenges

2.1 Correlating QoS and QoE

Over the last years the way scientists, engineers, operators and users treat, fulfill and evaluate QoS provisioning has dramatically changed. Considerable efforts have been devoted towards efficient resource utilization, resulting in the evolution from a best effort Internet packet forwarder to a QoS-aware framework, especially for real-time services. Nevertheless, despite the deployment of dynamic resource allocation, traffic shaping and scheduling mechanisms aiming at maintaining services' operation under acceptable networking oriented metrics, such as latency, jitter and packet loss, the final judge of a received multimedia stream still remains the end-user, i.e., a human. In line with the previous, Shenker, in a seminal paper [15] highlighted that "The Internet was designed to meet the needs of users, and so any evaluative criteria must reduce to the following question: how happy does this architecture make the users?" Towards this goal, the concept of utility functions has been adopted and borrowed from economics, allowing the normalization and direct confrontation of users' degree of satisfaction with respect to their multi-criteria service performance. Following this formalism, QoS provisioning problems in wired [12] and wireless networks [16] were designed, modeled and treated via a concrete NUM framework.

However, a human's actual needs and expectations cannot be defined or clearly mapped to strict networking metrics and thresholds, but rather depend on a broader scope of factors. Besides basic QoS networking parameters like bandwidth and jitter, more sophisticated ones include grade of service (GoS) and quality of resilience (QoR) [7], which refer to service connection time and network survivability respectively. Moreover, it also depends on the usage context and intent of usage of the service [29], user role in using a service [27], service content [28], and the users' cultural, socio-economic [21] and psychological state [26], [20]. In [17], for instance, it is shown that if visual factors supplementary to the oral speech are utilized, humans can tolerate higher noise interference levels than in the absence of visual factors.

Consequently, the concept of QoE was developed towards bridging the gap between users' pragmatic needs and provided services' QoS, by elevating users' subjectivity and singularity. While numerous definitions of QoE can be found in literature and standards, a recent definition that has emerged from the EU NoE Qualinet community defines QoE as [32] „*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 user's personality and current state. In the context of communication services, QoE is influenced by service, content, network, device, application, and context of us*e“. For instance, Wu *et al.* [30] have portrayed QoE as a user level, sitting on top of application, system and network levels of the protocol stack, with each level relying on underlying quality indicators. As such, application level QoS metrics (e.g., video frame rate, response times) are influenced by network and system QoS, and may further be directly correlated with QoE, noting however that QoE cannot be deduced only from QoS measurements. However, aiming at users' QoE maximization, though ideal, is not trivial in practice. For instance, while there is an obvious relationship between packet loss and QoE [18], as well as delay and jitter and QoE [13], the authors argue that no clear mapping can be made due to the complexity of the compression and delivery of the services. Moreover, the work in [11] suggests that there is no linear relation between QoE and QoS, but rather an exponential dependency highly related to the data type and content. Towards this goal, various research efforts have mainly concentrated on offline methods with emphasis on determining the factors that influence QoE, measuring and evaluating the corresponding QoE levels and then mapping them to specific network metrics. A typical user-related metric for measuring QoE is the Mean Opinion Score (MOS) [19], which is in general determined from subjective ratings of the content in question by real users. With subjective quality assessment methodologies being time consuming and costly, numerous instrumental, objective methods have been devised aimed at providing quality estimations [31]. However, estimations based solely on metrics such as Peak Signal to Noise Ratio (PSNR) or Mean Square Error (MSE) do not perfectly correlate with perceived quality, e.g., due to the non-linear behavior of the human visual system in the case of video quality assessment [45].

In the next section, generic utility based QoE optimization problems will be drawn, highlighting ways of treatment, challenges and open problems.

2.2 Utility-Based Optimization in the Context of QoE

Following the QoS paradigm shift, and towards enabling a concrete and efficient QoE provisioning framework able of treating the latter multiple and often diverse problem settings, NUM theory has also been exploited, allowing multi-objective subjective performance optimization. To that end, various recent research efforts mainly focus on dynamic schemes that utilize passive or active network monitoring mechanisms and a priori QoE mappings to satisfy the user, relying on existing QoS mechanisms. For instance, a dynamic rate adaptation mechanism is proposed in [22], that maximizes users' cumulative QoE utility-based performance, derived by PESQ (Perceptual Evaluation of Speech Quality) and SSIM (Structural SIMilarity) objective measurements for audio and video services respectively. Moreover, in [23], users' optimal transmission policies in terms of modulation scheme, channel code rate, and share of medium access on wireless networks for various services are determined using a greedy utility-based maximum throughput algorithm. Finally in [21] and [24] a user centric approach to QoE provisioning is considered, where users' viewpoint is taken into account to the overall system QoE optimization problem, either by employing pricing or preference indicators, respectively.

Utility functions have generally been used to specify the relation between relative user satisfaction and consumption of a certain resource. Examples of utility curves corresponding to different types of traffic are portrayed in **Fig. 1** (observed by Shenker [15]). *Elastic traffic* can adapt to different network conditions and is generally delay tolerant (e.g., TCP traffic in general, email, file transfer) with decreasing marginal improvement as bandwidth increases (the function is strictly concave). On the other hand, *discretely adaptive* traffic has strict bandwidth requirements and a sharp loss of utility in between certain thresholds (e.g., audio or video streaming applications operating at discrete codec rates). Commonly audio and video traffic may adapt to different delay/loss values, while bandwidth dropping below a certain intrinsic value causes a sharp performance drop. Corresponding utility functions have been labeled as *adaptive*. In the case of adaptive traffic, the marginal utility of increased bandwidth is small at both high bandwidth and low bandwidth.

