Manifesto from Dagstuhl Perspectives Workshop 16472

QoE Vadis?

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Abstract

The goal of the Dagstuhl Perspectives Workshop 16472 has been to discuss and outline the strategic evolution of Quality of Experience as a key topic for future Internet research. The resulting manifesto, which is presented here, reviews the state of the art in the Quality of Experience (QoE) domain, along with a SWOT analysis. Based on those, it discusses how the QoE research area might develop in the future, and how QoE research will lead to innovative and improved products and services. It closes by providing a set of recommendations for the scientific community and industry, as well as for future funding of QoE-related activities.

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Executive Summary

This Dagstuhl Manifesto is devoted to future trails that Quality of Experience (QoE) research is expected to take, and lines of activities that deserve to be supported by different stakeholders. Indeed, preceding Dagstuhl Seminars (09192, 12181 and 15022) have had strong impacts on the community forming and joint view onto the QoE domain, including its placement in relation to other areas. An overview is given in the Manifesto's state of the art section, together with a review of evaluation methods and a SWOT analysis. We then turn our focus on the question how the QoE research area might develop in the future, with focus on new applications and services, new methodologies, practical systems and relationships to adjacent research areas. Furthermore, innovative aspects and means to yield innovative and improved products and services based on QoE research are discussed, related to short, medium and long terms. In particular, a marriage between the adjacent areas of QoE and User Experience (UX) is proposed. Besides providing the "Fundamental Law of Quality of Experience", the recommendations for stakeholders in the QoE/UX domain address academic communities, industry partners and public funding agencies, respectively.

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1 Introduction

During the recent decade, the transition from the technology-oriented notion of Quality of Service (QoS) to the user-centric concept of Quality of Experience (QoE) has become an important paradigm change in communication networking research. Simultaneously, the field of QoE as such has significantly developed and matured. This is amongst others reflected in the series of three Dagstuhl Seminars 09192 "From Quality of Service to Quality of Experience" (2009), 12181 "Quality of Experience: From User Perception to Instrumental Metrics" (2012) and 15022 "Quality of Experience: From Assessment to Application" (2015).

The QoE-related Dagstuhl Seminars had a significant impact on the understanding, definition and application of the QoE notion and concepts in the QoE community, for instance with respect to redefining fundamental concepts of quality. That work was performed in close collaboration with the COST Action IC1003 Qualinet [1] that has been concentrating on QoE in multimedia systems and services, and is still actively convening experts from all over the world to regular meetings and exchanges. In particular, this collaboration has led to the widely regarded Qualinet White Paper on "Definitions of QoE and related concepts" [4] and to the launch of a new journal entitled "Quality and User Experience" [2], fostering the scientific exchange within and between QoE and User Experience (UX) communities.

Realising the urgent need of jointly and critically reflecting the future perspectives and directions of QoE research, the QoE-related Dagstuhl Seminars were complemented by the Dagstuhl Perspectives Workshop 16472 "QoE Vadis?", whose output is this Dagstuhl Manifesto. Its remainder is structured as follows: Section 2 provides a state-of-the-art and SWOT analysis of the current research landscape for QoE. Section 3 contains projections of how the area of QoE might develop in the future, and Section 4 postulates how it will lead to innovative and improved products and services. Finally, Section 5 provides a set of recommendations for the scientific community and industry as well as for future funding of QoE-related activities.

2 State of the Art

2.1 Background

In the last years grounding work on the definition on QoE has been performed. Before that time the psycho-acoustic community was referring to quality as the result of a perception and judgement process [9]. In parallel, the networking community was focused on the concept of Quality of Service (QoS), mainly related to low-level network metrics which are indicative for network and/or service performance. For example, the Telecommunication Standardisation Sector of the International Telecommunication Union (ITU-T) defined QoS as follows:

> "Quality of Service is the totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service." [8]

However, the practical use and implementation of the QoS concept left unexplained how the needs of the user are taken into account when characterising the service in terms of QoS parameters. In fact, QoS parameters only describe technical performance of the system or service under consideration, and leave out user perception and judgement. As a consequence, the concept of QoE was developed as user-centric counterpart of QoS.

Members of the COST Action IC 1003 "European Network on Quality of Experience in Multimedia Systems and Services" (Qualinet) [1], as well as attendees of the Dagstuhl

Workshop 09192 "From Quality of Service to Quality of Experience" set out to define QoE, and the discussion between these groups led to the now accepted definition of the resulting Qualinet White Paper:

> "Quality of Experience (QoE) is the degree of delight or annoyance of the user of an application or service. It results from the fulfilment 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." [4]

Based on this definition, a more holistic version that emphasises the process of experiencing has been published in [13]:

> "Quality of Experience (QoE) is the degree of delight or annoyance of a person whose experiencing involves an application, service, or system. It results from the person's evaluation of the fulfilment of his or her expectations and needs with respect to the utility and/or enjoyment in the light of the person's context, personality and current state." [13]

The Qualinet White Paper further elaborates on influence factors (IFs) contained in the definition as follows:

> "Influence Factor: Any characteristic of a user, system, service, application, or context whose actual state or setting may have influence on the Quality of Experience for the user." [4]

This includes the following three types of influence factors:

- "Human IF is any variant or invariant property or characteristic of a human user. The characteristic can describe the demographic and socio-economic background, the physical and mental constitution, or the user's emotional state." [4]
- "System IFs refer to properties and characteristics that determine the technically produced quality of an application or service [10]. They are related to media capture, coding, transmission, storage, rendering, and reproduction/display, as well as to the communication of information itself from content production to user." [4]
- "Context IFs are factors that embrace any situational property to describe the user's environment in terms of physical, temporal, social, economic, task, and technical characteristics [11, 10]." [4]

Delight and annoyance used in the above definitions are two emotional states that may help to characterise a user's current state. However, other dimensions that refer to a user's state (such as for instance arousal and dominance) may also be under consideration. The underlying assumption is that system performance (quantified in terms of QoS) may influence QoE, which in turn has a reciprocal interrelationship with the user's state: the current state of the user may influence the user's QoE judgement (for instance a user in good mood may be less critical towards quality impairments), and a positive or negative user experience may also lead to a change in the user's state (for example a user might get very annoyed due to performance issues). It is further assumed that the user state will have a relation to their behaviour. Behaviour may either refer to the behaviour when actually using a service (e.g. the click path when browsing a web page, on a micro level), or refer to the intention to use the service or the actual use of a service at all, on a macro level. Use of a service on the macro level can be assessed in terms of behavioural economics, and may result in business.

