A Note on Quality of Experience (QoE) beyond Quality of Service (QoS) as the Baseline— Working Paper WP-RFM-14-02, (version: 140818)

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Abstract

In this work, a new approach to the definition of the quality of experience is presented. By considering the quality of service as the baseline, that portion of the QoE that can be inferred from the QoS is excluded, and then the rest of the QoE is approached with the notion of QoE at a Boundary. With the QoEaaB as the core of the proposed approach, various potential boundaries, and their associated unseen opportunities to improve the QoE are discussed in this work-in-progress paper. In particular, property, contract, SLA, and content are explored in terms of their boundaries and also their associated QoEaaB. With an interest in the video delivery use cases, the role of the user type is considered, especially from the perspective of the isolation experience associated with multi-tenant operations. It is concluded that the proposed QoEaaB can bring a new perspective in QoE modeling and assessment toward a more enriched approach to improving the experience based on innovation and deep connectivity with the users.

Keywords: Quality of Experience (QoE), Quality of Service (QoS), QoE at a Boundary (QoEaaB), Smart Management

1. Introduction

With the big shift toward user-centric, service-centric, and transaction-centric interaction and business models, the role of users and their ‘experience’ along their journey of interaction with the provider has become an inseparable part of any design and assessment of providing systems and businesses. This vision has resulted in the addition of complexity and also variability of the user’s side to all other areas of a service providing solution. Various measures, metrics, and indices have been put forward to enable quantification of these complex aspects, including but not limited to, Quality of Service (QoS), Quality of Experience (QoE), Quality of Resilience (QoR), Class of Service (CoS), and Grade of Service (GoS) (ITU-T, 2006, 2008, 2011; Stankiewicz et al., 2011). Although the number of metrics by itself shows the intensity of the associated complexity, the QoE metrics alone seems to inherit a high degree of challenge because of explicit involvement of the ‘user’ in its ‘definition’; according to ITU-T Rec. P.10 (formally G.100), QoE may be defined as the overall acceptability\textsuperscript{1} of an application or service, as perceived subjectively by the end user (ITU-T, 2006, 2008).

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\textsuperscript{1}Overall acceptability may be influenced by user expectations and context (ITU-T, 2008).
Figure 1: a) An abstract illustration of overlap among the QoE, the QoS, and the MOS. b) The proposed concept of the QoEaB, illustrated as an enabler toward exploring areas of the QoE that are not accessible to the QoS and the MOS.

Although this approach to QoE is by definition correct, it requires an interpretation in order to become a quantifiable metric. Similar to many other subject-related metrics, the Mean Opinion Score (MOS) ‘measurement’ approach has been considered in quantifying the QoE (Fiedler et al., 2010; Stankiewicz et al., 2011). Although this seems to be a straightforward approach, the ‘multivariate’ nature of the problem, which mainly has its source from the end user component itself, could make the final conclusions insignificant or even wrong if proper multivariate analyses are not considered (Jackson et al., 2011). In contrast, the need to have a system-originated metric for the QoE and also conclusions drawn from the results of the MOS evaluations of the QoE in practice has led to developing models that try to directly relate the QoE to the QoS. We will discuss this aspect in more details in section 2.

In terms of the factors that influence the QoE, it has been argued that it is the small details, in addition to the price and the service performance, in the user journey that make the big differences in their experience (Bolton et al., 2014). Examples of these small variables could be i) emotions and ii) service recovery strategies, among others (Bolton et al., 2014; Chan et al., 2009; Smith and Bolton, 2002).

From the perspective of the user-provider relation, it is also worth noting that there is a similar dilemma to that of buyer-seller relation in association with the value-added tax (VAT). The experience a user would go through could be highly variable depending on whether they are an end user or an intermediate provider to other users. In the long-haul chain of interactions to the final end user, a provider may lose their ‘connectivity’ to the end user which in turn would impact their associated QoE. Therefore, the providers along the chain could benefit from flexible and generalizable QoE metrics that capture minor and major variation when passing across the spectrum of the ‘users’.

Although all approaches to quantify QoE, including those that are MOS-based and QoS-based, are correct and shed light on many aspects related to the QoE; we believe that there are areas in the experience and QoE domain that could not be directly accessed using these approaches. In other words, we try to model experience as a collection of various experience ‘perspectives’, which could form an ensemble to provide a comprehensive understanding of the ‘experience’. Figure 1(a) provides an abstract illustration of the proposed approach in which the overlapping areas between the QoE and the QoS, for example, practically show the ‘perspective’ to the QoE from the QoS point of view. The area that has
no overlap with other points of view is of our interest.\(^2\) In particular, the area shown by the QoE-at-a-Boundary (QoEaaB) in Figure 1(b) is the focus of this work. We argue that boundaries in general are the richest areas that absorb a considerable amount of the experience and therefore the QoE.

The paper is organized as follows. In section 2, a discussion on relations between the QoE and the QoS, and the need to consider the QoEaaB is provided. Then, in sections 3, the question of ‘boundary’ itself is considered, and various instances of this concept ranging from ‘property’, ‘contract’, ‘content’, to ‘time’ are discussed from a QoE point of view. A particular example of boundary of SLA in the case of multi-tenant service solution is discussed in section 10. Finally, in section 12, the conclusions and some prospects for the future are summarized.

