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Meta-Modeling QoE

Towards a Generic Methodology for Building QoE Models

Abstract: In this paper we propose a methodological framework for modeling Quality of Experience (QoE) for media services in a generic manner. We consider QoE as a multi-dimensional concept dependent on several factors related to the service itself, its resource requirements, its users, and its context of use. As a first step, we group these factors into four factor spaces and propose a mapping of them into a QoE space. We then focus on the application of this mapping in the context of networked media services by adhering to a layered approach for modeling QoE dimensions in relation to the aforementioned QoE-affecting factors. Such an approach facilitates understanding a service's QoE as a composite function of the performance of the underlying network, and the actual service implementation, under constraints imposed by some of the QoE-affecting factors. In order to illustrate the applicability of the proposed methodology, we present a case study for mobile video.

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1 Introduction and Related Work

Quality of Experience (QoE) is gaining increasing importance when dealing with user-facing services. While often confused in the literature with *Quality of Service* (QoS), QoE goes beyond what is usually covered in QoS research, introducing many aspects related to the service users and the context in which the service is used. Moreover, QoE is understood to be a multi-dimensional concept [1; 2], which ranges over different aspects of quality and how users perceive it.

With the increasing ubiquity and economic relevance of media services, Cloud-based (media) services, and multimedia in general, the ability to quantify QoE can be turned into a competitive advantage for service providers, and as a tool for users to get the most benefit out of the services they use. These benefits can be realized for example via QoE-driven optimization of the service delivery [3; 4; 5], or the definition of QoE-based SLAs, which are easily understood by customers.

In this paper we propose a methodology for modeling QoE, as well as an outline of how it can be applied in practice, by means of an example based on streaming video. The purpose of this methodology is to simplify the task of reasoning about QoE for any type of service, and to provide a formalization of the concepts involved. Our working hypothesis is that the multiple dimensions of QoE depend on a series of factors that affect quality (while the number of those factors is in principle very large, a limited number of factors can usually be identified that dominate the QoE as perceived for a given service, as has been found to hold in several domains [6] [7]). We propose a way to categorize QoE influence factors into four (multidimensional) spaces, and further map points from these spaces to a QoE space. Given that this mapping is a complex task, we propose to use a layered approach whereby we estimate QoE via the composition of quality at different levels of the overall "service-user" system. The ultimate aim of the proposed framework is to enable the exploitation of QoE as described above.

The quality of multimedia services has been considered across different levels, going from the specification of different quality abstraction levels (e.g., network, media, content as proposed by Nahrstedt and Steinmetz [8]), to further consideration of the impact of quality variation at each level on user-perceived quality [9] [2]. Bauer and Patrick [10] build on top of the standard 7-layer OSI model with additional human-computer interaction layers to account for human factors impacting QoE, namely display, human performance (addressing end user limitations), and human needs (i.e., reasons for using a system).

With it being clear that the wide range of *influence factors* that impact QoE go beyond those factors traditionally considered in the domain of QoS assessment, there has been a challenge to classify and model such factors for various types of multimedia services [11; 12; 13; 14; 15; 16; 17]. While a factor is a characteristic which influences QoE, it is not a part of the perceived QoE itself. In addition to understanding what impacts QoE, there is a need to understand and model what constitutes QoE, in terms of different subjective and objective quality metrics that can be identified and perceived by end users [18].

Studies spanning various disciplines have characterized QoE as a multi-dimensional construct comprising a number of subjective and objective factors, including user perception and affective state, system and network related factors, and usage context [19; 2; 1]. In the context of multimodal human computer interaction, S. Möller *et al.* [20] relate influence factors and performance metrics with QoE aspects (quality dimensions). Wälterman *et al.* [21] study quality dimensions related to speech transmission, and further model integral listening quality in terms of the identified dimensions.

Determining the correlation between influence factors and quality dimensions has proven to be a challenging task. A large number of studies have modeled the correlation between QoS and QoE [22; 14; 23; 6; 24], however often focusing only on overall user-perceived quality (often in terms of a Mean Opinion Score, MOS [25]). Wu *et al.* [2] have gone on to study the correlation of different dimensions of QoS and QoE, in particular for distributed interactive multimedia environments.

