Towards a Decentralized QoE Layer for the Mobile Internet

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Abstract — **Network selection on current mobile devices has to be done manually by the user and is furthermore strongly dominated by monopolistic telecom operators. A decentralized Quality of Experience (QoE) layer supported by a QoE knowledge base filled with automatically and user created QoE reports will offer a basis for user-centric and optimized network selection for users in the Future Internet. An automated handover from one networking interface to another can then be performed by a mobile or portable device automatically. This papers focuses on how a decentralized QoE layer for the mobile Internet can be achieved by describing how a QoE model is defined and QoE reports are gathered, shared and distributed. The content of this paper is based upon the results of the PERIMETER project. PERIMETER's main objective is to establish a new paradigm for user-centricity in advanced networking architectures. The PERIMETER middleware is briefly explained and testing methodologies for involving the user in the process of creating a user-centric QoE based mobile Internet are presented.**

Keywords - Quality of Experience; User-Centric; Seamless Mobility; Always Best Connected; Future Internet

I. INTRODUCTION

Telecommunication network management practices are strongly rooted in the monopolistic telecom operators. The liberalization of the operators has only changed the landscape in a way that there are multiple closed operators rather than one closed operator. As a result they are usually centrally managed, poorly integrated with outside components, and strictly isolated from external access. On the other hand the IP world has been about internet-working from its conception on. Furthermore the exposure of users to the prolific Internet services means that similar service models will have to be provided by the next generation telecom networks. The clash between these two opposite approaches poses important challenges for network operators. This is due to the fundamental risk associated with their networks turning into mere bit-pipes. In order for future telecom networks to be economically viable, they should provide similar user experience with Internet services, albeit in a more managed and reliable manner.

There lies the grand challenge of the so-called Telco 2.0 operators. The operators have to offer even more data intensive applications on their networks to make their operations profitable. This comes in a time, when the increasing data traffic is starting to hurt user experience, and pose itself as the biggest risk facing the operators [1].

Therefore, as we believe, a paradigm shift in the Future Internet is needed. Away from centralised, closed and single contract model towards an IP world where the user is consuming the services based upon their needs in the multiple-access multiple-operator networks of the Future Internet.

The approach presented in this paper is based upon the findings of the PERIMETER research project [2] which aims at establishing new paradigms for user-centricity in networking architectures. PERIMETER uses Quality of Experience (QoE) models to ensure user-centric optimal network usage. The finding of a user-centric QoE model is described in Section II. Section III focuses on the PERIMETER middleware and Section IV on how gathered QoE knowledge is spread in a mobile network. Section V describes the actual process on how QoE information is gathered and computed. The paper concludes with the testing methodologies as well as a summary and the future work ahead for the PERIMETER project.

II. DEFINING A USER-CENTRIC QOE MODEL FOR NETWORK USAGE – THE PERIMETER APPROACH

Nearly all portable and mobile devices nowadays contain a variety of network interfaces, among these GPRS, UMTS, WiMAX or WiFi. Additionally, today's devices allow the user to have a larger set of different contracts with different operators, e.g. with the use of multi-SIM-card-devices or by accessing WiFi hotspots. However, changing a connection from one networking interface to another is still the responsibility of the user. The PERIMETER approach

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targets at shifting this responsibility from the user to the device itself. Therefore PERIMETER is targeting a paradigm shift in the Future Internet where the user is in an Always Best Connected (ABC) state, where ABC is defined by the user's preferences and his or her environment. Additionally, if an unknown connection is encountered, e.g. a WiFi hotspot, the new connection is evaluated based upon the information and data gathered by other PERIMETER users – besides the physical data of the connection quality.

To define a QoE model of all connections available to the user, we need to identify parameters and user preferences which should be considered in the model. To identify these we use a scenario driven approach. In this approach real life scenarios are developed and the relevant elements are transformed into preferences and data input for the QoE model. The scenarios offer us sets of preferences and data input in the following categories:

- Connection cost
- Connection quality
- Security / Privacy
- Battery life

An excerpt of a common scenario is given below:

"Also, Linda, the lawyer that was conducting the transaction was concerned. It was not the cost of the call, but her privacy. She felt uneasy about how much private information could be disclosed from someone just knowing the existence of such a call. She really wanted no one to be able to trace her and to learn that she was not in her office but in another country where a huge deal was expected to finalise. And, even worse, if just one would know that she was talking with Helen at that time of the day…. She was aware that her calls leak location and identity, and could impart other information also. Her only hope was that nobody was keeping track of this call."