Figure 1 Causal relationship between QoS, QoE, user state, user behaviour, and business.

The behaviour of users when being confronted with systems or services is also the target of User Experience (UX) research, which addresses both functional and non-functional (or hedonic) aspects of experience, and how they relate to system design. Whereas there is a strong relationship between QoE and UX, and strong advances can be expected by combining both principles (see discussion below), we refrain from discussing the state-of-the-art of UX research, and rather refer to the Dagstuhl White Paper on User Experience [14], and to [16].

2.2 Problem Areas and Purpose

The concept of QoE, as defined above, has been mostly applied to multimedia systems and services in which there was a clear assignment of producers (e.g. a TV station), network operators (e.g. telcos), and users. For such services, the main purpose of QoE was to manage scarcity of resources. E.g., a network operator could decide which channel settings to apply in a given situation, thus potentially optimising the QoE for groups of users. This rather "channel-centric" point of view was recently extended to broader and more interactive services, such as web browsing, video conferencing, or online gaming. Such services are far more complex to deal with, as user behaviour and actions impact perceived quality to a significant degree, while user context may be of highest importance.

The causal relationship between QoS (technical), QoE (experienced), a user's internal state (e.g. emotional), user behaviour (observable and trackable), and business, is illustrated in Figure 1. In fact, the relationships between those items may be rather complex, in particular when the roles of the parties are less clearly defined, and when not all factors can be fully controlled, e.g. in Over-The-Top (OTT) services. Nevertheless, it is frequently helpful to address this relationship from one of two complementary perspectives, namely the producer or the consumer perspective:

1. The commercial goal of the producer is to make profit, and QoE should serve that purpose. In practice, understanding of QoE can be used as a part of a general service development process. In the simplest approach, the producer applies a bottom-up method in which system and service characteristics (QoS) are measured and adjusted. The measurements can be done by the producer or some external entity. They ask from the QoE experts how quality of experience has been affected. That understanding is then used to design better services. In a more complex approach, the producer tries to model the whole business process from QoS through QoE and customer behaviour to the profitability of producer business. Then, the chain depicted above can be used to optimise the business by changing QoS (e.g., picking a codec for a particular application) or application features, or to avoid negative business impact (e.g., churn).
2. The consumer perspective concentrates on the question: How well does a service with certain quality characteristics fulfil the needs of the consumers, and how can the service be adapted according to these needs? QoE is an integral part of that issue, but does not provide the whole picture. The needs include happiness, usefulness, and overall well-being of the consumers, amongst others. As also other aspects such as context, emotional state

and expectations affect the consumer's satisfaction, all in all we are only able to control a small portion of the factors influencing a customer's QoE.

2.3 Methods, Models and Tools

In order to optimise services for QoE, experienced quality needs to be quantified, and – to a certain extent – made projectable (which means especially the identification and quantification of those influence factors which are under our control). For this purpose, a number of methods, models and tools have been developed in the past. The following paragraphs provide an overview of the approaches which were followed.

Evaluation methods for QoE can typically be divided into methods involving actual users, and instrumented measurement approaches. Most QoE studies involving users take place in controlled lab settings, which are characterised by high internal validity and a high level of control, and typically manipulating one or more independent variables. However, other studies have been emerging which aim at increasing the ecological validity in QoE studies, to reach a higher number of users and in some cases to gain a better understanding of relevant influence factors. These include approaches for data capturing (of implicit and/or explicit, self-reported user feedback, data from the application and network conditions, etc.) on a mobile device "in the wild", studies in a lab environment designed to resemble the natural context of use to a higher degree, and analysis through crowdsourcing. The focus of QoE evaluation can moreover have different degrees of granularity, in terms of the considered temporal dimensions (e.g., longitudinal vs. instantaneous, cross-sectional time-span). Currently, most QoE studies focus on a short time span (using short stimuli and evaluations at one moment in time), but the interest in the long-term development of QoE is increasing and requires other methods, outside of the lab. Especially for regularly-used services the consideration of a single usage episode is not enough, and methods capturing a number of subsequent usage episodes need to be used [6].

2.3.1 Evaluation methods involving users

Typically, QoE evaluation studies involving human observers (sometimes called "subjective evaluations") are based on a series of recommendations from ITU regarding the assessment of quality in different application domains (for traditional services), containing information about how the experiment should be conducted, which scales should be used, what the test environment should look like, etc. The ITU-T P series and the ITU-R BS and BT series of Recommendations provide details in this respect. Participants in studies are exposed to certain stimuli (e.g., 10 second video excerpts) or interact with a system under certain test conditions, and are then asked to rate (mostly quantitatively) the experienced quality. Mostly, quantitative feedback is collected from test users, yet there have been some studies adopting a more qualitative approach. Through statistical analysis of the collected data, the impact of the controlled independent variable(s) can then be quantified.