In the context of utility-based multimedia adaptation, previous work has considered the mapping of points across multi-dimensional spaces [26], whereby points in an adaptation space (representing multimedia adaptation operations) are mapped to resource and utility (quality) spaces. Such mappings are also used in the scope of the MPEG-21 digital item adaptation (DIA) [27] standard to be used for optimizing multimedia content adaptation decisions.

While a large amount of work has been done on modeling QoE, what is missing is an approach to integrate the following notions which we identify as being key considerations:

1. Categorization of QoE influence factors (including factors related to the application/service, system and network resources, context, and end user characteristics and psychological state) and their mutual correlations,
2. Expression of perceived QoE as a composite function relying on identified factors and quality throughout the whole stack, and
3. Expression of overall (integral) QoE as a weighted combination of multiple perceived QoE dimensions.

In the following section we present a novel way to integrate these notions into a generic methodology for modeling QoE.

2 A model for QoE

As discussed above, QoE is a multi-dimensional concept dependent on many different factors. Moreover, the influence of a given factor on the way the quality of a service is assessed by a user may be quite different depending on the actual situation. For example, the way interactivity (influenced by network latency) will affect a teleconferencing service's QoE may vary significantly with its intended use. If the service is used mainly for lectures in an e-learning setting, the interactivity impairments introduced by higher latency are likely to be less important than in a service which is used primarily for work meetings where discussions are more interactive (cf. [28] for a detailed discussion of the interplay between delay and interactivity).

Investigating QoE as a whole is a challenging (and probably hopeless) task. It is then useful to structure the different influencing factors into logical groups. As a first approach, these factors can be roughly grouped into those related to computational requirements, data and storage requirements, and network requirements. Other factors, related to the geographical distribution of the user-base, its size, and the usage patterns it creates are also important from a performance point-of-view. Other services' types characteristics, not related to performance, do also have an impact on their QoE. One such characteristic is the cost of using the service. Whether a service is free or paid can make a significant difference in its users' expectations with respect to how it should perform, and how well it fulfills those expectations (a good introduction to QoE and pricing issues is given by Reichl and Hammer in [29]). Another characteristic of the service is its intended use, and what its users expect from it (e.g., enjoyment, or utility, or both) and how this can be quantified. From the users' point of view, the quality of a service depends as well on their physical characteristics (age, visual acuity, etc.) and on their socio-economic and cultural background.

In subsection 2.1, we propose a logical grouping of QoE's influencing factors.

Now the process of quality assessment by a user can be considered as a "function" depending on all QoE influencing factors. In order to understand this process, it is convenient to build a model for the whole system "infrastructure+service+context+user" trying to encompass the way influencing factors are interacting to provide the quality assessment function. We provide in subsection 2.2 such a model as a layer model adapted to the logical grouping of the QoE influencing factors. Of course, as a model, some QoE influencing factors are necessarily partially taken into account or even not considered at all. We however believe that such a model could be implemented for any service and could provide some pertinent approximations of the quality assessment process.

2.1 The ARCU Model

2.1.1 Four Spaces for QoE-affecting Factors

In order to provide a methodology for identifying QoE influence factors in an intuitive and systematic way, we categorize factors into the following four multi-dimensional spaces. First is the *Application* space (A), composed of dimensions representing application/service configuration factors. Examples of such factors include media encoding, resolution, sample rate, frame rate, buffer sizes, etc. Content-related factors (e.g., specific temporal or spatial requirements, 2D/3D content, color depth, etc.) also belong in this space.

We then have the *Resource* space (R), composed of dimensions representing the characteristics and performance of the technical system(s) and network resources used to deliver the service. Examples of such factors include network QoS in terms of delay, jitter, loss, error rate, and throughput. Furthermore, system resources such as server processing capabilities and end user device capabilities (e.g., computational power, memory, screen resolution, user interface, battery lifetime, etc.) are included.