2. The Definition of the QoE

As mentioned in the introduction, the ITU’s definition of the QoE requires additional interpretation in order to be quantified. One of the perspectives to this end has been on developing a relation between the QoE and the QoS. However, the QoS definition by itself is a challenge to be addressed. One approach to the QoS definition has been based on non-functional requirements (NFRs) of a service (Ameller, 2014; Bartolini et al., 2013; Briones et al., 2010). The NFRs can be associated with those requirements that specify system properties related to performance, security, and reliability, among others.

It has been observed in many studies that the nature of a service itself should be also considered in its evaluation. For example, services provided prior to a transaction are essentially different from those occurred afterwards (Berry et al., 2010). Moreover, it has been noticed that composability of the QoS is of great importance, especially when the complexity of the service orchestration and choreography increases (Briones et al., 2010). In terms of the QoE, the influential factors could go beyond the system itself, and a partitioning of three influential factors, i.e., of human, system, and context seems to be required (Reiter et al., 2014).

Many approaches have been considered to make the QoE a function of the QoS. For example, a relation has been developed between QoE and QoS based on a hypothesis that there exists an exponential interdependency between ‘parameters’ of the quality of experience and those of service (the IQX hypothesis) (Fiedler et al., 2010; Varela et al., 2014). In Goran et al. (2014), an exponential relation has been developed between the QoE of the IPTV services and the associated QoS parameters, such as the QoS of the application, network, and physical link.

In general, as has been acknowledged in many researches, the QoE has some important overlapping areas with the QoS. However, the overlapping area would not be a complete picture, and therefore the focus of this work is on the non-overlapping part. In particular, a subarea defined by the role of ‘boundaries’ on the QoE is the main target. When operating at the proximity of a boundary, the consequences of changes in the degree of the proximity or events of crossing the boundary could have a great impact on the user experience, and therefore they should be considered in the QoE. Identifying the boundaries would be the main challenge considering the fact that many of them would not have any

\(^2\) Although the MOS approaches seem to be capable covering the whole QoE domain, it could be argued that there are many aspects of the QoE that has never been thought of by any current user or opinion-question designer.
tangible counterparts. In this work, the perspective of the QoE, when the influence of boundaries is considered, is called the QoE-at-a-Boundary (QoEaaB). The next section provides some more discussion on boundaries, and also some instances of boundary are listed and discussed.

3. The Devil is at the Boundaries: QoE-at-a-Boundary (QoEaaB)

The first step toward a vision of the QoEaaB is a proper definition of boundary; a straightforward definition could simply be the boundary of ‘things’. Although in the common sense, a thing is usually a ‘property’ that can be owned, we will see in the examples below that there are other possibilities, ranging from contract to content, which could impose boundaries that would drastically influence a user’s experience, perception, and satisfaction. We start with the boundary of property, which itself could be tangible or intangible, and continue with other instances. The main focus would be on aspects that would be undiscoverable using other approaches to the QoE.

4. Boundary of Property

In general, ownership of a property is considered an advantage. However, with new categories of property in the horizon, especially considering intangible virtual properties, the liability and responsibility costs associated with ownership of a property have become a major burden. The QoEaaB of properties have two facets. The first facet is directed toward the isolation and separation of users’ property, while the second one focuses on the ‘inclusion’ of the user in the provider’s properties. Although our focus will be on the second facet, we would like to mention an example of the first one, in which compromise of the identify property (identify theft) of a user has been handled with a zero-liability policy in order to presumably preserve the QoE score (Grimmelmann, 2010). However, the user’s dissatisfaction reported in Grimmelmann (2010) shows that crossing the boundary of the user’s property could have a considerable impact on the QoE even when it is handled with the best practices.

A common definition of a ‘property’ is the well-known ‘bundle of relations’ (Chang, 2014), which is one step ahead of the ‘bundle-of-rights’ in the sense that it considers not only the owner but also all parties. Besides, from the rights point of view, the important ‘right to exclude’ has been suggested to be accompanied with the ‘right to include’, which would promote cooperation in various forms of inclusion including informal, contractual, and proprietary inclusion (Kelly, 2014). It seems that the right to include has great potential for the service providers, especially in increasing their interaction and connectivity with the users as well as building long-term relations. In another approach, the ‘property matrix’ has been introduced as a new definition considering two dimensions of property: i) the descriptive dimension which requires a thing to give rise to a right and ii) the normative dimension which requires being explained by the normative points (Morales, 2013). In another perspective, the property is defined as the law of things, in the form of an architectural theory based on information costs and the advantages

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3For example: 1. Rights of a person over a given thing, 2. Rights in rem (in contrast to rights in personam), and 3. Attachment to the thing (Morales, 2013).

4Such as: 1. The right to exclude, 2. A bundle of rights, 3. Rights of autonomy, and 4. Rights of value enhancement (Morales, 2013).
of using modularity to manage the associated complexity (Smith, 2012, 2014). In this theory, the things were considered as modules, and instead of a bundle, a ‘structure’ of relations among the features is proposed for the definition of a property.

In general, the boundary can be seen as the in rem aspect of property. Intangible properties such as information property, face more challenges in finding an on/off proxy for violation of rights, similar to the case of water as property (Smith, 2012). Although behavior at the proximity of the boundary of a property is considered here, there is another type of boundary that can be related to the property concept; the definition of property itself has boundaries, especially when put against the definition of tort. This boundary would involve the property rules and the liability rules as enforcers (Miceli, 2013).