The scenarios offer also a possibility to test the PERIMETER approach in a Living Lab [3] environment (see Section VI).

III. THE PERIMETER MIDDLEWARE

The PERIMETER middleware architecture is based on the traditional layered architecture approach. There are two types of PERIMETER hardware nodes, the PERIMETER Terminal which is a mobile handheld device with certain resource restrictions, e.g. storage space, and a Support Node which has no resource restrictions, such as a server or laptop.

The architecture depicted in Figure 1 permits users to experience seamless connectivity while on the move. The PERIMETER components include:

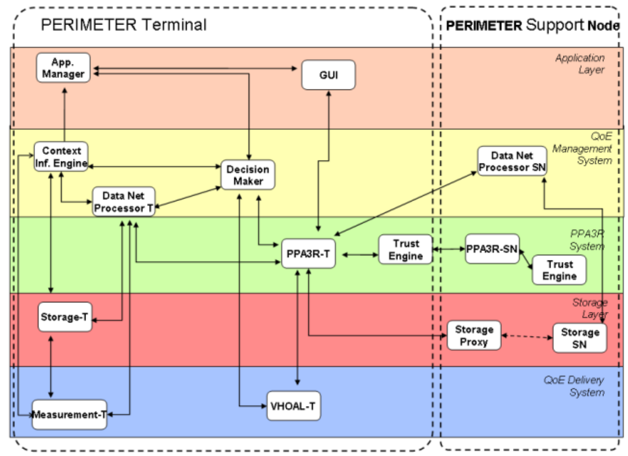

Figure 1. PERIMETER Middleware Architecture

- The *Application Layer* consisting of the Graphical User Interface (GUI) and Application Manager which provides the user with an intuitive interface to the entire PERIMETER system.
- The *Context Inference Engine (CIE)* which collects raw source data, such as geographical location and network information, and infers high level context information from this.
- The *Data Network Processor (DNP)* processes information relevant for making a decision about how satisfactory the current connection is for the user based on their context (from the CIE) and other contributing factors.
- The *Decision Maker* component decides whether a network switch is required based on information from the DNP and CIE. It also decides which network should be connected to.
- The *Privacy Preserving Authentication, Authorization, Accounting and Reputation (PPA3R)* module provides identity management, anonymisation and pseudonimization.
- The *Trust Engine (TE)* performs computations on data processed in the PERIMETER system, assigning trust and reputation values as appropriate.
- The *Vertical Handover Abstraction Layer (VHOAL)* and *Measurements* modules are charged with the task of seamless switching of networks.
- The Storage Layer takes care of storing and retrieving local and historical information using a peer-to-peer approach.

The interaction of these components provides a comprehensive architecture upon which the premise of the PERIMETER paradigm is built.

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IV. A DISTRIBUTED QOE KNOWLEDGE BASE FOR MOBILE INTERNET

QoE reflects the collective effect of service performances that determine the degree of satisfaction of the end-user, e.g. what user really perceives in terms of usability, accessibility, retainability and integrity of the service [4]. Until recently, seamless communications has been mostly based on technical network Quality of Service (QoS) parameters, but a true end-user view of QoS is needed to link between QoS and QoE. While existing 3GPP or IETF specifications describe procedures for QoS negotiation, signaling and resource reservation for multimedia applications, such as audio/video communication and multimedia messaging, support for more advanced services involving interactive applications with diverse and interdependent media components is not specifically addressed. Such innovative applications, likely to be offered by 3rd party application providers and not the operators, include collaborative virtual environments, smart home applications and networked games. Additionally, although the QoS parameters required by multimedia applications are well known, there is no standard QoS specification enabling to deploy the underlying mechanisms in accordance with the application QoS needs.

For the Future Internet to succeed and to gain wide acceptance of innovative applications and service, not only QoS objectives but also QoE have to be met. Perceived quality problems might lead to acceptance problems, especially if money is involved. For this reason, the subjective quality perceived by the user has to be linked to the objective, measurable quality, which is expressed in application and network performance parameters resulting in QoE. Feedback between these entities is a prerequisite for covering the user's perception of quality [5].