The *Context* space (C) is composed of dimensions indicating the situation in which a service or application is being used. A wide variety of dimensions may be considered in this category, including ambient conditions (e.g., lighting conditions, noise), user location, and time of day. Furthermore, the task (or purpose) related to using a given application is considered. An in-depth analysis of usage context factors (and their further classification) may be found in [30]. Dimensions representing the economic context may also be considered, such as service costs and SLAs specified between the end user and given service and/or network providers.

Finally, the *User* space (U) covers those dimensions related to the specific user of a given service or application. Example factors include demographic data, user preferences, requirements, expectations, prior knowledge, mood, motivation, etc. Studies addressing the influence of various user characteristics on quality perception (e.g., mood, attitude, personality traits) have been conducted by Wechsung *et al.* [31]. The particular role taken on by a user (e.g., user of a service and/or customer paying for the service) may be considered an important factor impacting user expectations, as considered previously by Kilkki [32] and later by Laghari *et al.* [33].

As compared to previous classifications, we believe that it is beneficial to distinguish between factors related to the actual application and media configuration parameters, and those related to the network / system resources, as these sets of parameters may be considered and managed independently and by different actors (e.g., by a network provider and a service / content provider). As an example we can consider the same application being delivered to different end users over different access networks, in which case we would consider factor variations in the R, C, and U spaces, while maintaining a constant point in the A space.

The proposed model (initially proposed in [34], and extended in this paper) is illustrated in Fig. 1. Dimensions in each of the spaces may correspond to different types of scales, such as e.g., ordinal, interval, and ratio scales. Points from the A, R, C and U spaces are further mapped to points in a QoE space. The QoE space is composed of dimensions representing different quantitative and qualitative quality features that can be perceived by an end user (e.g., perceptual quality / MOS, ease-of-use, efficiency, comfort, etc.). Depending on the service in question, the choice of quality dimensions will need to be made in such a way as to include all relevant aspects of QoE.

The *Mapping Function* (MF) can be considered as a function invoking different QoE assessment / estimation methods depending on the type of application. In the case of objective quality assessment, it can feed relevant input parameters to standardized models (provided they exist) to determine values for a given QoE dimension. In the case of subjective assessment, it will correlate input parameters with user quality scores.

2.1.2 Geometric View

The A, R, C and U spaces can be considered as different subspaces of a bigger space that we call the ARCU space. In a “vector space” like approach, ARCU can be con-