The uncertainty and confusion in handling boundary of properties is deepened in the case of intangible properties. The intangible properties are of great interest in ICT and other dematerialization industries (Farrahi Moghaddam et al., 2014). It is expected that, in a move toward a sustainable future, ICT-enabled solutions would replace a considerable volume of services provided by other industries in order to reduce resource consumption and GHG emissions (Farrahi Moghaddam et al., 2014). The scale of data and information collected by the service providers shows a great potential to ‘process’ this data property in a way the user could be ‘included’ across its boundary. The impact on the QoE would be exponential, while the provider would also enjoy the insights in return for the costs of anonymizing and other associated data processing tasks (Bhimani and Willcocks, 2014). This information transparency approach would also help in deterring opportunism which is a side effect of the information era (Steinle et al., 2014).

Another example that highlights the importance of the QoE is the case of artistic work properties, such as movies, songs, and books, etc. Traditionally, the artistic properties have been associated and practically mistaken with their physical carrier, for example DVDs. However, with the move toward online media, the carrier’s role is becoming less visible to the user, and at the same time its associated costs have been reduced thanks to resource-sharing aggregators, such as virtualization and cloud-based models. This has brought up the question of how to handle the boundaries of an artistic work without taking into account its carrier. We can observe that there is a great potential for novel ways of inclusion of user inside the artistic property in order to prevent the user from making hard decisions in terms of owning an ‘instance’ of the intangible work. An example of such inclusive boundary crossing could be limited preview licenses. We will discuss this matter more in the next subsection.

5. Boundary of Contract: Boundary of User Decision

The second item on our list of ‘things’ is the contract. It worth mentioning that the historical justifications for necessity of contracts would be no longer valid in all cases in near future, and therefore the whole concept of contract would require a complete reconsideration. That said, hereinafter we assume that the contract is a necessary part of any interaction between a provider and a user. Further on, it will be argued that the boundary of a contract would play a significant role on the QoE of the user.

A contract usually imposes a hard decision making. Although this may be vital in order to stabilize the operation on the provider’s side, many factors need to be considered. The first factor is the user
itself. Although it is assumed that a user, similar to all other actors, is a ‘selfish’ player, it does not guarantee that the user’s decision is always ‘optimal’ (Staub-Kaminski et al., 2014). A typical end user has very limited analytic resource capacity, therefore, they highly depend on their ‘connections’ in order to make a decision. The non-optimality of the decisions results in dissatisfaction and a poor experience for the user each time they approach the boundary of the contract that has been signed based on those decisions. Therefore, there is a potential that novel management techniques of the boundary of a contract could bring in great opportunities to increase the QoE and the QoE in general without scrapping the concept of the contract itself. One way of tackling this problem is providing options to modify a contract at any time. However, it is more desirable to provide the options the user has not even asked for. In other words, the ability to ‘observe’ the degree of the user’s proximity to the boundary, and thereupon offering in-kind options not only increases user’s satisfaction, but also helps in increasing their trust and loyalty in the provider.

In another direction, it has been pointed out that the contract concept is a better interaction ‘container’ than that of license when formalizing relations (Patterson, 2012). In the case of intangible properties in particular such as those of ICT, a license may fail to transfer the conditions required by the provider, and especially it may fail in obtaining the consent of the receiver on those conditions. This shows the complexity and challenges in designing and enforcing licenses, especially in terms of what crossing their boundary would mean. A more properly placed boundary, and more importantly, smart handling of the circumstances at the proximity/crossing of the boundary would provide a great chance in improving the QoE.

Finally, it is worth mentioning that the traditional definition of a contract would not be proper in the new visions to human ecosystems, such as that of Zero Marginal Cost Society (Rifkin, 2014), in which the capital cost of a service provider would become negligible, especially for intangible properties. In those cases, smart service providing models could create opportunities at the ‘boundary of the service’ itself.

6. Boundary of SLA

In many cases, the non-functional requirements are actually listed in the Service Level Agreement (SLA) instead of the contract. Therefore, the boundary of an SLA would have a critical role in defining the experience of an user. Formally, an SLA governs the management of non-functional parameters based on some restrictions aiming to optimize a cost function. It can be argued that the ‘cost function’ itself is the main factor that determines the boundaries of an SLA and also the behavior when crossing those boundaries.

The first question in terms of designing the cost function is who actually benefits from the service.

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5 This could be actually identified as the drive for many social networks.
6 Even, temporarily for a short period of time.
7 For example, open-source software, artistic works, etc.
8 In addition, the extra information cost resulted from the added restrictions, which finally would be translated into rights, would in turn increase the processing cost of every potential acquirer even if they do not have any commitments to make a purchase (Patterson, 2012).
Is this the end user or is it an intermediate ‘tenant’ that provides a secondary service to other users? In the former case, the QoE should be defined with respect to ‘an ensemble’ of end users, and therefore the traditional notion of ‘average’ would not be proper. In addition, the experience would have a ‘nonlinear spectrum’ of intensity, ranging from ‘delay in delivery’ to ‘no delivery at all’. The ensemble view on these experiences should be well defined, considering possible conflicts between the ‘individual’ and ‘society’ perspectives toward the experience. In other words, the ‘rare’ but ‘abnormal’ experiences requires a special attention in the cost function in order to protect the experience of the ‘individuals’ from being ‘shadowed’ by the ‘frequent’ normal experience events associated with their ‘society’. This brings up the notation of the ‘boundary of an ensemble’. To be more precise, this requires another level of service in order to handle the requests to be included in the ensemble. The experience of this secondary level service could be very extreme, and therefore could have a drastic impact on the out-of-the-ensemble users’ impression of the provider. Although imposing a boundary for the ensemble would be critical in preserving the quality for the insiders, smart handling mechanisms of the newcomers’ inclusion requests are necessary. These smart mechanisms would probably be dynamic, ‘temporal’, and highly reliable on the elasticity of the ensemble and that of the provider’s resources.