The PERIMETER project investigates a user-centric networking paradigm for future telecommunication networks, where users not only make network selection decisions based on their local QoE evaluation but also share their QoE evaluations among each other for increased efficiency and accuracy in network selection, as depicted in Figure 2. In this paper we present the conceptual framework introduced by PERIMETER to achieve such user-centric network architecture for sharing and exploiting user quality of experience data. The focus here is on the utilization of a distributed *knowledge base (KB)* of QoE reports for improving network access selection decisions, while the actual implementation of the KB is out of the scope of this paper. The reader is referred to technical reports and public deliverables of the PERIMETER project for further details [2].

In order to make user-centric decisions and share user experiences based on the QoE, a software entity must first evaluate and quantify QoE for a given set of inputs including the network interface and the application running on the user terminal. Named as the Data Network Processor (DNP) in PERIMETER, this entity is responsible for calculating, from network performance measurements, user's context information and user's feedback, a QoE descriptor (QoED).

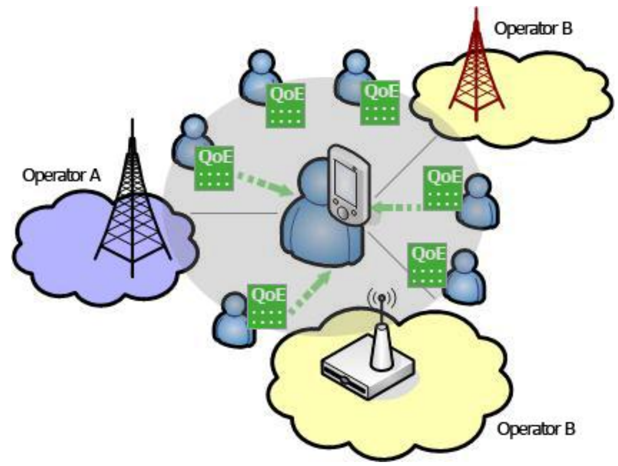

Figure 2. Future user-centric networking paradigm based on a QoE framework.

Each QoED item is an aggregate and synthetic description of the quality of the user's experience. It consists of a set of key parameters that summarize the quality of service from a user's point of view:

- Mean Opinion Score (MOS) for different types of applications
- Cost rating
- Security rating
- Energy saving issues

Once the QoED is calculated, it is uploaded onto a distributed *knowledge base (KB)*, which is a peer to peer storage module running on user terminals and on the so called support nodes specifically deployed by the operators with the incentive of obtaining user QoE reports more efficiently. The distributed knowledge base of QoE reports can then be probed with a QoED query (QoEDq) in order to obtain past QoE reports of other users for decision making, as will be described later in more detail. A QoEDq consists of a set of optional parameters that are used to filter network performance and user's context information stored both locally and globally. These filters apply to:

- Network connection, to get performance information and QoED items associated to it
- Application information, to get QoED items calculated for applications of the same class
- Geographical location, to get QoED items calculated at the same area
- User's id, to get QoED items calculated by a certain user

A QoEDq item may contain all or just a reduced set of parameters, allowing a wide variety of queries: QoEDs associated to a certain provider or a certain technology, etc. The calculated QoED items are mainly utilized by the

Decision Maker (DM), which will be described in the following section.

The DNP may generate QoED reports in two different ways: (i) Subscription based reports, where a certain component, which acts as a client from the DNP's point of view, subscribes to the reception of QoED reports according to a specific QoEDq. (ii) Unsolicited reports, where the DNP takes the initiative and sends a QoED report to all the components that offer a receiving interface for this type of events. The unsolicited reports are triggered by events that are related to an imminent handover action due to a significant change of network conditions, for example, signal loss. In this case, the QoED specifies the network that triggered the event and the actual user's context description (location, application under use, etc.).

V. USER-CENTRIC DECISION MAKING FOR IMPROVED QOE

The knowledge gathered by the DNP through local and remote QoE reports, user context information, and user preferences are all fed into a controller entity on the mobile device, named as the Decision Maker (DM) in PERIMETER. This is the entity that makes use of all those QoE related inputs to take allocation decisions for all the applications running on the terminal. The decisions that the DM is responsible for taking are what we call *allocation decisions*, where different applications running on the terminal are allocated to different access networks operated by different network providers. From this perspective the atomic decision is the movement of an application from a certain Point of Attachment (PoA) to another. This decision is made based on local and remote QoE reports, abstracting the network and subjective user satisfaction, context reports, and user preferences. The main purposes of the DM can be listed as follows:

- Take allocation decisions on which operator will be chosen for the applications
- Utilize local and remote QoE reports for the decisions
- Utilize context reports for the decisions
- Utilize user preferences for the decisions
- Infer the failure mode that has led to degradation in the QoE

The novel PERIMETER approach, in which users share their experiences, allows novel decision algorithms to be developed. Within this scope, the DM differentiates itself from the state of the art decision mechanism in the following aspects:

- *Failure Mode Inference*: The DM is able to discern the cause of the problem that has led to the degradation in QoE. The degradation can be due to a problem at the application service provider side, core network side, access network side, or at the air interface, as depicted in Figure 3. This novelty has two advantages. First of all, it minimizes the number of allocations that require handovers, which puts burden on network components, and degrades the QoE even more for their durations. Secondly, the users are not concerned with the actual cause of degradation in the QoE. They have a holistic view of the application and the service agreement. If an application is not running on an operator network properly, they will most likely blame the network operator, and give a bad MOS input. Thus there is an incentive for the operators to select decision mechanisms that are able to discern the causes of the connection problems. This information can also be used for network optimization purposes.
- *Reasoning*: The fact that users will be exchanging information about subjective measures on their applications requires a common understanding and agreement on the concepts that make up these subjective measures. This necessitates a semantically enhanced representation of the stored information. Reasoning algorithms will be used for performing Failure Mode Inference and taking the appropriate decisions based on the inferred failure mode.
- *Distributed Probing*: Thanks to the PERIMETER middleware, a distributed database of network performance data as experienced from different locations is available. This allows a practical implementation of the distributed probing of the network. This approach is used for Failure Mode Inference at the first stage, but it will be investigated for further utilization purposes that may benefit the network operators as well.

The DM requests sets of remote QoE reports, which are delivered in form of statistical distributions, a mathematical representation of the QoE reports. Within the Failure Mode Inference these distributions are fed into a Bayesian Network, which outputs the probability that a specific failure in some part of the network occurred. The comparison of user generated QoE reports is based on the assumption that users connected via the same Access Point share the same or at least parts of the route to a certain service and thus experience similar problems accessing their service or using a specific application.

In order to deduce which part of the network is affected by impairments (e.g. congestion), those QoE reports are requested from the distributed Storage that complement the view on the network. Following our assumption this includes remote user QoE reports of the currently used PoA and service. These two sets of QoE reports correspond to random distributions, one distribution of users' experience of our PoA and one of users of other PoAs using the same service or application.

Based on these two distributions from randomly selected users the most likely source of an impaired local QoE should be inferred. The events within each distribution are further categorized into two quality states that reflect users MOS,

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namely good and bad. These quality states can now serve as an input to the Bayesian Inference mechanism that is capable of performing inference in the face of incomplete knowledge (randomly chosen subset of users) and uncertainty (unconsidered causes for the QoE degradation). The outcome of the reasoning process in the Failure Mode Inference (FMI) component is either that a failure in a specific part of the network is most probable (in the Access Network (AN) or in the Service Domain (SD)) or the cause for impairments might remain unsolved.

While the FMI is used for the current allocation only, another inference mechanism called Prospective Network Analysis (PNA) makes use of remote QoE reports to determine the QoE that can be expected for a specific prospective PoA. Again remote QoE reports are requested, this time for the prospective PoA and the used service. The received distribution is then used to calculate the mean MOS for the prospective PoA. If the outcome of the PNA suggests that the prospective network has most probably no positive effect on the QoE the application will remain at its current PoA.

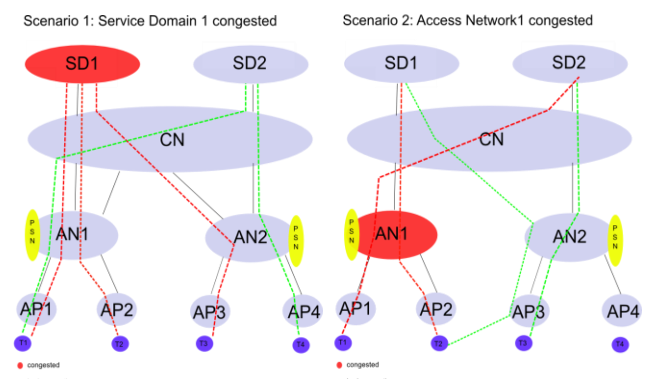

Figure 3. Different modes of failure in a multi-operator, multi-access-technology environment.