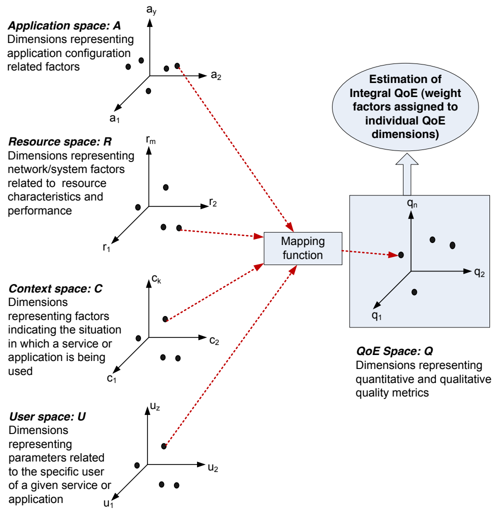

Fig. 1. The ARCU Model

veniently considered as the direct sum[1] of the spaces A, R, C and U, that is ARCU $=$ A $\oplus$ R $\oplus$ C $\oplus$ U. A point in ARCU can therefore be represented as a quadruple (a, r, c, u) of "vectors" whose coordinates are associated to the values of the different dimensions in the spaces A , R, C and U. It characterizes the state of the *application-resources-context-user* system. It turns out that in any given situation, the various dimensions in the ARCU space are generally not independent. For instance, for a given application, a user might expect a higher level of quality on a desktop computer than on a smartphone in a mobile situation. His expectation is a dimension in the U space but it depends on dimensions lying in the C space (fixed or mobile situation) as well as in the R space (capabilities of the device being used). As a consequence not all points in the ARCU space are necessarily associated to an actual feasible situation. Pushing further the geometric analogy, we can characterize the correlations existing between the various dimensions in the ARCU space as a system of equations of the form $f_i(a, r, c, u) = 0$, with $(a, r, c, u) \in$ ARCU and i in a given index set I. Now, a given system S: *application-resources-context-user* can be represented as a "subvariety-like" constrained set of points of ARCU, defined with $\Sigma_S = \{(a, r, c, u) \in \mathsf{ARCU} \,|\, f_i(a, r, c, u) = 0, i \in I_S\}$. A point in Σ_S is called a *feasible point* and any such point corresponds to values in the A, R, C and U spaces that can effectively be realized in a real situation. Notice also that an equation of the form $f_i(a, r, c, u) = 0$ in Σ_S does not necessarily depend explicitly on all the coordinates a, r, c and u. For instance at the network level, the throughput is usually correlated with the packet loss rate. This correlation leads to an equation of the form $f(r) = 0$ (r is a multidimensional vector). Since feasible points in ARCU are in general correlated, their correlations will induce correlations of the possible dimensions in the QoE space, i.e. the image of the mapping function $\mathrm{MF} : \mathsf{ARCU} \mapsto \mathsf{QoE}$ will send Σ_S onto a subset $\widetilde{\Sigma}_S \subset$ QoE representing the *feasible values* for the different dimensions in QoE. Knowledge regarding feasible values in the QoE space would prove valuable in terms of QoE estimation.

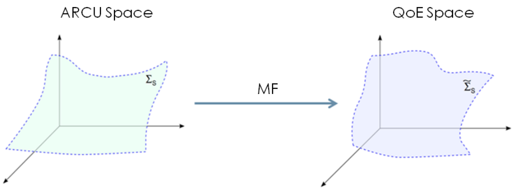

Fig. 2. The mapping of feasible points between the ARCU and QoE spaces.

The constrained subset Σ_S defines all feasible points when using system S. Now, in a specific scenario (a real usage case), some dimensions in ARCU will be kept at fixed values. For instance, the service is used by a given user on a given device. During a given service session, one can consider that all parameters in the U subspace are kept fixed. The psycho-physical characteristics as well as the social, psychological and historical characteristics of the user can be considered as fixed, and be represented by a vector u_0 in U. Similarly, all the characteristics of the device will be kept fixed. In the subset R, the dimensions corresponding to the characteristics of the device (but not of the underlying network, or the device's load) will correspond to a vector r_0 of fixed values. The vector r in R corresponding the situation can be represented as a direct sum of the form $r = r_0 \oplus r'$ where the coordinates of r' are not fixed (for instance, the loss rate or throughput). Altogether, the set of feasible points in Σ_S is defined as $\Sigma_S \cap \{u = u_0\} \cap \{r = r_0 \oplus r'\}$. Remark that the equation $u = u_0$ can be rewritten $f(u) = 0$ with $f(u) = u - u_0$ (and similarly for the constraint on r), that is, considering a given situation amounts to specifying correlations in the ARCU space.

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[1] This is actually a slight abuse of language for simplicity's sake, as the A, R, C, and U spaces usually have more than the zero vector in common, see below for more on this.

2.1.3 Integral QoE

Following the mapping to a QoE space, we can consider how to then go from a point in a multidimensional space to a measure of integral QoE. The term "integral quality" may be used when the quality due to the totality of quality dimensions (or features) is considered, as discussed by Raake [35]. The overall evaluation of subjective quality should be based on a weighted, possibly non-linear, combination of quality dimensions. Two issues need to be addressed with regards to quality dimensions: (1) how much a given dimension contributes to integral QoE, considered in relation to other identified dimensions, and (2) in which way a given dimension contributes to integral QoE (e.g., vector model type vs. ideal point model as cited previously in [1]). Different dimensions may be of different relative importance (depending on the application considered, its purpose / type, the user's task, user preferences, etc.), and hence be assigned different weight factors. For example, "content reliability" is very important for a telemedicine application and contributes in large to overall QoE, while the same dimension contributes to a smaller degree to the overall QoE of a gaming application.