Important for making resource allocation decisions is the understanding of the marginal utility change given a change in resource allocation. Reichl et al. [14] have studied the interrelation between QoE metrics and utility functions and argued that logarithmic functions derived based on QoE evaluations occur often in practice.

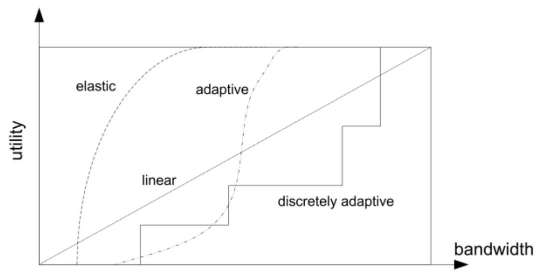

Fig. 1. Example utility curves for different types of traffic

With QoE being of a temporal nature, it can change over time given variations in QoE influencing factors (e.g., network conditions, service state, user preferences, usage context, etc.). Utility functions to be considered for resource allocation may take on different forms during a service's lifetime, for example due to different active media flows, different delay/loss values, change in user terminal (e.g., increased bandwidth and higher resolution will not increase user perceived utility if the user's terminal does not support such a resolution), etc. Aristomenopoulos *et al.* [4] discuss the dynamic service's utility adaptation based on user preferences. On the other hand, in the work done by Ivešić *et al.* [8], the choice of the most suitable utility-functions towards optimal resource allocation is dynamically made based on currently active media flows.

Related to the observations by Reichl et al. regarding applicability of logarithmic laws in user quality perception to QoE of communication services, Thakolsri *et al.* [5]

apply utility maximization in the context of QoE-driven resource allocation of wireless video applications. The authors note that certain video quality fluctuations remain unperceived by end users, and exploit this observation in their problem formulation. More specifically, they show how the multiobjective formulation of maximizing average overall quality while minimizing perceived quality fluctuations provides higher average utility for all users as compared to formulations that do not consider quality fluctuation.

In the case of multimodal sessions with multiple media components (e.g., audio and video), different utility functions may correspond to each media component, with overall session utility expressed as some form of a weighted combination. Utility-based multimedia adaptation decision taking has been previously applied in the scope of the MPEG-21 digital item adaptation standard, and further addressed in the scope of multi-modal media streams by Prangl et al. [33]. A key issue in making multimedia adaptation and resource allocation decisions is consideration of user preferences, e.g., indicating relative importance of individual streams (comprising a single session) such as audio and video (Skorin-Kapov and Matijasevic [10]).

The benefits of QoE-driven resource allocation can range from providing increased end-user/customer satisfaction, to maximizing the number of simultaneous customers (from an operator point of view) while maintaining a certain level of user perceived quality [22]. Different types of generic QoE optimization problems are portrayed in **Fig. 2**. In a single user case, the focus is on QoE optimization of a given user session taking into account current terminal, network, and service constraints and driven by user QoE estimation methods [3]. On the other hand, multi-user domain-wide QoE optimization problems involve making domain-wide resource allocation decisions across multiple sessions [4], [22], [8]. In practice, the formulation of the objective function for optimizing resource allocation may differ depending on whose interests are being considered (e.g., users' or network operator's). Different examples include: (1) maximizing the (weighted) sum of utility functions across end users, expressed generally as functions of QoS parameters, (2) maximizing the number of "satisfied" users, i.e., with utility above a certain threshold, or (3) maximizing operator profit, by minimizing operator costs. Methods for solving multi-objective optimization may be applied, such as formulation of a composite objective function as the weighted sum of the objectives, or consideration of a Pareto-optimal tradeoff (e.g., between user and network operator or service provider objectives). Possible constraints to be considered include available network and system resources, terminal capabilities, service/user requirements, and cost related constraints (e.g., available user budget). Hence, different actors involved in service delivery (user, network operator, service provider) can be considered in the QoE optimization process, along with their corresponding objectives and constraints.

2.3 Challenges of QoE-Based Resource Management

Numerous challenges may be identified related to the issue of performing QoE-based resource management. The initial concern involves modeling QoE for a given type of

	Single user QoE optimization	Multi-user QoE optimization
Multimedia sessions comprised of multiple media flows	Maximize *QoE* for a given user *i*. *QoE* expressed as a weighted combination of uni-modal QoE values. Uni-modal QoE values expressed as functions of network resource parameters (at constant values of other influence factors, e.g., usage context, user parameters, service) [10]	Maximize total or average *QoE* for users *1,...,k* (with possible joint goal of minimizing operator costs or maximizing operator profit). QoE_i expressed as a weighted combination of uni-modal QoE values for media flows comprising the session of user *i*. Uni-modal QoE values expressed as functions of network resource parameters (at constant values of other influence factors) [8].
Sessions considered as single media flow	Maximize *QoE* for a given user *i*. QoE values expressed as functions of network resource parameters (at constant values of other influence factors).	Maximize total or average *QoE* for users *1,...,k* (with possible joint goal of minimizing operator costs or maximizing operator profit). QoE values expressed as functions of network resource parameters (at constant values of other influence factors) [6][23].

Fig. 2. Different types of generic QoE optimization problems (for given examples decision variables assumed as network resource parameters)

service in terms of identifying QoE influence factors and their relationships to QoE metrics. Following specifications of relevant QoE models, monitoring and measurement mechanisms are needed to collect relevant parameters (e.g., related to network performance, user, context, application/service, etc.). Challenges lie in identifying which parameters to collect, where/how to collect data in a scalable manner (e.g., network nodes such as base stations, gateways/routers, application servers; end user terminal), and when to collect data (e.g., before, during, or after service delivery). Finally, mechanisms utilizing collected data for the purpose of QoE-based resource management are needed. Different formulations of QoE optimization problems have been discussed in the previous subsection. Additionally, such mechanisms may involve applying various control mechanisms at the base stations within access networks [6], applying policy management rules at the gateways or routers within the core network [22], conducting adjustments at the servers in the service/application [43], content or cloud domains, or the combination thereof [44]. Practical challenges to be considered involve scalability (e.g., support for a large subscriber base), added complexity (e.g., monitoring and parameter collection, optimization calculation, signaling overhead), and additional resulting costs.