VI. TESTING THE APPROACH

The proposal of a distributed knowledge base and user-centric allocation decisions based on this KB in PERIMETER requires an experimentally driven research approach in order to (i) fine-tune and optimize the decision parameters in the proposed framework, and (ii) ensure healthy progress of software development through the implementation-testing cycle. On these grounds, PERIMETER makes a distinction between the definition of *testing* and that of *experimentation*, and each is handled differently within the project.

A. *PERIMETER Testing Process*

In PERIMETER, testing is considered to be the continuous process needed in software development. The Agile software development methodology [6] was chosen for use within the project as it was considered to be the most adaptable, fluid and iterative methodology from those evaluated. Coupled with this, it has been successfully applied to large scale projects previously (for example [7] and [8]) and has been proven to lead to higher quality software when compared to using traditional methods [6]. In PERIMETER, the use of Agile is combined with a Test Driven Development (TDD) [9] approach to provide the adaptable, fluid and iterative development and testing cycle that is required [10].

The need for processes, supporting tools and automation is necessary for the success of most software projects, but is essential for the success of large scale experimental ventures. PERIMETER employs a number of processes and tools [11] to aid the processes of team collaboration and communication, testing, continuous integration (Hudson) and structured software development.

In this stage of development and testing, i.e. in a continuous build environment, a number of testing processes including unit (white-box), functional (black-box) and integration testing, are conducted to ensure that the developed software is brought to a level where it achieves its functional objectives.

B. *PERIMETER Experimental Process*

In PERIMETER, experimentation is needed to guarantee the success of the research, its innovation and the usability aspects of the project. These are verified in two large scale, state of the art testbeds, one in Waterford Institute of Technology (WIT) Ireland and one in Technical University of Berlin (TUB), Germany. These testbeds are interconnected over a Layer 3 connection. This interconnection was then matured to a Layer 2 federation in the final phase of the project. PERIMETER has also applied for, and was successful in procuring a FEDERICA slice (5 virtual nodes) for use in the project [12].

Conformance tests are performed on the PERIMETER system installed and running on the federated testbed to ensure that key components of the system are functioning as expected. These tests are complemented with interoperability tests to ensure the end-to-end functionality of the system is as expected. These processes are tested against the scenario under analysis, in the scenario-driven approach used in this project in order to demonstrate that the testing process is robust and to ensure the verifiability and reliability of the results. It is essential that both testing processes were repeatable and reproducible in order to achieve this. Application testing for the specific applications running on the federated testbeds is also performed.

This process is further complemented by the employment of a user-driven approach to the requirements specification and the determination of features and subsequent testing phases with the use of Living Labs [3] and dedicated usability sessions. Performance and scalability issues are addressed with the introduction of emulation and simulation of network conditions.

C. Role of Testbeds in PERIMETER

The distinction between testing and experimentation in PERIMETER allows the role of the federated testbed within this process to be further examined. The build environment which is used for the testing process allows a certain level of testing to be achieved. However, it is within the federated testbed environment where a greater level of realism can be determined with the testing and experiments conducted. The use of the testbeds allows the system to be tested from beginning to end in a realistic environment using real platforms, applications, devices and users. Without the federated testbed, the cost of achieving this level of realism would be greatly increased.

Testbeds can be successfully used to control the cost of achieving realism in experimental activities [13]. In PERIMETER, it was found that not only does the use of the federated testbed control the cost; it actually does this without actually increasing cost but whilst increasing the level of realism achieved.

VII. SUMMARY AND OUTLOOK

The increasingly dynamic nature of the telecommunications scene is expected to go beyond the technical domain and also cover business models and socioeconomic aspects of telecommunications, eventually giving rise to the user-centric network vision foreseen by the PERIMETER project. There are many challenges, both technical and socioeconomic, that need to be addressed for this vision to come true, such as the need for a standardized view of QoE among all stakeholders that should act as a common performance and valuation criterion. In this paper we have focused on the exploitation of an open QoE knowledge base for more intelligent and user-centric interface selection, which can also provide benefits network operators in terms of resource utilization.

Currently the development PERIMETER system is in its final stage and Living Lab tests with real users are being conducted in two inter-connected testbeds, one in Waterford, Ireland and one Berlin, Germany. The tests will provide experimental results on user acceptance and about PERIMETER's usability in a real life environment.

ACKNOWLEDGMENT

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