If we assume that the QoE space is composed of dimensions $q_1, ..., q_n$ with corresponding weight factors assigned as $w_1, ..., w_n$, then we can express integral QoE (QoE^*) as

$$QoE^* = f(w_1 q_1, ..., w_n q_n) \tag{1}$$

Further analysis of QoE dimensions may involve multidimensional analysis techniques (e.g., using Multidimensional Scaling and Principal Component Analysis [21]), which are out of scope for this paper.

2.2 A Compositional Approach to QoE via Layers and the ARCU Model

As discussed above, we base our approach on the hypothesis that the QoE, as perceived by the users, is dependent on several different factors related to the service itself and its implementation, its context of usage, and its users.

The ARCU model described above is a convenient way to categorize the factors influencing the human perception of quality, their correlations and to characterized the dimensions of the QoE using the mapping MF between ARCU and QoE. However, identifying all these factors is a difficult task, if possible. Similarily, the mapping function MF is likely hard or impossible to know in detail. At best, we can expect to be able to characterize the dimensions in the ARCU space having the most influence on the QoE and to use them to approximate the MF mapping. While knowing the actual mapping function might not be feasible, a large array of options (e.g. machine learning and other statistical methods) are available to approximate it with sufficient accuracy for practical purposes.

Guided by the OSI layered approach, it seems convenient to design a layered model for the whole "service-user" system. Such models have been defined for example in Bauer and Patrick [10]. Bauer's model, however, does not include the contextual aspects. Here we propose a 6-layer model for the service-user system. When the service uses network resources, these 6 layers model can be expanded to an 11-layer model, extending the model in [10]. The proposed layers are:

- *User Layer*: this layer represents all factors corresponding to a human considered as a user. Factors considered include those related to the socio-professional class of the users, their level of education, and their history. All factors related to the users' *needs* (communication, entertainement, work ...), which may be at the root of their motivation and willingness to use the service, are also considered.
- *Human Layer:* this layer represents the psycho-physical aspects of the perception. It is related to the users abiliy to perceive the various media and characterises for instance their visual, audio and haptic sensitivity.
- *Context Layer:* this layer characterizes the overall context of use of the application. Parameters in this layer include those related to the physical and geographical context as well as the usage context (type of task, stress, etc.).
- *Interface Layer:* this layer corresponds to parameters related to the means by which users interact with the application, such as screen, mouse and keyboard. It does not include, however, the user interface of the application itself. This layer includes factors *describing* the interface (size of the screen, availability of a mouse ...), the physical resources allowing the interface to actually provide a service are however considered as factors pertaining the Resource layer.
- *Application Layer:* this layer include all characteristics of the application or service, including its im-

plementation, its user interface, its resource requirements, etc.

- *Resource Layer:* this layer covers all the characteristics of the system related to supporting or running the application or service. For instance, in the case of a network service, this layer corresponds to the 6 first layers of the OSI model. In a Cloud context, it might include factors related to the Infrastructure or Platform performance.

When considering a human sitting in front of a computer and using an application, the 6 layers can be thought as a physically user-centred splitting of the set of QoE-influencing factors, from the most distants ones (the network) to the closest ones (e.g. user motivation). More precisely, it can be thought as a way to model the following situation: first, an application needs resources to run (CPU, network connectivity, throughput etc.). The factors in the Resource layer characterize these resources. Their values can strongly influence the behaviour of the application. Now, the application presents information to the user using an interface. This information may however be modified, perturbed or degraded by the ambient (physical) context before being perceived by the user. For instance, an audio signal may be degraded in a noisy environment. Similarily, a visual signal may be degraded by ambient light reflected on the screen. This possibly modified information is then perceived and its quality evaluated at the psycho-physical level by the human brain (the Human layer). Finally, a given such "psycho- physical" evaluation may results in very different assessments of the quality depending on the user characteristics (that is personality, motivation etc.) represented in the User layer. Considering the Human and User layers separately, while to some degree arbitrary, is useful as a means of separating the perceptual aspects of QoE from those related to other factors such as socio-economic level, cultural background, etc. This is also partly due to our current better understanding of the physiologically-related aspects of quality perception (e.g. good models of the human visual and auditory systems) as opposed to the other factors considered in the User layer.