Having provided some insight into utility-based optimization approaches and challenges in Section 2, discussing how the existing concept originally drawn from economic theory has been applied in the context of QoE related research, more detailed discussions of certain QoE-driven resource allocation approaches are given in Sections 3 and 4, focusing on user- and network centric decision-making approaches, respectively. While a detailed discussion of meeting the challenges of QoE-based resource management is out of scope for this chapter, we comment on these challenges in the context of approaches discussed in the following Sections.

3 User-Centric Approach to QoE Provisioning in Wireless Networks

The increased interest in QoE provisioning in forthcoming fixed and wireless networks has attracted much attention from the community and various research attempts focusing on the correlation of QoS to QoE have been proposed, mainly focusing on offline MOS objectives tests and network's auto adaptation towards maintaining services' performance under acceptable levels and thresholds [21], [30]. However, experience has been proven to depend on several subjective metrics, including various psychological factors, like mood or the importance of the content to the user. For example in a noisy environment, the presence of subtitles in a video footage can significantly improve users' experience, while also pricing incentives may drive users' behaviour towards tolerating higher interference levels. This implies that no automated mechanism, independently of its complexity and flexibility, is capable of properly dealing with such abstract and often diverse factors. The latter highlights the need for engaging the end users when testing and evaluating QoE. Staelens *et al.* [41] propose an end-user quality assessment methodology based on full-length DVD movies, which encourages subjects to watch the movie for its content, not for its audiovisual quality, in the same environment as they usually watch television. By providing a questionnaire, feedback can be collected concerning the visual impairments and degradations, which were inserted in the movie. Moreover, Chen *et al.* [42] extend the idea of measurements gatherring by proposing Quadrant of Euphoria, a user-friendly web-based crowd-sourcing platform, offering the community end-user subjective QoE assessments for network and multimedia studies.

It is thus imminent that aiming at capturing and determining QoE levels as perceived by the end-user, QoE control should be enabled and conducted at a point in the deliverfy chain as close to the user as possible, idealy at the end user terminal.

3.1 Autonomics in Wireless Networks

The vast increment of Internet and mobile users, their corresponding services' growing demands on resources and firm QoS expectations, as well as the existence of various available fixed or mobile access network types, assemble the view of the current networking environment, which is mainly characterized by its heterogeneity, multiplicity and complexity. Moreover, within a heterogeneous integrated wireless system, in most cases only the mobile node has the complete view of its own environment, in terms of offered services and their corresponding resource prerequisites, as well as a user's subjective needs and requirements. This becomes even more critical when the available services belong to different providers or even network operators. Therefore, contrary to traditional architectures where network/nodes' performance is monitored and controlled in a centralized way, future wireless networking envisions as its foundation element an autonomic self-optimised wireless node with enhanced capabilities. Such a vision and evolution, supported by the 3GPP LTE Self-Organising / Self-Optimising Networks (SON) initiation [38], proposes the introduction of various self-

* functionalities to the end-users allowing them to act and re-act to various events, towards self-optimizing their services' performance. The later presents a promising alternative service oriented paradigm that allows to fully exploit the proliferation of wireless networks, and enhancing users' experience, in terms of improved service performance, QoE, and reduced costs. As such, an autonomic node has the ability and enhanced flexibility to realize a control loop that dynamically, a) exploits locally available information (e.g. types of available services), b) monitors its service performance (e.g. signal strength, connection type), and c) makes optimal service-oriented decisions (e.g. request a HD streaming service) by setting and solving an appropriate optimization problem.

In this scope, NUM theory is envisioned as the enabler to devising network-wide novel autonomic mechanisms capable of optimally driving nodes' behaviour. Moreover, as illustrated in Fig. 3, a generic methodology, extending NUM to the field of autonomics, i.e. Autonomic NUM - ANUM, has been proposed, allowing the design of theoretically-sound autonomic architectures.

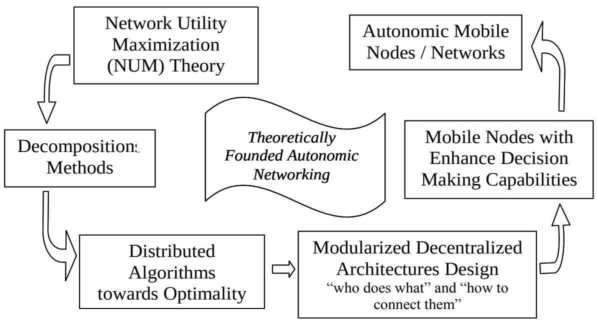

Fig. 3. From Describing to Deriving Autonomic Architectures - A Unified Methodology

3.2 Utility-Based QoE Provisioning in Wireless Networks

Aiming at autonomic QoE provisioning in a multi-user, multi-service heterogeneous wireless network, and considering involved users'/humans' subjectivity, QoE is envisioned as the vehicle that interconnects users/humans, applications and QoS-aware Radio Resource Management (RRM) mechanisms. Aristomenopoulos et al. [6] propose a QoE framework that allows users to dynamically and asynchronously express their (dis)satisfaction with respect to the instantaneous experience of their service quality, as subjectively perceived considering various psychological and environmental influencing factors, at the overall network QoS-aware resource allocation process. Towards this goal, the dynamic adaptation of users' utility functions is proposed, which in turn allows the seamless integration of users' subjectivity in the network utility-based RRM mechanism, enabling cross-layering from the application layer to the MAC layer.