The role of SLA is more critical when resource sharing and virtualization approaches are in place. The semi-intangible nature of the virtualized resources requires proper handling of the QoE and quality of isolation metrics. In Hobfeld et al. (2012), various challenges from migrating services to cloud environments have been identified. In addition to many factors, such as latency, management, and multi-party communication, the SLA and pricing has been listed to be required to provide flexibility in terms of guarantee of video quality versus price. This is in line with the QoE at the boundary of ‘delivered video-quality’ as a property. In terms of isolation of services and its associated metrics, a metrics based on the impact of abiding and disruptive workloads on the QoS is introduced for the case of end users’ service requests (Krebs et al., 2014a). Generalizations to handle multi-tenant placement in the form of resource management and request admission control approaches have been developed in Krebs et al. (2014a,b,c). In contrast to the case of ‘ensemble of end users’, where the boundary of the ensemble was the most influential area, in the case of multi-tenancy it is the boundary of the semi-intangible resources assigned to a tenant that determines the quality of experience and isolation. Dynamicity and shrinkability of these resources, which somehow originates from the lack of a governing contract, would make the boundary highly variable, and therefore this could increase the frequency of the boundary crossing events and their associated experience and costs. It seems that some sort of ‘grading’ protocol or standard is required in terms of virtualized resources in order to reduce their variability while maximizing utilization of the associated [tangible] infrastructure resources. In section 10, the case of multi-tenant services is discussed in greater details.

7. Boundary of Context

The context has been well identified as a key factor in determining the QoE (De Moor et al., 2010), and boundary of different contexts would be the most challenging area to handle because of possible confusion in identifying the dominant context or negligence of the direction of the ‘transition’ across the
boundary of adjoined contexts. We will explore this instance in more details in future work.

8. Boundary of Content

Although the concept of content was earlier addressed in section 4 from the perspective of property, it appears crucial to discuss it separately here. In general, information, data, and many other forms of intangible properties could make a big difference in the QoE at their boundaries. A popular example is the artistic content, such as movies, shows, and so on.

A fast growing content-related service sector is associated with online video delivery. Although the business models have a wide spectrum from paid IPTV/OTT models (Goran et al., 2014) to ad-based models such as YouTube, all models are gradually converging to use a ‘generic’ broadband media such as the Internet or smart grid’s telemetry backhaul (Gomez-Cuba et al., 2013, 2014), in delivering the constantly increasing video qualities. This move has brought a common set of challenges to all these models. Various boundaries could be identified and then tapped on in order to improve the QoE, and at the same time reduce the associated natural (environmental) footprint. Some of these boundaries are directly related to the content itself: i) the boundary of encoding/decoding, ii) the boundary of observable video quality, and iii) the boundary of centralized vs. distributed content. Other associated boundaries that can be listed includes human-computer interface (Farrahi Moghaddam et al., 2014), transport protocols (Hofbeld et al., 2014; Rufini, 2014), and micro-registration of streams which will be discussed in greater details in the following subsection.

In terms of protocols, there is a big concern that their designs suffer from a high degree of inefficiency that would translate in degradation in the QoS and QoE even when the ‘physical’ transport media is capable of delivering beyond the required bandwidth (Hofbeld et al., 2014; Rufini, 2014). It has been shown that simple management mechanisms added to the standard TCP protocol could increase the performance toward the ‘dark fiber’ limit (Rufini, 2014). However, it can be argued that such mechanisms should be standardized and officially imported into protocols in order for us to extend their application to all instances. Otherwise, there would be a chance that a promising protocol is abandoned because of its low performance in its primitive form observed in the QoE statistics.

8.1. The Case of a Netflix-like Video Provider/Distributor and ISPs

There has been a big discussion and debate on handling the video traffic through the chain of content distributors, content-delivery networks (CDNs), and retail ISPs (Frieden, 2014; Krämer et al., 2013). Although there have been concerns on whether the associated observed congestion is really related to resource shortage (Frieden, 2014), we assume shortage-driven congestion in the discussion below.

The resource management in overloaded networks is a challenge, and would require revisiting over-promising SLAs traditionally offered to the end users, and imposing quota on the delivered bits rather than the bandwidth alone. In addition to these static approaches, much more can be achieved in the form of collaboration between the content providers and ISPs toward increasing the QoE of the end user even with bandwidth-limited networks.