Just as the User layer involves aspects of QoE that are currently not well understood, the Context layer can (and likely does) involve a significant number of factors that affect quality but are currently not well understood. We expect that as our understanding of these factors, as well as our means for measuring them improve, QoE models built on this approach will have a significantly “thicker” context layer.

When networked services are considered, the Resource Layer can be expanded into the 6 first layers of the OSI reference model. Related to this layered approach, a layering of quality notion can be defined. Layered approaches for quality have already be defined by S. R. Gulliver and F. Ghinea [9] and more recently by P. Reichl [36] for instance. Let us denote by P_L the set of perceived quality influencing factors contained in the layer L. In a layered approach, each layer L provides a service to layer $L+1$. We define the quality Q_L of the service provided by layer L as a function of the factors contained in layer L and of the quality of the service provided by layer $L-1$ to layer L, that is

$$Q_L = Q_L(P_L, Q_{L-1}) \tag{2}$$

Remark that, since the quality function Q_{L-1} depends explicitly on the function Q_{L-2} the influence of the quality of the services provided by layers i with $i < L$ is implicitly reflected in Q_L.

The quality functions Q_L associated with each layer L are just a convenient way to model the impact of layers $L_i,\ i \in 1, \cdots, j-1$ on layer L_j. Depending on the layer L, the semantics associated with Q_L may vary. For instance it does not really make sense to speak about a “quality of context”, but the Q_L function corresponding to the context layer may for example reflect a bias on the quality introduced by certain aspects of the context. An example of this would be the E-model’s so-called “advantage factor”, which takes into account the user-perceived convenience of using a mobile phone, and increases the rating of a call in that context, all other factors being the same. This bias function would be, in the simplest case, just the identity function.

The relation between the various dimensions in the ARCU space and the factors in the layer model allows characterizing more precisely the meaning of the quality function Q_L. The mapping from ARCU onto the layers is then naturally defined as follows:

- The U space is mapped onto the factors in the User and Human layers
- The C space is mapped onto the factors in the Context and Interface layer
- The A space is mapped onto the factors in the Application layer
- The R space is mapped onto the factors in the Resource layer.

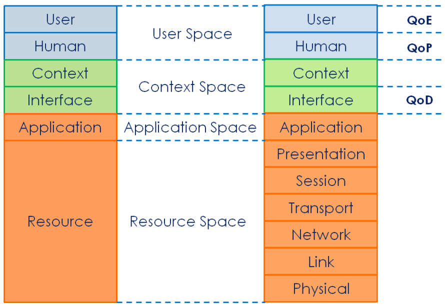

Fig. 3. The layer model and its relations with the ARCU spaces.

With this correspondence, the dimensions of the QoE space are mainly sitting in the Human layer and in the User layer. Using a scale $\mathcal{Q}$ to quantify quality (e.g. a MOS-type scale), we can see the *Quality of Perception* (QoP) and the *integral QoE* (QoE^*, mentioned in Section 2.1) as $\mathcal{Q}$–valued functions of the Human and User layers, respectively. Thus,

$$\begin{aligned} QoP &: \text{Human Layer} \mapsto \mathcal{Q} \\ QoE^* &: \text{User Layer} \mapsto \mathcal{Q} \end{aligned}$$

Using relation (2) yields $QoE^* = QoE^*(P_{\text{User}}, QoP)$ where $P_{\text{User}} = \{p_1, p_2...\}$ stands for the set of parameters in the User layer. Approximations for the $QoE_{\mathcal{I}}$ function can be obtained, for example, using a Taylor expansion that can be approximated using weighted sums of nonlinear polynomials in QoP and in $p_1, p_2, \ldots$.