The realization of the aforementioned framework (Fig. 4 [6]) requires **a Graphical User Interface (GUI)** that would a) display and capture user's available options (i.e.

various video qualities), and b) present the consequences of his actions in terms of pricing. Upon a user's preference indication, user's service is altered via the **dynamic adaptation** of his/her utility function, and the corresponding RRM mechanism is engaged, towards provisioning the requested resources by solving the resultant **utility-based resource allocation** problem. At this point the feasibility of a user's request as well as its compliance with operator's **policies** can also be introduced towards incorporating for example service performance bounds or fairness among users. Finally, imposed **pricing/billing schemes** correlating a user's QoE-aware behavior, with the corresponding cost of his request can be deployed, providing incentives for users to behave in non-selfish ways that both improve network overall utilization and maximize operators profits.

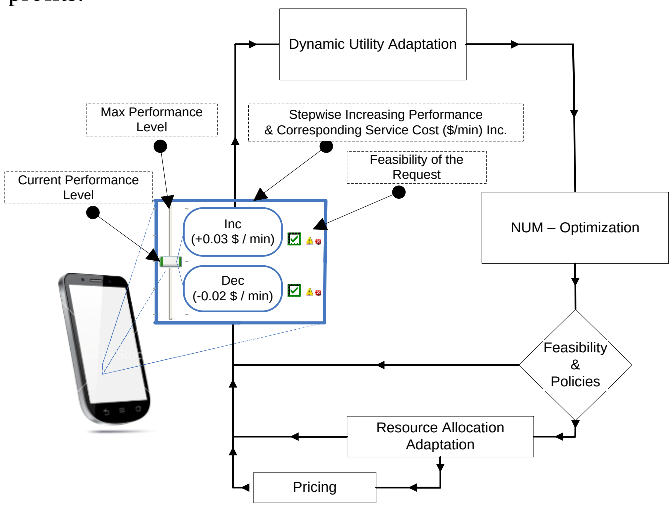

Fig. 4. Quality of Experience Provisioning via NUM

It is important to note that the proposed approach relies on already existing resource allocation mechanisms, acting complementary upon them, i.e. enabling services' dynamic utility adaptation, thus adding minimal overhead to the overall architecture. This allows the adoption and incorporation of the proposed QoE framework to any utility-based RRM mechanism, enabling QoE provisioning in a plethora of wireless networks, ranging from single cell, to autonomic integrated heterogeneous networks. In the following we present how the latter QoE methodology can be extended and transformed to an autonomic framework enabling QoE provisioning in heterogeneous wireless networks.

Initially, following a generic NUM formulation of a resource allocation problem in a wireless single cell (or access point) with N users, each mobile user is associated with a proper sigmoidal, concave or convex utility function $U_i(x_i)$ which represents his degree of satisfaction in accordance to his expected resource(s) x_i allocation (e.g. transmission power, transmission rate, etc.). Thus, to achieve the optimal resource allocation the following fundamental version of NUM is periodically set and solved at the base station, i.e.

$$\max_{\overline{X}} \sum_{i=1}^{N} U_i\,(x_i, \overline{X}, a_i)$$
$$s.t.\ \ \sum_{i=1}^{N} x_i \le X_{\max},\ \ 0 \le x_i(t) \le X_{\max}\ \ for\ i = 1,...,N \tag{1}$$

where $\overline{X} = (x_1,...,x_N)$ is the network's resource vector and X_{max} denotes cell's available resources' bounds due to physical limitations. Finally, a_i denotes the fixed variable(s) that determines the attributes of function U_i such as steepness, inflection point, etc.

In line with [6], to introduce users' subjectivity in their service's utility functions and thus, in the network NUM problem (1), the online dynamic alteration of the attributes of a user's utility is permitted. The Dynamic Utility Adaptation (DUA) of a utility is represented as $U_i\,(x_i, \overline{X}, a_i(t))$, where $a_i(t)$ is a time-dependent tunable parameter, altering in an autonomic and asynchronous manner the attributes of utility U_i (e.g. steepness, inflection point, e.t.c.). The selection of a proper tunable parameter depends on the form of the utility as well as the service that represents, and should be made in line to the principles:

- A user's parameter $a_i(t)$ should be a step wise function of his preferences (i.e. $a_i(t+1) = a_i(t) \pm A_i \cdot I_i(t)$, where $I_i(t)=1$ if the user indicates his preference in time t and 0 otherwise, and A_i a fixed predetermined variable).
- A user's parameter $a_i(t)$ and thus, his utility function adaptation, should affect the network's RRM mechanism in such a way to reflect his preferences, e.g., the higher the value of the parameter that determines the unique inflection point of a real-time user's sigmoidal utility (as a function of its achieved rate) the higher his throughput expectations.

The application of the latter methodology for enabling QoE in a diverse heterogeneous wireless network in an autonomic manner requires the extension and proper formulation of traditional utility based RRM mechanisms to flexible, dynamic and adaptive ANUM QoE-aware resource management mechanisms. In the following the modified NUM problems for WLAN and CDMA networks are presented, while a control loop enabling autonomic QoE provisioning is portrayed.