An example of such collaboration could be at the ‘boundary’ of the video streams themselves. During the prime time hours in particular, numerous streams originated from the content provider or their CDNs
could again be aggregated over short time intervals of a few seconds, for example 5 seconds. We propose a technique called the ‘micro-registration’ of streams to enable considerable reduction in the required total bandwidth in the exchange of a few seconds launching delay for the end users. The aggregated streams can be seen as virtual penetration of the CDNs within the access networks. They could be imagined as ‘cars’ of a train on which new end users are boarded depending on their service request timing. Although the suggested registration time of 5 seconds is much bigger than the suggested 2 seconds limit of the ‘channel zapping’ delay (Lee et al., 2010), we could argue that in our case the user has targeted a specific content and therefore they are not in a random ‘channel browsing’ mode. This makes the extended delay bearable by the user, especially if they are aware of it as part of their service. At the same time, the proposed dynamic, temporal, and smart aggregation of the content streams would provide an implicit way to mistake VoD operation with broadcasting, and in turn would allow semi-multicast approaches to be used in order to handle the bundle of streams (Deering, 1991; Ramos, 2013a,b).

In contrast to the use case of the previous paragraph, in which content has its traditional meaning of either profitmaking or nonprofit business, new challenges are on the horizon with the rise of digital social networks. Exponential growth of the number of connected individuals and their associated devices to billions (Ericsson Inc, 2011) would result in exponential increase in the number events such as personal videos going micro-viral. These content making/sharing episodes are: i) more variant, ii) more ‘localized’, and iii) more ephemeral, and their nature makes them highly dependent on the seamless integration of social and Telco networks. This would push the Telcos to provide Over the Top (OTT) as a service, possibly in the form of Over the top of Telco Clouds (OTT-TC or OT³C). In future work, an approach will be proposed based on smart integration and also a generalization of the micro-registration technique in order to reduce and contain the energy consumption and footprint of personal content broadcasting.

Another approach to address limited bandwidth of networks could be built on the boundary of content. In contrast to traditional understanding of a content that was more about its physical carrier than the content itself, the new ways of access enable more general representations that could go beyond limits of the physical world. One advantage would be to represent an online content in a non-local manner over a vast geographical area. The non-local representation is beyond the cloud-based representation, because in the later although the content could migrate across a vast area, it is always attached to one of those ‘locations’ at any time. The non-local representations, which have been exploited before in the context of point-to-point content sharing, allows a content to be partially present at various locations at the same time. The non-local approach would relax the constraints to deliver the content from the provider/CDN to the end user per service request. Although there will be some questions in terms of copyrighted content, development in terms of content encryption and handling could provide practical solutions (Cieply, 2014; Silverston et al., 2009). Moreover, ever increasing volume of distributor-originated content would practically lead to a copyright agnostic future. The concept of non-local representation of data

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9It shares a metaphorical analogy with the transportation sector, in which the public transport scenario (i.e., the train) reduces the energy consumption and the natural (environmental) footprint while increasing the fluidity of the traffic and reducing the commuting time compared to the individual transport scenario (i.e., personal cars). Similar to the transportation section, all these benefits depend on development of a mutual collaboration among all the actors involved including the landlords (peering ISPs) and train operators (Netflix).
could be further pushed toward other concepts such as data ‘immersion’ and ‘ICT as a part of life’.

Finally, as mentioned in section 4, there are various boundaries of content including the boundary related to encoding/decoding (Grois et al., 2013; Shafique and Henkel, 2014). This boundary could be also tapped in to increase the QoE even when the congestion is high in the network.

9. Boundary of Time

Finally, we would like to mention that boundary of time intervals could have a significant influence on the perceived QoE. Usually, these boundaries are much smaller than the time intervals themselves. However, the associated negative memories could be much more resilient than positive memories at other moments (Moscovitch et al., 2011). One day-to-day example is the rush hour traffic congestion for commuters. Another example could be the prime time hours in the evening for the TV/video users. A final example could be peak hours in electricity-scarce regions that would result in blackouts as an extreme experience.

Another dimension associated with the boundary of the time intervals is the service providing journey itself. Usually, such a cycle consists of several sub-services that should be chained together to build the main requested service. All these ‘chaining’ actions could impose extra processing charges to the user, and therefore could lead to less trust. In contrast, practices, which take the user from the starting point and automatically move them across the intervals and chain links in the form of a service omnibus, would greatly improve the QoE and also rate of success per request.

10. A Case Study of the Boundary of SLA: Multi-tenant Cloud Services

As mentioned in section 6, various SLA boundaries could be considered depending on the nature of the actual users involved. In this section, a case study of the multi-tenant scenarios is discussed. In these scenarios, each user or tenant actually represents a group of users. Therefore, depending on the nature of a tenant’s business, its users would show statistics that could have not been accounted for by the tenant when they set their service layer objectives (SLOs). Although in an isolated operation, where there is only one tenant being served, handling the risk associated with users variability of the tenant is the sole responsibility of the tenants themselves, the risk would propagate to other tenants in actual realistic multi-tenant cases. Although these events of service denial would be highly rare, and mostly show temporal correlation with “social events”, the fear of negative experience of the users would result in the reluctance of many potential tenants to join the multi-tenant ways of operation. In addition, it is worth noting that these exponential growth events initiated from service requests of a tenant in the multi-tenant solution could show similar statistics to denial of service (DoS) attacks. However, they should not be classified as attacks because the request issuer has no intention to harm. We will discuss this point more at end of this section.