Following P. Reichl *et al.* [36], the quality function at the Interface Layer is called the *Quality of Design* and denoted QoD.

3 Case Study – Streaming Video

In this section we present a case study on how to apply the proposed methodology to a concrete instance of a networked media service. We study different QoE dimensions of streaming video, based on a set of experiments published in [37] in which 34 users rated 3 non-distorted videos and 15 videos distorted by loss that were played on two mobile devices, in random order.

3.1 Experimental Settings in the ARCU Space

Table 1 summarizes the mapping of the experimental conditions into the ARCU space. As can be seen, the study focused on the impact of losses, and thus several dimensions had very constrained ranges, often with only one value. If the impact of those dimensions were to be studied, further values along them and a larger number of test instances would be needed. In particular, we do not present an analysis of the dimensions along the U space, as larger user groups are needed to provide statistically meaningful results on them. Further details of the experiments and results are shown in [37].

Space	Dimension	Range
A	codec	h.264
	content	foreman, football, hall monitor
	resolution	QVGA (320×240)
	bit rate (Kbps)	768
R	loss rate (%)	0.0, 0.4, 0.8, 3.0, 5.0, 7.0
	bandwidth (Kbps)	≥ 768
C	device type	laptop, smartphone
	environment	ITU-R BT.510–11 compliant lab
U	gender	male, female
	age	19–41
	nationality	Australian, Bangladeshi, Chinese, Indian, Iranian, Mexican, Pakistani, Sudanese, Swedish, Syrian
	watches videos	rarely, often, frequently
	watches videos on phone	never, rarely, often, frequently
	sight correction	yes, no

Table 1. Mapping of experimental settings into the ARCU space

3.2 Formulae for the Layered Model

The quality of the video is affected by losses in the network, which are a parameter from the resource domain. As UDP was used as a transport protocol (parameter P_{T}), the network-induced loss is "handed through" to the application without any impact of the transport layer, reflected by $Q_{\text{T}} = Q_{\text{N}}$. The network-level quality Q_{N} is a function of the loss, and as the latter is emulated, there is no impact coming from the lower layers (physical and data link). Thus, we arrive at

$$Q_{\text{A}} = Q_{\text{A}}(Q_{\text{N}}(L), P_{\text{A}}|_{P_{\text{T}}}) \,. \tag{3}$$

The PEVQ tool (a commercial implementation of the ITU-T J.247 standard [38]) evaluates the interface-related quality parameter from the video, belonging to the A domain, which as denoted above (2), reads

$$Q_{\text{I}} = Q_{\text{I}}(Q_{\text{A}}, P_{\text{I}}) \,, \tag{4}$$

with P_{I} capturing the impact of the interface. Table 2 shows a set of approximations of $Q_{\text{I}}(Q_{\text{A}}(Q_{\text{N}}(L), P_{\text{A}})|_{P_{\text{T}}, P_{\text{I}}})$

P_{A}	Q_{I}	R^2
Football	$Q_{\mathrm{I,Blu}} \simeq \min\{1.087 \ln(L) + 1.827, 10\}$	0.912
	$Q_{\mathrm{I,Blo}} \simeq \min\{2.963 \ln(L) + 4.014, 10\}$	0.990
Foreman	$Q_{\mathrm{I,Blu}} \simeq \min\{1.296 \ln(L) + 1.602, 10\}$	0.958
	$Q_{\mathrm{I,Blo}} \simeq \min\{2.668 \ln(L) + 3.479, 10\}$	0.916
Hall monitor	$Q_{\mathrm{I,Blu}} \simeq 0.494 \ln(L) + 0.991$	0.975
	$Q_{\mathrm{I,Blo}} \simeq 1.386 \ln(L) + 2.572$	0.959

Table 2. Approximation of PEVQ-determined quality parameters as functions of loss.

for 'Blu'r and 'Blo'ckiness and for different videos indicated by P_{A}. The approximations show a strong correlation with the measured data. The logarithmic nature of the fitting suggests that the quality is related to the order of magnitude of the losses.