CDMA Cellular Network. Adopting the methodology presented in [39], the following mapping holds, $x_i \equiv p_i$, denoting cell's downlink transmission power allocated to user i and $\sum_{i=1}^{N} x_i \le X_{\max} \equiv \sum_{i=1}^{N} p_i \le P_{\max}$, denoting cell's overall power constraint. Moreover, the consequent objective function of user's i achieved goodput can be modeled as: $U_i\left(R_i^{\max}, p_i, \gamma_i\right) = R_i^{\max} \cdot f_i(p_i, \gamma_i, a_i(t))$, where $R_i^{\max}$ defines user's i maximum downlink transmission rate, γ_i user's i instantaneous signal to noise and interference ratio (SINR) achieved at the mobile terminal, and f_i is a sigmoidal function of the achieved SINR function representing the probability of a successful packet transmission. The latter intra-cell problem can be solved by directly applying the Lagrangian based algorithm in [39].

Wireless LANs. In a similar way, in the case of WLANs [3], x_i denotes the bandwidth allocation from access point (AP) to user *i* i.e., $x_i \equiv s_i$ and $X_{\max}$ the corresponding AP's maximum effective capacity i.e., $C_c^{\max}$. Moreover, the consequent bandwidth allocation problem can be modeled in tune to (1) as an optimal contention window assignment problem by initially setting $\sum U_i(s_i, a_i(t))$ under proper effective capacity constraints, where $U_i(s_i,a_i(t))$ is a sigmoidal function representing user's *i* degree of satisfaction in accordance to his expected allocated effective bandwidth, and finally solved in accordance to [40].

In both cases, functions *f* and *U* for CDMA and WLAN systems respectively are sigmoidal functions in general defined as:

$$U_i(x_i, v_i, b_i) = c_i \left\{ \frac{1}{1+e^{-b_i(x_i - v_i)}} - d \right\} \tag{2}$$

where $c_i = (1+e^{v_i b_i})/e^{v_i b_i}$, $d_i = 1/(1+e^{v_i b_i})$ and v_i, b_i are two tunable parameters of the sigmoidal function. Parameter v_i determines the function's unique inflection point, while parameter b_i determines function's steepness. Intuitively, the value of function's inflection point v_i, determines user's *i* goodput expectations. Moreover, due to the inherent attribute of parameter $a_i(t)$ to imply users' priority among others in being selected for receiving network's resources by the RRM mechanism and thus, attaining larger goodput values, parameter *v* is selected and exploited by the proposed dynamic QoE framework (i.e. $v_i \equiv a_i(t)$) towards enabling end-users' QoE optimization as follows. When a user experiences low perceived quality of service and requests for a higher service quality then, by decreasing the value of his $a_i(t)$ parameter, in a stepwise manner, user's achieved goodput will be increased, and vise versa. It is important to note that the latter adjustment is performed only when it causes no deterioration of the performance of the rest of the users. In any other case, the user is informed that his request is infeasible.

Having successfully incorporated and properly formalized the QoE provisioning framework to the RRM mechanisms of both CDMA and WLAN networks, by adopting the ANUM principles we define the following control loop, residing at the end-users, enabling autonomic dynamic QoE provisioning in heterogeneous wireless networks.

Quality of Experience Control Loop at the End-User

Step_1. The user constantly monitors his service perceived performance and its corresponding cost via the GUI.

Step_2. If no action is taken, i.e. $I_i(t+1)=0$ go to Step_1. Otherwise, the new $a_i(t+1)$ value is calculated.

Step_3. The service's utility is dynamically adapted and disseminated to the Base Station (or Access Point).

The Base Station (or Access Point) solves the corresponding NUM problem, indicating the feasibility (including policies) of user's request.

Step_4. Resource Management Mechanism allocates the requested resources accordingly. **Go to Step_1**

In case a new user wishes to enter the system, or a new service request occurs, a QoS-aware admission control needs to be performed by the Base Station (or AP).

This way, if there exists a feasible resource allocation vector capable of provisioning the newly requested resources, without deteriorating the performace of the already connected ones, then the new user/service is admitted, otherwise is rejected as infeasible.

As already mentioned, the latter dynamic QoE mechanism, via exploiting ANUM theory, is designed and built as a complementary, yet powerful functionality, allowing the seamless integration to existing wireless systems. Specifically, given the operation of the RRM mechanism in each wireless cell, the QoE mechanism acts and reacts on demand, while its decisions will only be evaluated by the RRM mechanism in the next time slot, thus requiring no synchronization. Moreover, it relies only on already existing locally available information, i.e. the perceived quality of the service the node acquires, imposing minimum signaling overhead, while the autonomic nature of the QoE mechanism implies no dependencies on the size and type of the integrated system, thus suggesting it is fully scalable. Finally, indicative numerical results on the performance and effectiveness of the proposed approach reveal the benefits, both from end-users', in terms of increased QoE, and operator's point of view, in terms of increased profits [6].

4 Network-Centric Decision-Making Approach to QoE Management in Converged NGNs

Trends in the development of telecommunication systems indicate the move towards a converged, multi-service all-IP NGN aimed at offering end users integrated services anywhere, anytime [7]. In this Section we discuss approaches whereby QoE-driven resource-allocation stems from a more centralized, operator-centric view of service and resource control in line with ITU-based NGN recommendations [34] and 3GPP specifications [36], [35]. It is important to note that end users are involved in performing QoE/QoS monitoring and reporting, while optimal resource allocation decisions are made in the network. Thus, QoE-driven domain-wide resource allocation may be considered only as a part of the overall QoE management solution provided by a network.

4.1 QoE Management in the NGN Architecture

The ITU-T NGN architecture [34] is based on the concept of independence between the transport stratum and service stratum. In the service stratum, service control functions are based on an IP Multimedia Subsystem (IMS) [36] and support the provisioning of real-time multimedia services, independent of a given access network. The application support functions and service support functions can impact sessions on behalf of services. During session negotiation, QoS requirements are extracted by session control functions and used to issue resource reservation and authorization requests to the resource admission control subsystem (RACS).