2.3.2 Instrumental evaluation methods

Instrumental evaluation methods do not involve explicit user feedback, but provide data which is expected to be linked to experience, and which potentially allows to estimate QoE. The data can stem from different angles:

- *Measurements taken from the user*
  - Behavioral measurements: Such measurements can include, e.g., the number of clicks, the viewing behaviour, user actions (e.g., muting video, refreshing a page), errors in executing a certain task, collecting gaze information (e.g., through eye-tracking), etc.
  - Physiological measurements: Increasingly, the usefulness of physiological measures and tools for QoE studies in general, and in particular to investigate how it relates to emotion as one aspect of a user's state, has been investigated. These include, e.g., Galvanic Skin Response (GSR), heart rate variability, Electroencephalogram (EEG), Near-InfraRed Spectography (NIRS), Electromyography (EMG), and functional Magnetic Resonance Imaging (fMRI).
- *Measurements taken from the system*
  - Signals: Signals, such as video, speech, audio, but also other environmental signals captured by the system (e.g. in the case of Internet of Things applications) provide a rather comprehensive and continuous description of what information is transported to the user. Access to these signals may, however, sometimes be difficult, and the user reception of these signals (such as viewing or hearing characteristics) need to be taken into account when estimating their impact on QoE.
  - Parameters: Parameters, such as codec, throughput, bandwidth, buffer size, delay, etc., are performance metrics (thus, QoS) which may be related to QoE.
- *Measurements taken from the context*
  - These can include measurements that provide information about the context in which the experience takes place, e.g., location, temperature, static vs. nomadic use, etc., using different types of sensors (often used in combination with the collection of explicit user feedback through self-reports, e.g., in the Experience Sampling Method).

2.3.3 Prediction models

Prediction models *estimate* QoE or certain aspects of it, mostly on the basis of measurements taken from the system. Only few such models are known which use measurements taken from the user or from the context as input information.

- Signal-based models: Models where the signal represents the model input can be distinguished according to the availability (or not) of a clean, non-degraded reference signal
  - Full Reference: Full reference to compare the signal to is available.
  - Reduced Reference: Reduced reference (i.e. a simplified version of the non-degraded reference) is available.
  - No Reference: Only the degraded signal is available, no reference to compare to.
- Parametric models: Parametric models aim to predict QoE for a certain scenario, based on input parameters related to the system or the signal. Depending on whether the parameter values are measured during system operation, or estimated from planning values of a new system, these models can be classified into
  - Monitoring models
  - Planning models

Planning and optimising QoE is the task of **QoE management**. Up to date, this has commonly been addressed from complementary perspectives [15]. On the one hand, QoE-driven application management addresses monitoring, control, and adaptation on the user and application host/cloud level, by optimising the quality of OTT services [7]. On the other hand, QoE-driven network and system management mechanisms concern vendors, providers and operators, with the aims to obtain insight into impairments perceived by users and their

relationships to QoS [5] and to identify root causes of potential QoE problems. QoE control and optimisation mechanisms deployed in the network focus on optimised network resource allocation and efficiency, admission control, QoE-driven routing, etc. Those mechanisms are especially critical for wireless and mobile networks, characterised by variable resource availability and inherent resource limitations [12].

However, there is an ongoing need for research and development efforts in the QoE management domain in order to yield approaches that overarch applications, services, systems and networks. For this, there are promising integrated and cross-layer approaches combining both application and network management mechanisms [3], in particular in the context of new networking paradigms such as Network Function Virtualisation (NFV) and Software Defined Networking (SDN). With services being delivered via a chain of different providers, there is a clear need to address the potential of QoE management mechanisms in the context of new business models. Specifically, collaborative models between the network and application service providers may improve QoE with a positive impact on the user state. This calls for the definition of specific interfaces where QoE-related data is exchanged between the stakeholders, cf. Section 4.2.

2.4 Applications

The application areas for QoE may be classified into consumption and interactive (real-time and non real-time, e.g. email) services. Regarding the former, visual consumption services, such as video streaming, television, and image transmission dominate the field, followed by audio and data transmission such as file transfers. Recently, the incorporation of QoE concepts in multi-sensory, augmented and virtual reality consumption services has been observed. On the other hand, interactive services such as speech (in particular telephony), web browsing and other web applications, online gaming, cloud services, and video conferencing have been in the focus of QoE research. Given the expected major impact of Augmented Reality (AR) and Virtual Reality (VR) applications in the near future, preliminary works on the evaluation of the quality has also been conducted in this area. Furthermore, there are new applications of QoE in emerging contexts such as those where Internet of Things (IoT) applications are deployed. It has to be noted that the level of maturity of QoE research, methods, models and tools for these emerging services is far lower than for the "classical" video, speech and audio services.

2.5 SWOT Analysis

A SWOT analysis has been carried out by the attendees of the Dagstuhl Perspectives Workshop 16472 "QoE Vadis?". The following statements represent unfiltered viewpoints and judgements of the participants.

Strengths

QoE concepts have matured. In particular, QoE definitions have evolved to a stable, well-accepted status. Influence factors and QoE as well as quantification of quality improvements are well-understood. Practically usable methods and tools for a set of applications have been developed, with practical impact. As a consequence, QoS-driven network and service management are gradually being replaced by QoE-driven management techniques, providing

Figure 2 Evolution from QoS to QoE to QoL.

telcos (amongst others) with better methodologies. There is an increased focus on bringing technological innovation closer to the end-user/customer, for instance through more user-centric design processes. The community has evolved towards a multi-disciplinary group, which is reflected by the methods used. Also, there is a clear economic relevance.

Weaknesses

We perceive a set of lacks, for instance of a theoretical framework to guide research and design, especially in new application areas; of large and open databases to be used for QoE analysis; of longitudinal QoE studies and models; and of measures to assess the user state and the implications of QoE for user behaviour. Furthermore, strongly interdisciplinary aspects not sufficiently covered so far, such as interaction design; user emotions; cognition; needs; preferences; and behaviour. Studies suffer from low degrees of generalisability, for instance between lab studies and studies in the wild; between similar services; due to application-specific models; and due to fast changes in the services and their settings.

Opportunities

More interdisciplinary work will enable more accurate models and help to get a better understanding of the influence factors. Knowledge can be transferred to enable QoE-prediction in new application areas (within and beyond multimedia). The business potential of QoE can be enhanced. Consumers can be provided with better consumer information on communication services. An approach for "Quality of Experience by design" can be developed. Likewise, user happiness and well-being can be increased ("happiness by design"). Also, the "tyranny of the *Mean* Opinion Score (MOS)" may end, by modelling and exploiting individuality and variations among users instead of staying with MOS-typical averages and aggregations.