In general, multi-tenancy is of interest because of its potential in enabling resource sharing as well as also elasticity. The latter, i.e., elasticity, can be seen as a practical exercise of the ‘right to include’

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10 Such as sport matches (Evens et al., 2011) or the TV prime time hours.
11 It usually stands on the top of the resource sharing, and is sometimes mistaken to be its equivalent.
Tenants willingly participate in a ‘community’ in which they foresee that by providing other tenants with their prospective designated resources by the time they do not require them, they can in return have access to other tenants’ resources at the time they are in need of more resources.\(^{12}\) Although an ‘elasticity’ agreement actually seems to be a generic ‘resource sharing’ agreement, there is a critical difference between these two. In a ‘generic’ resource sharing operation, the participants could ‘freely’ use the resources without an explicit ‘regulation’ in place; this is usually the case of public resource provided to everybody. In these cases, the low level of usage compared to the high volume of available resources would make the generic resource sharing model acceptable for services provided by public bodies. In contrast, in the ‘elastic’ resource sharing operations, the resource pool is actually a potluck indirectly put in by all the participants, and on top of it there is a federal regulator, i.e., the provider of the multi-tenant operation who is responsible to optimally operate the resource allocation among the tenants.\(^{13}\)

The advantage of multi-tenant operations would be considerable, especially when the tenants have some skewed features, such as different operation time zones. However, it would bring a great challenge considering the fact that the size of tenants, their inter-competition, and selfishness would be highly heterogeneous, and therefore opportunism could be exploited. The fear of such a possibility would in turn discourage participation in such a federated resource sharing model. Therefore, complex and smart resource sharing strategies should be developed in order to attract the trust of prospective tenants. Otherwise simple strategies, such as first in first out, would not be of any help. Two boundaries could be identified in multi-tenant solutions: i) the boundary of elastic resources that are horizontally shared among the tenants, and ii) the boundary of the service request entry.

10.1. Boundary of Elastic Resources

Various approach have been explored for the elastic boundaries within the resources (Krebs et al., 2014a,b,c). In short, the problem could be simplified to an optimization problem to set individual weights for every tenant in real time. Following the notation of (Krebs et al., 2014b), the fitness function could be a ‘linear’ sum of individual fitness functions of every tenant:

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J[w] = \sum_{i=1}^{n} J_i (w_i),
\]

where \(w = (w_i)_{i=1}^{n}\) is the set of tenants’ weight, and \(n\) is the number of participating tenants. For a typical tenant \(i\), \(w_i\) at any time indicates the ratio of the resources that would be allocated to them.

\(^{12}\)Although the resources are actually provisioned by the provider, the tenants could virtually claim that they are the resource contributors.

\(^{13}\)It is worth nothing that, in between the two cases of ‘unregulated’ and ‘federally-regulated’ communities, lies another level of community management more commonly known as ‘confederally-regulated’ community (Brzinski et al., 1999a,b; Hamilton, 1787). In the confederal communities, the requirement of having a federal body, i.e., the multi-tenant service provider is relaxed at the cost of lower level of capability to regulate the interactions and resource sharing among the community members. Although federal models are usually preferred, the confederal models would be inevitable when the competition level among the members of the community goes beyond a threshold that would nullify the trustability in any federal body to fairly allocate the resources. We will explore this aspect in the ICT ecosystems in future work.
The cost functions of an individual tenant cost function was defined as:

\[ J_i(w_i) = h_i(l_i)p_i(l_i)v_i(w_i), \]  

(2)

where \( h_i(l_i), p_i(l_i), \) and \( v_i(w_i) \) are functions of heaviness, penalty, violation, and the workload of the tenant \( i \), respectively (Krebs et al., 2014b). The heaviness \( h_i \) was defined as the ratio of the workload of the tenant \( i \) to the averaged workload of all tenants:

\[ h_i = l_i/n \sum_j l_j. \]

The penalty function \( p_i(l_i) \) was defined as a flipped sigmoid function to account for excess of \( l_i \) compared to the quota of tenant \( i \): \( q_i \). This function can be expressed as a function of the ratio of \( l_i \) to \( q_i \):

\[ h^0_{i,i} = l_i/q_i. \]

Finally, the violation function was defined as an exponential function of difference between the response time and the guarantee value \( g_i \) of the tenant.

We propose various enhancements for the multi-tenant fitness function:

1. **Nonlinear combination of individual fitness functions**: when tenants’ size varies on orders of magnitude, the fitness of some of the tenants would act as an outlier that would compromise the service for other tenants. Nonlinear transforms are a possible approach to regularize these outliers without explicitly removing them from the calculations (Breaban and Luchian, 2013; Cunningham and Ghahramani, 2014; Zhou and Barner, 2013).

2. **Addition of memory to the system (reputation of individual tenants)**: There is a weakness to a memory-less fitness function since it would repeat the same mistake providing the fact that the same workload faulty configuration appears. By including a minimal memory, such as that of a Markov model,\(^\text{14}\) the optimizer could learn from the incidents in the past, and then it could reduce the probability of compromising the guarantee of those tenants that work within their quota in future incidents. This could be also incorporated in the form of a reputation factor for each tenant that keeps track of their volatility behaviors. In addition, the memory-enabled models could be used to develop predictive models, as discussed in the next item.

3. **Addition of short-term behavior prediction**: even with the most accurate fitness model, the response time to an incident of exponential increase in the workload of a tenant would suffer some delays. These delays are mainly caused by the requirement to ‘see’ the ‘violation’ in the service in order to apply weight recalculcation. By adding predictive models, which are inferred from the possibility of an incident in highly short intervals based on temporal trends, the optimizer could react and accordingly adjust the weight prior to the event in order to avoid any ‘glitch’ in the service.