A discussion of the challenges in assuring E2E QoE in NGNs is provided by Zhang and Ansari [1]. The authors focus on E2E communications between end users and/or application servers spanning across different access networks (wireless or wireline) and core networks, belonging to multiple operators and based on multiple technologies. Each network performs its own QoE management, and hence actual QoE experienced by an end user will depend on the QoE management mechanisms (or lack thereof) supported by networks traversed along the E2E session path. Feedback provided by end-users is critical in identifying actual user QoE and providing input for such QoE management decisions, which may further drive adaptive transport functions and application configuration parameters. Different end users will exhibit varying preferences and subjective evaluation for the same application or service, and also across different applications/services. The proposed solution stores per-user, per-terminal, and per-service QoE functions in a QoE management block belonging to the NGN service stratum and interacting with the underlying transport stratum to negotiate network-level QoS.

Skorin-Kapov *et al.* [9], [10] have proposed support for enhanced per-session application-level quality matching and optimization functionality by way of a QoS matching and optimization Application Server (QMO AS) included along a session negotiation signaling path (described in further detail in Section 4.2). This concept is illustrated in **Fig. 5** in the scope of a generic NGN environment. Communication end points are portrayed as either end users or application servers (AS) offering applications and services. In an actual networking scenario, the QMO AS may be included in a service provider domain as a generic and reusable service capability, supporting optimized service delivery and controlled service adaptation in light of changing resource availability, user preferences, or service requirements. A business model is assumed whereby the SP is responsible for coordinating the quality negotiation process, while relying on the services of sub-providers (e.g., 3rd party application/service providers, network providers) in order to secure E2E QoS. Utility mappings for multimedia services (comprised of multiple media components) are specified in a *service profile* and signaled from an application server AS to the core network, or retrieved from a service profile repository. Thus, the *service profile* specifies the service resource requirement (as related to service configuration parameters such as e.g., type of media flows, encodings, resolution, etc.). Service requirements are matched with signaled (or retrieved) user parameters (preferences, requirements, capabilities) specified in a *user profile*, network resource availability, and operator policy when calculating optimal resource allocation requests for a given session. Parameters contained in both service and user profiles represent important QoE influence factors to be taken into account when optimizing QoE. Furthermore, the QMO AS may implement interfaces to additional information sources to retrieve additional contextual data, e.g., user location or charging data, to be included in the QoE optimization decision-making process. A further explanation of the QMO AS, and how its functionality may be utilized as input for the purpose of QoE-driven resource allocation (Ivešić et. al. [8]), is given in Section 4.2.

A related approach to the one previously discussed has been proposed by Volk *et. al.* [25], and studied further by Sterle *et al.* [2]. Volk *et al.* have proposed an automated proactive, in-service objective QoE estimation algorithm to be run by a service enabler AS in the NGN service stratum, based on collection of a comprehensive set of

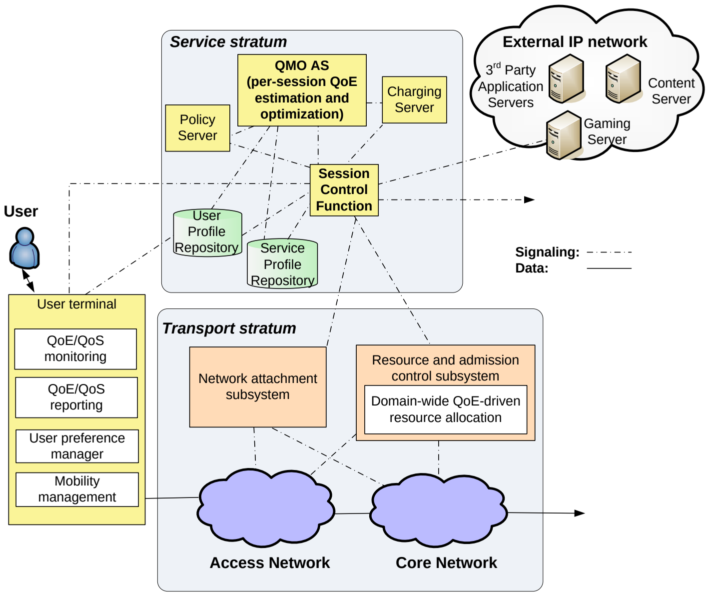

Fig. 5. QoE-driven resource allocation in a generic NGN environment

QoE influencing parameters. The proposed algorithm is invoked along the session establishment signaling path, and performs both QoE estimation and QoE maximization calculations. Attempts to maximize QoE are based on making adjustments to identified quality performance indicators. The authors point out the benefits of conducting overall QoE estimation on an AS running in a service delivery environment as opposed to relying only on QoE estimations conducted closer to the user as including: (1) the wide range of quality related information sources available in the network (e.g., databases providing information regarding user profiles and personalized communication scenarios, service profiles, QoS monitoring, charging related information, operator policy) reachable via standardized protocols (e.g., SIP, Diameter), and (2) the potential for proactive in-service quality assurance and control.

4.2 QoE-Driven Dynamic Resource Allocation for Adaptive Multimedia Services

In this Section we discuss in further detail the approach studied by Ivešić *et al.* [37], [8] related to QoE-driven resource allocation for adaptive multimedia services. By adaptive services, it is assumed that a service configuration may be varied in various ways (e.g., using different codecs, bit rates, resolution, etc.) in order to address the wide variety of terminal equipment, access networks capabilities, and user preferences. It has been noted that in the case of multimedia services comprised of multiple media components, user preferences regarding the relative importance of different components may vary.