Threats

User privacy might be affected. QoE may be considered solved, or not relevant for new application areas. Implementing QoE might not be cost-effective. There are signs for an identity crisis of QoE: A clear target of QoE is still missing; it is difficult for experts and non-experts alike to capture QoE concepts; and the position and visibility of QoE as compared to adjacent areas (e.g., UX, Customer Experience) may be considered weak.

3 How the QoE Research Area Might Develop in the Future

The state-of-the-art analysis exhibited an evolution trend from QoS to QoE, and lately to QoL (Quality of Life) as sketched in Figure 2, indicating an increase of QoE involvement into the society and into people's daily life. New concepts, methodologies and principles are expected to bring QoE research towards this direction.

Following the SWOT analysis, several research areas are proposed for QoE to

- cover a wider range of applications and services (breadth);
- build more accurate models and develop new methodologies to gain better understanding of users and predict QoE (depth);
- generalize the results to more practical scenarios and provide more feasible solutions to stakeholders (practicality);
- establish a closer partnership with adjacent research areas to broaden the studied perspectives and enhance research efficiency (efficiency and visibility).

3.1 Expansion to New Applications and Services

Traditional QoE is focused on multimedia services. With the development of new enabling technologies (IoT and immersive technologies, such as augmented reality, virtual reality, 3D presentation and capturing), new services emerge with new formats and requirements. QoE research needs to move beyond traditional multimedia services and extend to new emerging services and applications such as E-Health; work experience; learning and education; and immersive services and communications, in new scenarios like smart city and smart home. New models and methodologies are required to describe the QoE of these new services and to capture the key quality issues (or influence factors).

The challenges are two-fold. First, the quality features of these new services are either unclear or have only partly been investigated. As a consequence, it is hard, if not impossible, to predict and characterise the potential quality dimensions in order to model them. Second, new services are developed and launched at a speed (in a scale of weeks/months) much faster than QoE research (in a scale of years) can be performed. Conventional QoE research approaches take a long time to finalise and standardise QoE assessment methods for a specific service (e.g., identify quality dimensions, run lab tests, standardise subjective test methods, develop prediction models, etc.), which is no longer suitable in the new era. In order to reduce the risk of significantly lagging behind the service development, QoE has to come up with new approaches to speed up the process, i.e., building functional/feasible QoE models for new applications quickly.

3.2 Development of New Methodologies

In parallel to the development of QoE models for new services, there is also a need to develop new methodologies to investigate the aspects that are critical for QoE research but were not (fully or precisely) tackled by previous QoE work.

One of the biggest challenges in QoE is the interrelation between human emotions, cognition, attitude and behaviour, and the role of QoE in that context. Its study requires a multi-disciplinary approach, involving expertise from user experience (UX), social science, different sub-strands (e.g. experimental, social, etc.) of psychology, physiology etc. In order to develop techniques that can formalise, model, measure and analyse human behaviour, several factors need to be addressed. The first question is how to describe the user behaviour at both micro- and macro-level. Second, since many services tend to be interactive, then the question arises how to describe the interactive activities between users, between users and machines, and how to evaluate the impact of such interactions. Third, user behaviour is a continuous and complex process. Current work mainly assesses QoE in a short term

(e.g., from ten seconds to a few minutes). Practical service usage spans over a longer time period, which complicates the user behaviour and thus requires new models to capture the user affective state and the dynamic behavioural variations. Fourth, it is still a somewhat open issue how to practically measure the user behaviour, e.g., what data should be collected from the system and from the users, respectively, and how the user data should be collected, e.g., implicitly or explicitly.

User behaviour is one key factor influencing QoE. There are many other factors contributing to QoE which are required to be investigated, some of which have already been mentioned in the state of the art section earlier in this document. Representatives are mobility for mobile broadband services and non-multimedia-type factors for new IoT use cases. Considering that the overall QoE is a compound effect of these factors, research has to be done to understand both the impact of individual influence factors and their combined impact. The resulted high complexity requests more advanced approaches of data analytics. Finally, QoE assessment should also become more capable of evaluating the impact of adaptive approaches (e.g. dynamic adjustment of the performance in real time), which are more commonly used by service providers. Current evaluation methods are not suited for this purpose, and therefore need to be adapted and extended, such that the impact of adaptive operations on the overall QoE (either during a session or over a number of sessions) can be investigated.

3.3 Generalisation to Practical Systems

In order to make QoE visible and valuable to industry, QoE needs to provide more insightful and practical solutions to practitioners besides theoretical and experimental results. As a response to the request from service providers and operators, a repository of objective models and/or a toolbox could be designed and then used by them to predict QoE for different services, quantitatively and qualitatively. However, since many mature QoE models were developed in the lab environment or in a small-scale scenario for specific services, several issues are raised up in regard to how to generalise these models to practical systems with a much larger scale while maintaining similar performance and usability.

First, a large-scale QoE framework cannot support the same complexity and resource consumption as subjective lab tests can. More objective (or hybrid) assessment models are needed to embed QoE functionalities into a system. A possible approach could be to i) define a set of key influence factors or measurable metrics that are sufficiently powerful to study the QoE of the services; ii) give a quantified indicator of QoE; iii) derive a prediction model to calculate the QoE indicator from the defined measurable metrics.

Second, data collections and QoE predictions have to be automated in order to enable large-scale QoE measurement and monitoring. This may require association with other technologies like machine learning and IoT that will allow for automated and intelligent monitoring, prediction, and improvement of QoE.

Third, current QoE models and results are limited by their application range. It is hard to transfer a QoE model from one to another, different service. A more generalised framework is demanded to facilitate QoE prediction in next generation networks with diverse services.

Finally, the innovation cycle of QoE model creation for novel services and application domains clearly needs to speed up, without of course lowering the quality of the models themselves. Several examples from the history of QoE, including, e.g., the evolution of sound quality models; more than one decade of research on the E-Model; or the tedious struggle

towards modelling QoE for IPTV demonstrate the need for significant further effort to be put into innovation cycles with both sufficient speed and quality to render results that are useful to the practitioners in the field.