\(^\text{14}\)For example, a Hidden Markov Model (HMM) or similar yet more complex models (Yu, 2010).
to other tenants. Memory-based and pattern-based models could be used for such a purpose.

4. **Load-adapted guarantee values**: the quota of a tenant and its guarantee, i.e., $q_i$ and $g_i$, are in practice independent control parameters of the optimizer. Although the ratio of $l_i$ to $q_i$ was used in the penalty function, the ratio of $l_i$ to all workload quotas would be an important parameter in managing possible variability high levels.\(^\text{15}\) Therefore, there would be three heaviness variables: the first two are the previously defined $h_i$ and $h_{i,i}^0$ that measure the ratio of the $l_i$ to the averaged workload and its quota, respectively. The third variable is denoted by $h_i^0$, and is defined as the ratio of the workload to the averaged quotas:

$$h_i^0 = l_i / \sum_j q_j.$$  

The direct consequence of introducing $h_i^0$ would be the requirement to have a load-adaptive $g_i$. In other words, $g_i$ should be compromised when there is an increase in either $h_{i,i}^0$ or $h_i^0$. The reference values for $h_{i,i}^0$ and $h_i^0$ would be 1 and $q_i n / \sum_j q_j$, respectively.

5. **Addition of ‘binary’ inter-tenant fitness functions**: in a heterogeneous multi-tenant community, many tenant ‘pairs’ could be identified based on common features of paired members (two competitive tenants would easily form a pair). By defining binary inter-tenant fitness functions for each of these pairs, the response of the service optimizer in providing a fair and optimized resource allocation could be improved. In particular, many isolation measure could be implicitly implemented using these binary functions. Furthermore, addition of binary terms would help to convert the main fitness function into a standard form that could be rapidly solved using global optimizer, such as the graph cut optimizer (Boykov and Kolmogorov, 2004), without any requirement to use iterative numerical solvers. Hereupon, we propose a new fitness function:

$$J \left[ w \right] = \sum_{i=1}^{n} J_i \left(w_i\right) + \sum_{i,j=1}^{n} C_{i,j} J_{i,j} \left(w_i, w_j\right),$$  

(3)

where $J_{i,j}$ represents the inter-tenant fitness function of tenants $i$ and $j$ of a typical pair tuple $(i, j)$, and $C_{i,j}$ is the correlation between $i$ and $j$. A value of zero for $C_{i,j}$ would mean that the pair $(i, j)$ does not exist. The inter-tenant terms would explicitly depend on the heaviness variables. For a pair of completely correlated tenants, the $J_{i,j}$ is proposed:

$$J_{i,j} = \prod_{k \in \{i,j\}} \left( R \left( \frac{w_k - h_k^0}{h_k^0} \right) \right) + 0 \left\| \frac{w_i}{w_j} - \frac{h_{i,i}^0}{h_{j,j}^0} \right\|,$$  

(4)

\(^{15}\) Although a model based on $h_i$ and $h_{i,i}^0$ would be robust for quasi-static competitive tenants, the ‘normal’ behavior would change from time to time depending on the averaged workload experienced. These changes would not be acceptable in the multi-tenant operations in which each tenant implicitly puts in a portion of the resources in the federated community. Therefore, it is expected that the ratio of the workload to the averaged quota of all tenants should be considered in the modeling.
where $R(\cdot)$ is the ramp function:

$$R(\eta) = \begin{cases} 
\eta, & \eta \geq 0 \\
0, & \eta < 0
\end{cases}.$$  

The second term has a coefficient of zero assuming ‘total’ competitiveness between the members of the pair. However, in milder cases, where there are less levels of competition, this coefficient can be defined as a function of $C_{i,j}$.

The proposed model in equation (3) horizontally explores the boundary of SLA in multi-tenant resource sharing operations. In future, we shall explore its potentials.

10.2. Boundary of the Service Request Entry

The second boundary in terms of our case study is the service request entry. In contrast to common sense understanding of this boundary, we would like to make a challenge and explore possible opportunities to create better experience for the tenants. Figure 2(a) shows the standard picture of a multi-tenant service solution. The actual configuration could be different, but the main components are the same. As mentioned earlier, the rare events of exponential growth of tenant service requests could default the whole multi-tenant community. Although the screening firewall and the admission gate components are planned to disable intentional attacks and regulate request streams, in extreme cases, the information processing of these components could exhaust their available resources, and therefore lead to an unpreventable default. Even in case the abnormal tenant is identified, the challenge will still be in effect because the stream would be directed to the service provider by the transport media.

The approach proposed in Figure 2(b), illustrates smart transport media that could direct the requests and their fragments\footnote{For example, packets in the IP networks.} not only based on their destination address, but also by considering the ‘source’
Figure 3: An illustrative example of the real-time response of the messaging mechanism to an exponential growth in the service requests from a tenant in a multi-tenant scenario. There are two access transport media (ISP networks) that connect the provider to the tenants and the tenant-authorized request sources. a) At $t = t_0$, the exponential trend (tripled after each time interval) is discovered at a 30% load on the screening component of the provider. b) At $t = t_1$, the redirected message has propagated to the first node of the networks. A bearable load of 45% is noticed on the transport media’ nodes. These nodes redirect this load to the non-local TRH. The regulator hub would direct a safe portion of the traffic to the service provider. c) At $t = t_2$, the total load from the exploding tenant is 270% of the capacity of the screening node. However, with propagation of the message within the transport media, the load on the individual nodes at the ‘edge’ of the redirected message ‘wave’ would be still safe and around 68%. The redirected traffic is regulated at the TRH as planned. d) For the purpose of comparison, the load on the screening node would be 270% at $t = t_2$, if not considering the redirected messaging mechanism and the TRH. This is a certain default for the screening component and therefore the whole service solution.