The previously discussed QMO AS (shown in **Fig. 5**) is invoked at service establishment and gathers input parameters (related to the user profile, service profile, and operator policies). An initial parameter matching process is conducted to determine feasible service configurations, followed by a utility-based optimization process used to determine the optimal service configuration and resource allocation (referred to as the optimal operating point) for the given service session. The resulting operating point is the basis for the optimal service *configuration*, i.e., the specification of flows operating parameters (e.g., frame rate, codec), resource requirements (e.g., bit rate) and a utility value that represents a numerical estimation of the configuration's QoE. Besides the optimal configuration, several suboptimal configurations are calculated and ordered by their decreasing utility value, thus forming a *Media Degradation Path* (MDP). The goal of the MDP is to serve as a "recipe" for controlled service adaptation, achieving maximum utility in light of dynamic conditions. For example, in the case of a user indicating that he/she prefers audio over video for a given audiovisual service, an MDP may be constructed so as to first degrade video quality in light of a decrease in network resource availability, while maintaining high audio quality. Hence, in light of decreased resource availability, a suboptimal configuration can be activated (thus preventing unpredictable degradation of a service). Since the media components of the service are not necessarily all active at the same time, the configurations are grouped by the *service state* they pertain to, whereby the service state refers to a set of service components simultaneously active during a given time period.

Fig. 6 illustrates an example MDP for a 3D virtual world application with the possibility of activating a video stream or an audio chat. The MDP consists of three service states with several corresponding configurations defined for each state. Since states 2 and 3 consist of two service components each, their configurations should ensure that the available resources for virtual world and video or audio are divided according to user preferences in case of activation of a suboptimal configuration. Similarly, in state 1, suboptimal configurations can use smaller levels of details for the virtual world, rather than causing slow download of a virtual world. In this way, the knowledge about the service and the user is encompassed in the MDP.

Calculated per-session MDPs may be passed on to a resource and admission control entity responsible for making domain-wide resource allocation decisions (we note that possible dynamic changes in user preferences signaled by an end user may lead to recalculation of the MDP). Optimal resource allocation among multiple sessions has been formulated as a multi-objective optimization problem with the objectives of maximizing the total utility of all active sessions described by their MDPs, along with operator profit. The regarding problem class is multi-choice multidimensional 0-1 knapsack problem (MMKP). The problem formulation has been given in [8] in the context of the 3GPP Evolved Packet System (EPS), which maps session flows to one of 9 different QoS Class Identifiers (QCIs) – identifiers standardized by the 3GPP that define different types of standardized packet forwarding behavior. (Note that this is only one possible problem formulation, focusing on discrete optimization and assuming a weighted combination of multiple objectives. Examples of other optimization objectives are discussed in Section 2.2.)

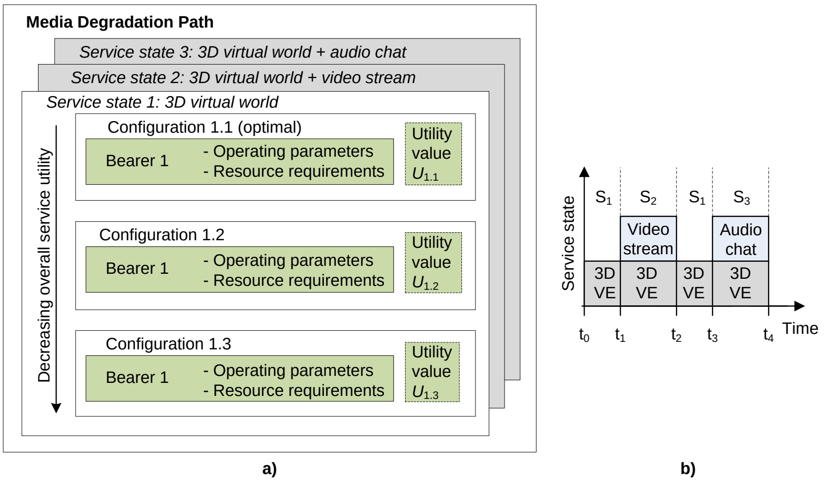

Fig. 6. (a) Example Media Degradation Path, **(b)** possible service scenario (different service states active at different intervals of service execution)

The formulation is as follows. Let n be the number of sessions, p_u the number of configurations of the currently active state of the session u. Let the configuration i of session u have z_{ui} media flows, such that the flows 1, …, h_{ui} pertain to downlink and the flows h_{ui}+1, …, z_{ui} pertain to uplink. Let $\mathbf{b}_{ui} = (\mathbf{b}_{ui1}, \ldots, \mathbf{b}_{uiz_{ui}})$ be the bandwidth requirements of the configuration i, with $\mathbf{b}_{uij} = (b_{uij1}, \ldots, b_{uij9})$ being the vector describing bandwidth requirements of the media component j with regards to each of the 9 QCIs. It is assumed that only a single QCI bandwidth is greater than zero (i.e., j is mapped to a single QCI) while the others are equal to zero. Let $U_n(\mathbf{b}_{ui})$ and $P_n(\mathbf{b}_{ui})$ be the normalized users' utility and operator's profit of a configuration i and w_u, w_{ut}, and w_{pr} weight factors for user u (different weight factors may be assigned to different users, e.g., "premium" and "regular"), users' utility and operator's profit respectively. The normalization is conducted to enable the fair comparison of configurations belonging to different services, by dividing the utilities of all the configuration of the regarding service state from the MDP with the utility of the first configuration (the highest one), and the profits with the profit of the configuration that brings the highest operator's profit (not necessarily the first one). Let B_{kD} and B_{kU} denote the total available bandwidth of QCI k for downlink and uplink respectively. Then, the optimization problem is formulated as:

$$\max \sum_{u=1}^{n} \sum_{i=1}^{p_u} \left\{ w_u x_{ui} \left[w_{ut} U_n(\mathbf{b}_{ui}) + w_{pr} P_n(\mathbf{b}_{ui}) \right] \right\} \quad (3)$$

such that:

$$\sum_{u=1}^{n} \sum_{i=1}^{p_u} \sum_{j=1}^{h_{ui}} x_{ui} b_{uijk} \le B_{kD}, k = 1, \ldots, 9 \quad (4)$$

$$\sum_{u=1}^{n}\sum_{i=1}^{p_u}\sum_{j=h_{ui}+1}^{z_{ui}} x_{ui} b_{uijk} \le B_{kU}, k = 1,...,9 \quad (5)$$

$$\sum_{i=1}^{p_u} x_{ui} = 1, x_{ui} \in \{0,1\}, u = 1,...,n \quad (6)$$

The solution to the maximization problem is the list of the selected configurations from all active sessions (determining in turn the resources to be allocated to each flow), indicated by the binary variables x_{ui}. Since the MMKP problem is NP-complete, finding the exact solution quickly becomes too time consuming. Therefore, dedicated heuristics may be applied in order to obtain good results in short computational time. Additionally, if a large number of sessions are affected by the optimization process, the resulting signaling overhead used to notify session entities of new configurations would need to be considered. A simulator tool used to evaluate the above given formulation is described in [8].

In the context of the NGN, this approach may be applied in the scope of RACS, or applied at a lower level for optimized resource allocation in a given access network, such as a cell area covered by an eNodeB base station in an LTE network. In the latter case, MDP information would need to be calculated at an application-level and passed to lower level resource allocation mechanisms implemented by a base station. Applicability of the proposed approach in the context of LTE resource scheduling is a current area of research.

5 Discussion and Conclusions

Using as a basis the notion of utility-based QoE-driven resource allocation, we have described two different types of approaches which have been proposed to tackle such problems: primarily user-centric solutions, and primarily network-centric solutions. We summarize key differences as follows:

- A user-centric approach takes explicitly into account the user experience while a network-centric approach can be considered as an implicit way of treating QoE. However, it should be noted that certain network centric approaches also support the collection of end-user QoE-related feedback.
- With regards to optimization objectives, network-centric approaches aim at maximization of global, multi-user QoE while at the same time explicitly minimizing operator costs or maximizing operator profit. A user-centric approach would primarily focus on maximizing all users' utilities by meeting in a real-time manner their individual QoE requirements, with network operation optimality implicitly ensured by proper resource allocation mechanisms.
- Scalability in user-centric approach is ensured by allowing the user device to partially participate in the optimization process, while in network-centric approaches scalability can be achieved by considering aggregated objectives (referring to joint consideration of the objectives of multiple users in a given domain).

- User-centric approaches may require more powerful and smart devices capable of autonomic decision-making related to self-optimization of service performance, while network-centric approaches may work even with more conventional end devices and legacy systems. Furthermore, a user-centric approach would be able to operate in a multi-provider environment without direct involvement of the operators/providers (e.g., a user switching from one provider to another to improve QoE), given that such operations are permitted.
- With regards to triggers/events driving resource (re)allocation decision making, in a user-centric approach such triggers may be considered as coming from individual users through their expression of quality requests, while in a network-centric approach, the network will commonly detect when to perform resource re-allocation (e.g., based on identified network congestion, operator policy, input from charging system, etc.). In the latter case, network-based resource allocation decision making may also be invoked based on detected changes in service requirements (e.g., an existing service is modified with the addition/removal of a media component) and in certain cases based on signaled changes in user preferences.

Considering the applicability of the different approaches, a network-centric approach is closer to the NGN/IMS operator-centric model adopted by telecom providers looking to maintain as much call/session control as possible (related both to QoS and charging), while the Internet community is looking towards a more decentralized network model with intelligence being pushed towards the network edges. Increasingly, however, operators are also looking to incorporate user-centric experience management into their network management solutions.

It is clear that in order to estimate true QoE, quality-related feedback needs to be collected from the network edges, i.e., directly from the end users. Consequently, it will be necessary for network-centric approaches to ultimately combine notions described as user-centric given that QoE is inherently user-centric. The user perceived QoE related to delivered services, however, will in most cases depend largely on the underlying network performance. With resource allocation decisions being inherently made in the network, an end node capable of making decisions reflecting how to maximize the given end user QoE (e.g., by incorporating dynamic preferences indicated by end users) can provide valuable input for the network decision making process. On the other hand, certain information which may be relevant in making optimal allocation decisions (e.g., operator policy, subscriber data, service priority, network resource availability) may only be available in the network.

In such a case, information related to QoE management needs to be exchanged among different players involved (users, application/service providers, network providers, etc.). End user benefits include improved QoE, service provider benefits include increased user/customer satisfaction, and network provider benefits include reduced costs based on more efficient resource usage together with increased customer satisfaction.

6 Open Research Issues

While it is clear that user and network centric approaches to QoE-driven resource allocation problems differ as described in the previous section, an open research issue would be to provide a more detailed analysis and comparison of the achieved results when solving the resource allocation problem from a user point of view as compared to solving the problem from a network point of view. Such an analysis would involve determining whether the solutions would be very different or if there would be a certain degree of correlation.

Additional possibilities for future research involve combining the key benefits of user and network-centric approaches in order to achieve a scalable QoE-driven resource allocation solution for future networks. Furthermore, with the advent of QoE-related research leading to a better understanding of QoE models and the correlation between numerous QoE influence factors and QoE metrics, new formulations for solving QoE optimization problems (in particular for new and emerging services) will need to be considered.

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