3.4 Relationship to Adjacent Research Areas

Facing the challenges of speeding up the QoE model development process and automating QoE monitoring and prediction in practical large-scale systems, QoE needs to partner with adjacent areas (e.g., UX and machine learning) to seek more effective methods and models.

UX and QoE have many commonalities, and are complementary to each other (UX is more into qualitative assessment whereas QoE is focused on quantitative evaluation). It is natural to build a bridge between QoE and UX so that transferable knowledge, tools and results can be exchanged and reused in both areas. By identifying the areas with common interest (e.g., VR/AR), QoE may adapt well-developed UX methodologies and tools to assess quality dimensions of new services, and modify/apply UX methodology and results to the engineering/algorithmic perspective of QoE.

Analytical tools are necessary for successful QoE assessment. As a significant use case to improve QoL, the special features and demand of QoE should be brought to the machine learning/AI/big data community. The high complexity, the multi-dimensional and multi-sensory features, the inclusion of user behaviour in the generated data and the demand for explicit interpretation of analytical outcomes may require the development of new advanced machine learning algorithms.

In addition, a physiological point of view is useful to describe how expectations and experiences are formed. Business and economic perspectives will help to reveal the relationships between QoE, satisfaction and service provisioning, e.g., willingness to pay, charging and pricing, resource allocation, operation planning and optimisation (which solution is more cost-efficient, fewer customers with high quality services vs. more customers with low quality services?), and the impact of net neutrality. Specifically, means have to be found to incentivise different stakeholders to cooperate in the effort of improving QoE.

As an example, a concept of "QoE by Design" or "QoE in Design" is proposed that basically covers all the above aspects. The idea behind "QoE in Design" is to integrate QoE into the service design process from the beginning, instead of waiting until the service is launched. During the design phase of new services, QoE dimensions will be identified, including the finer-grained user behaviour changes. Functions will be added to instrument systematic measurement of the identified QoE dimensions in a large-scale context. During the proof of concept phase, beta users will be included in the process of defining service characteristics and field tests will run with representative panels and reliable prototypes. After the services are launched, the system will continue monitoring quality dimension measures and user behaviour, which will feed back to refine and modify the service design.

4 How QoE Research Will Lead to Innovative and Improved Products and Services

As outlined in the state-of-the art, the consideration of QoE leads to several benefits for the stakeholders. From a technical point of view, QoE-driven products and services allow to

minimise annoyance and to solve technical problems that hinder good user experience and QoE, e.g. by utilising QoE monitoring, while user experience monitoring barely exists.

However, QoE research has focused mainly on the **QoE ego-system** rather than on the **QoE eco-system**. This means that QoE has been mainly addressed within a single session on a short-time scale for a single user of one concrete application. Thereby, different facets have been addressed by the research community like subjective user studies to identify QoE influence factors for particular applications, QoE models to quantify and capture the effects of those influence factors, and QoE monitoring approaches to provide means for QoE management for improved QoE.

In this section, the question is addressed how QoE research will lead to innovative and improved products and services. To this end, the entire QoE eco-system and the stakeholders along the service delivery chain to the end user need to be considered. In comparison to the traditional QoE ego-system thinking, the QoE eco-system faces manifold research challenges. It is required to extend current QoE research by the different perspectives of the QoE eco-system, and to incorporate user experience. The following items are the market needs where QoE may have an impact.

- The service / system providers (operator, media content producer, vendors, software developers, communities of users) need methodologies and tools to manage the quality of provided services in order to be more competitive.
- Current and future products and services should focus on customer experience, reflecting the business value of QoE.
- People's quality of life needs to be central in the services and products design, addressing the societal value of QoE.

4.1 Analysis of Technical Infrastructure and Artefacts in Requirements Analysis

To come up with innovative and improved products and services, the workflow in the design process of the service and products needs to be revised in such a way, that QoE is included in the process, and put into a relationship with technological aspects.

As an integral part of the requirements analysis of products and services, ethnographical observations have to be carried out to understand the workflow of a specific domain in context, and to infer recommendations whether and how a technology can be used to improve the workflow, and thus the happiness of stakeholders. Typically, stakeholders' behaviours and activities are the focus of observations and analysis. If existing infrastructure (e.g., internet connectivity) and technological tools (e.g., desktop) are considered as 'background' (i.e. not serving as data collection tools or objects of evaluation), they are not analysed at the same granularity level or as systematically as stakeholders' behaviours/activities. However, such background artefacts can have significant effect on stakeholders. QoE can provide a model how to systematise or parameterise these potential factors to bridge the gap.

4.2 Innovative Aspects Through QoE Research

QoE research introduces a facet of innovative aspects. The transition from the QoE ego-system to the QoE eco-system incorporates all stakeholders and their needs. Thereby, QoE is supposed to **remove technical barriers** and allow for a **better communication** between

stakeholders. **QoE models** enable a-priori testing of new applications, especially interactive applications, in different contexts, and thus provide a better holistic point of view on user delight or annoyance.

The introduction of QoE-enabled Application Programming Interfaces (APIs) and semantics through a **semantic layer** will allow relevant stakeholders – providers, operators and customers – to have **transparent access** to agreed-upon QoE-relevant data. Such a semantic layer with open APIs allows for new or improved services and products in the market, such as applications/services and their management. Thus, the semantic layer is a key enabler for **increased competition on fairer grounds** amongst different providers. Mutually agreed-on QoE data may serve as key differentiator and bring the customer in a stronger position, being able to choose between different competing providers. For instance, **QoE-driven recommendation functionalities** can be implemented on that layer, e.g. to offer the user contents across platforms, while **real-time QoE feedback** allows for dynamic (re-)configuration of applications, services and underlying resources in order to yield a sustainable balance between QoE provisioning and related spendings. Obviously, QoE-enabled APIs have the potential to foster the creation of the QoE eco-system, and to act as key enabler for QoE improvements and innovation.