The PEVQ tool estimates the quality at the perceptual level (Human Layer) in terms of MOS from such quality indicators, as blockiness, blurriness, jerkiness, etc., as defined in [38], providing the perceptual quality estimate Q'_{H}:

$$Q'_{\mathrm{H}} = Q'_{\mathrm{H}}(Q_{\mathrm{I,Blo}}, Q_{\mathrm{I,Blu}}, \dots)\,. \tag{5}$$

In case of the user rankings, the QoE is given by

$$Q_{\mathrm{U}} = Q_{\mathrm{U}}(Q_{\mathrm{H}}(Q_{\mathrm{C}}), P_{\mathrm{U}})\,, \tag{6}$$

where Q_{H} is the perceived quality, P_{U} captures the impact of the user group, and

$$Q_{\mathrm{C}} = Q_{\mathrm{C}}(Q_{\mathrm{I}}, P_{\mathrm{C}})\,, \tag{7}$$

where P_{C} captures the difference between laptop and smartphone. As discussed in Section 2.2, Q_{C} expresses a bias rather than a quality measure and reduces in our case to the identity function, i.e. $Q_{\mathrm{C}} = Q_{\mathrm{I}}$, irrespective of P_{C} [37]. Thus, the user ratings are given as

$$Q_{\mathrm{U}} = Q_{\mathrm{U}}(Q_{\mathrm{H}}(Q_{\mathrm{I}}(Q_{\mathrm{A}}(Q_{\mathrm{N}}(L), P_{\mathrm{A}}, P_{\mathrm{C}})))|_{P_{\mathrm{T}},P_{\mathrm{I}},P_{\mathrm{U}}}). \tag{8}$$

and the resulting model approximates them with

$$Q'_{\mathrm{U}} = Q_{\mathrm{U}}(Q'_{\mathrm{H}}(Q_{\mathrm{I}}(Q_{\mathrm{A}}(Q_{\mathrm{N}}(L), P_{\mathrm{A}}, P_{\mathrm{C}})))|_{P_{\mathrm{T}},P_{\mathrm{I}},P_{\mathrm{U}}}). \tag{9}$$

As can be seen, analyzing the service in terms of the ARCU model in combination with the layered approach as described in relation (2) provides insight into the structure of the dependencies of QoE on lower-layer parameters, combined with information about which parameters have been varied and how they impact QoE.

4 Conclusions and Future Work

In this paper we have presented a methodology for understanding the QoE of media services, which can be applied to different service contexts. In particular, we have proposed a way to classify factors that affect service QoE, and to map them to different QoE dimensions in a QoE space via the ARCU model. This multidimensional view of QoE can also be collapsed into an integral QoE notion (QoE^*), which provides an overall value for quality. We have also developed a way to account for the inter-dependencies between different factors, and integrated it into our formalization.

Concerning the mapping function that takes quality-affecting factors from the ARCU space into the QoE space, we have proposed a layered approach, in which the quality at a given layer is dependent on that of the lower layers and parameter that belong to the layer in question. We have also proposed a mapping from the ARCU space into the different layers in the model, so as to simplify the study of service QoE.

In order to illustrate the use of the proposed methodology, we have presented a case study for streaming video QoE, mapping several quality-affecting factors (with a focus on variable network losses) into three quality dimensions (jerkiness, blurriness, and blockiness), as well as an integral quality value. We have combined the different quality dimensions into the integral quality with very high correlation with the subjective assessment results.

With respect to future work, there are several research lines currently under study. As mentioned in Section 2, services are often multi-modal, and different modalities often will have different dependencies on quality-affecting factors, as well as different impact on the QoE space. Moreover, the modalities active at any given time are variable. We are currently working on integrating these multi-modal and temporal features into our formalization, and studying the ways in which an overall view of QoE can be gleaned in a multi-modal context.

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