features in their decisions. This solution interestingly resembles the Software Defined Network (SDN) concept. However, in contrast to many other applications, controller-based solutions would not be applicable here at the Internet scales because of independence, heterogeneity, and highly-distributed nature of the transport media. A preferred approach to a smart transport media would be based on ‘smart protocols’ and ‘trusted messaging mechanisms’ that allow rapid reaction to abnormalities even before full deployment of the redirected configuration across all transport media. A non-local Traffic Regulator Hub (TRH) in this solution in considered to handle and regulate redirected requests. Figure 3 shows an illustrative and simplified response of the smart transport media to a redirected request warranted on an exponentially growing request stream of a particular tenant.

Although mechanisms such as Remote Triggered Black Hole (RTBH) (Turk, 2004) and source-based remotely-triggered blackholing (S/RTBH) (Kumari and McPherson, 2009), have been practiced to mitigate distributed denial of service (DDoS) attacks in the form of blackholing the whole traffic directed to a victim destination or the portion of the attacker traffic sourced from a specific location, the proposed mechanism here can be seen to be different from various aspects. Firstly, the exponential growth in the service request cannot be classified as an attack, and therefore it should not be handled with the attack mitigation approaches. In other words, every service request from the abnormal tenant or from the other

\[17\] The criteria do not need to be limited to addresses and many other features of the tenant, and their authorized sources could be used in the decision making.

\[18\] The transport media could be ISPs at different tiers among other media.

\[19\] Based on Unicast RPF Loose Check (Greene and Jarvis, 2001; Savola and Baker, 2004).
tenants should be treated as a legitimate request. The proposed TRH provides a second chance to the requests from the exponentially growing stream. Secondly, any harm to the service provider access would substantially affect its other tenants, and therefore the acceptability of multi-tenant concept would stay low within the prospective tenants. The proposed mechanism would provide a way to split the streams aimed to the multi-tenant provider, and protect the quota-abiding streams. Thirdly, the service requests from a tenant could be less source-specific and more ‘task’-specific. Therefore, a more complex language at the protocol level is required in order to code the specs of the sender rather than its address, and then use the coded information in order to make smarter decision at the routing nodes. It is worth noting that decoy routers and servers have been proposed in order to redirect the traffic of an attacker off the victim servers (Okada et al., 2014). In contrast, the proposed TRH concept can be seen as another multi-tenant service solution that serves many multi-tenant providers at a hierarchically higher level. In other words, the same beneficiary advantages of the multi-tenant business model could become the motivation for a multi-tenant TRH business that allows sharing the TRH’s TOC among its customers (which are actually other multi-tenant businesses). This could be of great interest considering the rareness and possible uncorrelated nature of the exponential growth events across different businesses. Moreover, the fact that the TRH service would be placed outside the immediate access networks of the providers would further protect them even in the case of failure of the TRH service itself.

10.3. Multi-tenancy approach to virtualized radio access

Although the focus of the case study of this section has been on compute services, a similar approach can be used in the case of bandwidth or access services. In particular, and thanks to developments toward virtualized base stations of cells of various sizes (Costa-Pérez et al., 2013; Ghebretensä; et al., 2010), it is possible to plan a multi-tenancy service that serves Telco operators. Although the operators would have still their own access networks, the service provider will leverage on the benefits of resource sharing that would benefit all participants. Moreover, aggregation of the operators’ base stations in the form of the service provider’s would reduce challenges and also costs associated with interference, especially in dense urban areas. However, the challenge would be the high level of competition, and therefore a highly trustable resource management is required to attract the operators. In future work, an extension of the multi-tenancy management proposed in section 10.1 will be developed for the case of virtualized radio access networks.

11. Monetization of the QoE

In contrast to the QoS that can be directly referred to in the SLAs and then be monetized, the QoE features could not be processed in the same way unless they are explicitly integrated or reflected in the QoS. In contrast, the QoE could provide an implicit mechanism to induce the loyalty of users to the provider, increase the user base, and improve the internal efficiency that make the business more profitable. The QoEaaB can be seen as a instrument to discover and identify innovative and user-involved actions that would provide a user with the peace of mind and at the same time would offer the provider with unique innovations that may ‘differentiate’ them from the rivals.
12. Conclusions and Future Prospects

Quality of experience has attracted many researchers considering convergence to a parity among providers in terms of many other metrics. In this work, a new approach to the QoE has been presented in order to provide a pathway for exploring unseen and novel opportunities to create high-quality experience for the users. The main aspect of this approach is the ‘at a boundary’ concept that results in the QoE at a boundary notion. Various boundaries were examined and discussed, especially the boundary of property, contract, SLA, context, content, and time were considered. In addition, specific boundaries associated with different user types were discussed. As a case study, two boundaries associated with the multi-tenant solutions have been explored, and some fitness functions and configurations have been proposed in order to provide better experience to the tenants. In future work, each of these aforementioned boundaries will be considered as an opportunity to improve the QoE, and proper metrics to assess their potentials will be developed.

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