By taking into account QoE, the provider demonstrates that it **cares about the user**. This has also the effect of making the users keener on making their data available. On the one hand, the use of user data to quality-related goals is restricted to limit privacy concerns. Thereby, data may also be shared at an aggregation level at the upper layers. On the other hand, the users may be provided with information related to QoE which may e.g. bring insights when facing QoE problems or enable the user to overcome QoE issues when using a service, e.g. switching off background applications. As a result, regulators will be pushed to change the **privacy regulations** on the usage of user data, thereby balancing the need for open data against privacy requirements.

4.3 Means and Approaches Fostering QoE-driven Innovation

These aspects can be introduced along with the following items on different time scales.

(a) **On the short term**, within the next five years, a variety of means and approaches will foster QoE-driven innovation and improvement of services.

One key element is **machine learning and data analytics**. This approach can be used to predict QoE on the basis of system and user related data (e.g., user behaviour and status). Thereby, user comments and feedback from external fora can be exploited to assess the perceived quality and user behaviour. **Sentiment analysis** may then be a promising approach for obtaining an enriched data set for QoE assessment. But QoE also represents a useful input to the use of machine learning and data analytics in (i) the assessment of the user experience and user behaviour, and (ii) in the management of the network.

In general, **better QoE models** are another key enabler for innovation and improvement. Key aspects are an extension of QoE models that match different user profiles and implement personalisation. Furthermore, QoE models need to address the different perspectives of the QoE eco-system, e.g. by incorporating user behaviour as part of the model, or by identifying and including relevant internal and external context factors including physical, cultural, social, or economic context. As an example, QoE models used in WebRTC need to be improved, impacting a large number of WebRTC-based applications.

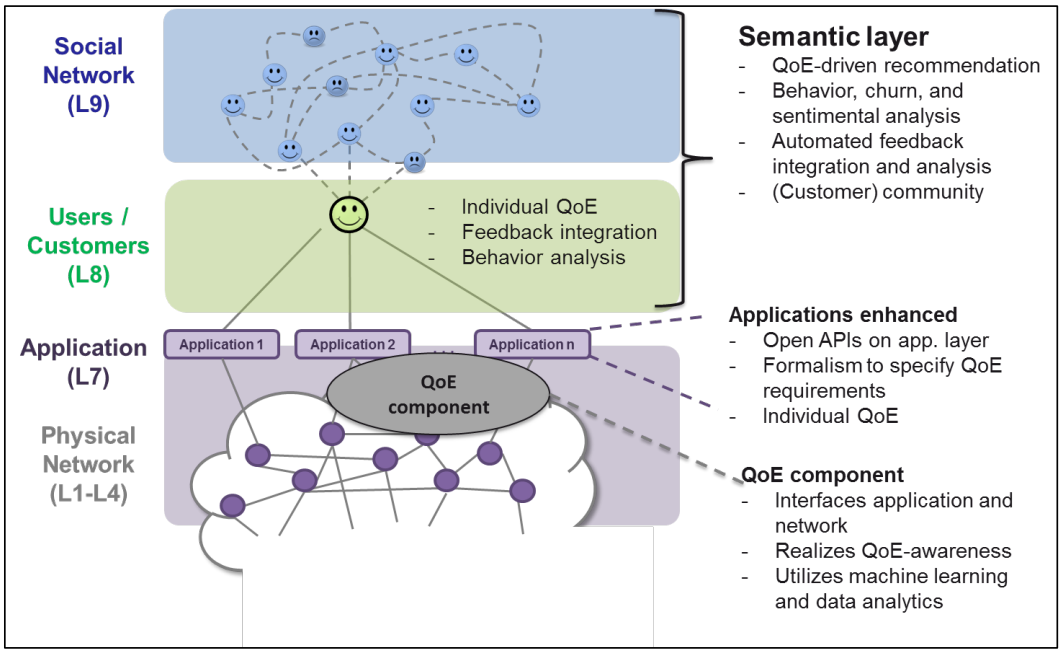

Figure 3 Semantic layer on top of the network layers.

Those QoE models need to result in **direct and operationable methodologies and tools** that improve existing or upcoming products (e.g., concrete adaptive streaming improvements; coding). Another innovation example is the compensation for poor behaviour (in terms of QoE or user experience), leading to an **overall better experience with the service in the longer term**, after facing temporary disruptions (e.g., vouchers; explanations; discounts). QoE can drive the design and implementation of applications and services, for instance to avoid unexpected or aberrant behaviours when the network behaves badly (e.g., by providing tools and mechanisms to allow for graceful degradation of the user experience). The tools and techniques need to be **transferred to practitioners**. Beyond academic dissemination, rather self-contained, **vulgarisation/popularisation** efforts are required to reach all stakeholders and practitioners.

(b) On the medium term (i.e. within 3–7 years), various innovation enablers and technological solutions are foreseen which partly rely on the short term means. Innovation is fostered through improved competitiveness by improving QoE/UX in new or existing services.

Such a major innovation driver is a **semantic layer** which interfaces the different stakeholders and allows exchanging information, which is illustrated in Figure 3. The key elements are **open APIs** in the application layer and a **formalism to specify QoE requirements**, to create QoE-aware services and applications. For example, APIs for telcos will allow services to specify requirements, which can innovate service assurance for OTTs. QoE could be a critical component in these approaches. Getting closer to the user and the user experience can be realized via sophisticated **feedback integration** to collect and analyse user experience data. As part of this semantic layer, measurement approaches and tools are provided incorporating knowledge of the QoE key influence factors and QoE models.

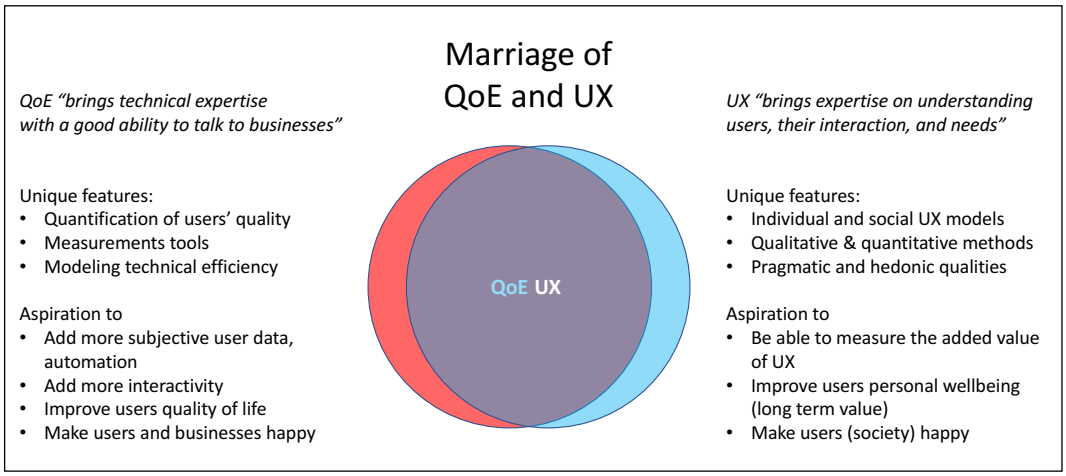

Figure 4 Marriage of QoE and UX.

From the perspective of a provider, QoE is an enabler to **customer relations**. One way is to gather information about the users' personal experiences and to leverage existing models for "average users". **Personalised QoE prediction** may be done in a general enough way, and packaged for use by concrete services. Another way is to **analyse customers' feedback** and mapping it to QoE disruptions (e.g., to check historic issues). Such a **QoE tool for customer relations** supports the improvement and innovation of services and products. This also includes customer communities. The building of customer communities may be promising. For example, if one can provide QoE estimates in real time, that information can be provided to the user, and their feedback can be gathered. It is a research topic to investigate which feedback would be useful to collect or which compensation types would be appropriate for the situation.
With telcos transitioning to **QoE-driven policies** for e.g., network design, base station deployment, etc., tools are required for realizing those policies. Thereby, QoE could complement these activities, focusing on the technology and performance requirements of e.g., proposed designs. QoE research provides a bridge to industry to foster innovation, e.g. in the MPEG-5 standard for multi-sensory services.

(c) **On the long term**, a **"next generation of QoE/UX-aware" designers and engineers** are to be formed, who will be able to use the tools and techniques of QoE research to better develop new products. This requires to educate students accordingly. **QoE by design** or integrating **QoE in the design** should be considered as fundamental part of the workflow in the design process of the service and products. This also means to merge the UX and QoE communities' expertise, objectives and vision, the **"marriage of QoE and UX"**, which would help to improve on existing unique features, follow aspirations, and link addressed stakeholders, as illustrated in Figure 4.
The marriage of QoE and UX may lead in the long-term to the next generation of QoE/UX-aware designers and engineers who are able to fulfil new requirements:

- **Teacher** of future generations: requires to establish the educational environment to train them about QoE/UX.
- **Developer** of new tools to enable innovation: requires to follow an integrated approach of QoE/UX in the development process.
- **Manager** to convey the ideas to businesses: requires to communicate the added value of QoE/UX to businesses and customers.

Finally, the combination of QoE and UX will foster and improve services and products from different domains: Multimedia/Entertainment/Gaming, IoT/Wearable Interfaces, Multisensory Interaction. This may allow to integrate current UX efforts into QoE research towards user acceptance, trust, safety, emotions, user wow, engagement, fun, flow, immersion, and presence.

5 Recommendations for Stakeholders in the QoE/UX Domain

Quality of Experience (QoE) and User Experience (UX) are increasingly gaining importance from several viewpoints corresponding to the different stakeholders in the ecosystem. In this final section, we provide recommendations towards enabling the development of the domain.

More specifically, we consider three stakeholder categories in detail, i.e. scientists working in the field, industry, and public funding agencies. For all them, the "Fundamental Law of Quality of Experience" applies, which, thriving on notorious historical examples, could be formulated as follows:

R0: It's the end user, stupid!

Putting the end user into the centre of the innovation cycle is indispensable for the sustainable success of the future service-oriented industry as a whole, as s/he is the one with complete information about service experience, and who eventually has to pay for it. Hence, we strongly recommend that any stakeholder focus strongly on the end user, his/her expectations and real needs.

5.1 Academic communities

R1: Promote interdisciplinary research.

It has become abundantly clear that much closer collaboration needs to take place between the involved scientific communities, i.e. QoE, UX, and behavioural economics. We recommend the organisation of workshops and symposia involving all these communities, for example in a setting such as Dagstuhl. This, along with joint research efforts, will lead to the sharing of knowledge, methodologies and tools that is needed to further the development of the research agenda and impact. As a result, a solid theoretical and practical foundation for both QoE and UX communities will be achieved. At the same time, joint publication venues for all relevant topics related to QoE and UX shall be provided, along the lines of, e.g., the recently founded "Quality and User Experience" journal [2].

R2: Provide access to open data and tools.

Despite the associated difficulties, we emphasise the importance of gathering QoE-related data from operational services and applications, which will enable us to, e.g., better understand key influence factors, develop more accurate models for QoE, and effective QoE management mechanisms. In addition, open source tools for supporting the creation, sharing and evaluation of data should be developed and maintained by the scientific community.

R3: Drive investigation beyond the comfort zone.

While the current state of the art already provides a comprehensive toolbox for QoE research, it is considered extremely important to emphasize topics and methods outside of the established framework. For instance, future research should address a deeper understanding of the time-scales involved in QoE and UX modelling, as well as the use of bleeding-edge analytical, statistical and modelling methods (including big data, deep learning, and other machine learning techniques). While this might offer an opportunity to speed up the often time-intensive process of creating appropriate QoE models, especially for new application fields, it will be pivotal to also increase the quality of the models themselves, which provides an equally challenging task.

5.2 Industry partners

R4: Turn QoE from reactive to proactive research.

With most current services, QoE is at best an afterthought, often resulting in user frustration and churn. Hence, inspired by the concept of "Security by Design" which has become prevalent in modern services, as it helps dealing with a large number of security problems, we propose fostering a "QoE by Design" approach to service development, whereby QoE informs the service or system design choices, so as to facilitate a positive user experience. Thus, QoE needs to become an integral part of system and service design, which in turn requires resources, dissemination and exploitation efforts, and expertise from other domains, such as UX. Hence, our main recommendation for maximising the impact of QoE and UX in the business domain, is the adoption of the "QoE by Design" approach described above. This will enable the development of innovative QoE-aware offerings.

R5: Implement mechanisms for direct quality feedback.

We strongly recommend investing efforts in raising awareness of the importance of QoE for end users, and get them involved by promoting constructive feedback to the service providers, instead of simply churning. To this end, quality feedback gathering mechanisms could be easily integrated into all sorts of applications, enabling users to directly and easily submit QoE-relevant feedback to the service provider(s). In analogy to the wide-spread "Help" or "Like" facilities, there could be a "Quality feedback" mechanism that provides an intuitive means for users to give feedback about their quality of experience in a timely and unobtrusive manner.

R6: Join forces within industry.

Exchanging QoE-related information between business stakeholders (e.g., telcos, over-the-top providers, infrastructure providers, content providers) towards the implementation of QoE monitoring and management solutions helps optimising services and thus creates a win-win situation for all sides. To this end, we encourage the creation of an openly accessible repository for vulgarisation of domain knowledge and dissemination of tools and methods, especially to foster the adoption of the "QoE by Design" approach. Further, we suggest the integration of customer experience management work-flows. Moreover, the business implications of QoE and UX need to be further studied, and their value communicated

in a clear way to industry players, especially concerning sustainable business models and opportunities. Legal considerations, in particular related to network neutrality, need to be considered in this context as well.

5.3 Public funding agencies

R7: Support QoE research as scientific approach to a substantial and unsolved problem.

For early multimedia services, Quality of Service (QoS) provided a coarse approximation of user-perceived service quality. This has become unsatisfactory especially since the explosive development of new services and applications, each with very different needs. On the other hand, based on the ubiquity of fast Internet access, these services play an ever more important role in the daily life of users and our society. It is therefore essential to ensure that the quality experienced by the users is up to their expectations, both to avoid user frustration, and also its negative impact of business. Hence, QoE has to go far beyond merely being "QoS 2.0", which requires significant on-going interdisciplinary efforts, where – for instance – the "QoE by Design" approach introduced above will provide a significant step forward.

R8: Understand QoE as key paradigm for the future digital society.

New technologies such as virtual and augmented reality, ubiquitous computing and the Internet of Things have a strong potential to improve services in key areas of our society, like e-health, ambient assisted living, smart cities, etc., thus improving the quality of life to citizens. However, if these new applications fail to meet the quality requirements and expectations of their users, their impact may be severely limited, and worse yet, it may have negative and even fatal consequences (in critical areas such as telemedicine, or self-driving vehicles). Hence, we suggest supporting industrial or research endeavours that lead to openly accessible means for implementing the proposed QoE by design approach. At the same time, research into privacy and trust related issues involved in the collection of data for QoE purposes will ensure that the rights of the users are upheld. Finally, from an inclusiveness point of view, QoE technologies will help ensuring that all user groups, including marginalised ones, receive adequate service quality.

R9: Create a cross-disciplinary and cross-institutional research community.

We recommend the promotion of educative actions supporting the formation of new professionals and early-stage researchers in the joint QoE and UX fields, so as to address the needs discussed previously. These efforts should actively involve a broad range of different disciplines, ranging from communication technology to humanities and arts, and should be based on the cooperation of different faculties and/or academic centers.

R10: Support market diversity and sustainability.

QoE and UX are expected to be key aspects for the adoption and sustainability of innovative technologies and services, which will increase user engagement and satisfaction, as well as user acquisition and retention, which in turn will improve the profitability of businesses. Furthermore, easy access to QoE technologies will enable smaller industry actors to differentiate their offerings and be able to compete with larger incumbents. The integration of QoE and

UX will help address the business viability (as per the above), technical feasibility (exploiting QoE enablers) and desirability (considering UX) of new services, and allow for their success.

5.4 Conclusions

Hence, summarising briefly, we believe that further developing QoE has the clear potential to provide a key contribution for the evolution of the future digital society. It will require joining forces both in research and industry through broad interdisciplinarity, enforcing the links between adjacent research areas and communities like QoE and UX, increasing accessibility of data through open data approaches, and integrating innovative methodologies like, for instance, machine learning. Together with the envisaged "Quality by Design" approach and the proposed emphasis on appropriate feedback mechanisms, the "turn to the user" will offer highly promising opportunities for the future networking and service market, which by now has also been acknowledged by the EU in the context of the upcoming "Next Generation Internet" activity.

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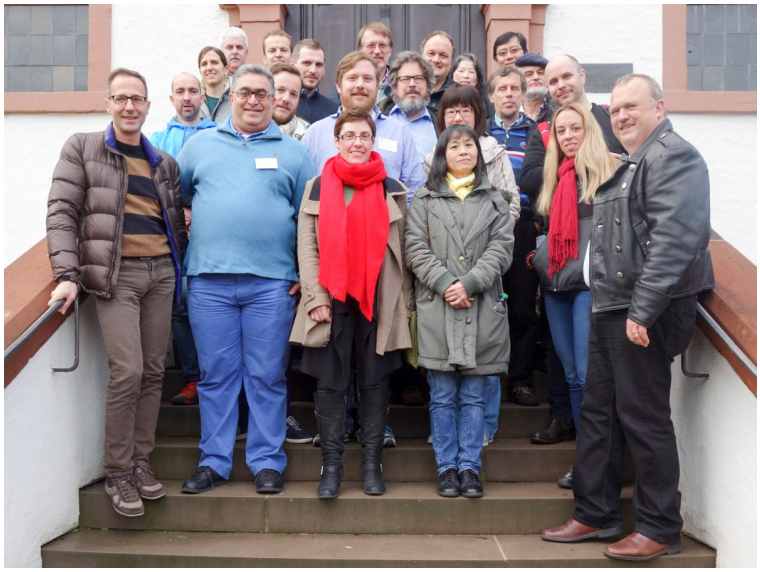

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