The Quality of Experience Perspective toward 5G Technology

Laura Pierucci

Abstract

Quality of experience (QoE) is the subjective acceptability of the quality of a telecommunication service perceived by the user. This paper expands the vision to new QoE acceptability for the future 5G networks and analyzes the impact of the main challenges of 5G on QoE. An efficient QoE estimation method tailored for 5G systems is also proposed based on the neural network (NN) approach. Due to their ability to fully learn the causal relationship between network parameters of quality of services (QoS) and the resulting QoE, NN can be suitable to gain QoE self-optimization for 5G. Again, new increasingly smart user devices will be delegated to handle the most burdensome tasks of ensuring user satisfaction.

Introduction

Mobile broadband subscriptions will reach 6.5 billion by 2018, according to the Ericsson Mobility Report [1], and these subscribers will make an unprecedented number of requests for real-time multimedia applications. Mobile data has surpassed voice traffic, with few words and many connections (a high percentage of this traffic is generated by access to social networks), and smartphones overtaking client PCs. The increasing demand for data services over the Internet has driven the development of the third generation (3G) and fourth generation (4G) standards in the last five to 10 years, starting with the Third Generation Partnership Project (3GPP) High Speed Packet Access (HSPA) standard in 2005, passing through Long Term Evolution (LTE) in 2008, and LTE-Advanced in 2011, to the standardization of the fifth generation (5G) system, expected in 2018. In parallel, IEEE has standardized various other wireless local/personal area systems, thus 4G mobile terminals already have WiFi, Bluetooth adapters, etc., as well as Global System for Mobile Communications (GSM) and 3G integrations. A unique terminal will absolutely be used on 5G systems, but it should also be able to have a variety of wireless access for the same session.

The focus in 5G is on the needs of user equipment (UE) by changing the *cell-centric* concept of the network to a *device-centric* design [2]. The vision is that of a dynamic network consisting of many interconnected end-user devices or sensors, in the context of Internet of Things (IoT) closely related to the concept of *network densification* [3]. New traffic generated from various device-to-device (D2D) communications, such as in smart grid, smart homes and cities, and e-health scenarios with different communications characteristics, will need intelligent management requirements.

Future 5G networks will also be characterized by high bandwidth content with speeds in excess of 10 Gb/s, various mobility levels, and energy and cost-efficient solutions with the augmentation of the wireless world's intelligence, but they should also meet the satisfaction of users, the so called *quality of experience*. Traditionally, in 3G-4G systems the QoS is considered in order to estimate the performance of the mobile network for a service with a guaranteed service level [4]. QoS is intrinsically a technical concept and it enables network operators to isolate traffic into flows based on attributes, such as traffic types (voice, video, or control) or application requirements (throughput, latency, and/or jitter), and then transport each flow accordingly, resulting in a growing need for network optimization and maintenance. The user does not evaluate the individual network element, but he considers the overall system performance, the price of the service, the perceived quality of the content and the easy of use of an application, that is, the QoE.

This article starts with the main concepts and definitions of QoE provided in the context of 3G and 4G systems, then expands the vision to new QoE acceptability in 5G networks. We address how the new reference guide should assess the QoE methodologies and how the key challenges of 5G can improve user satisfaction. Moreover, an efficient QoE estimation model based on the use of NN is also suggested as being suitable to adopt in 5G systems.

This article is organized as follows. We describe the QoE concept developed in 3G and 4G networks. The main challenges of 5G systems are highlighted and their impact on QoE is analyzed. We present an analysis of the QoE estimation model based on NN. Finally, the conclusions are provided.

The author is with the Universitá di Firenze

This work was supported in part by Telecom Italian Mobile.

QoS/QoE Concepts

The rising interests in new real-time and multimedia applications lead to higher levels of quality of service.

The QoS was introduced to optimize the operation of the network for providing a service with a guaranteed service level. The objective metrics used to determine the end-to-end QoS are typically packet loss, delay, jitter and throughput. The user does not perceive the individual network element but feels the overall system performance. Therefore, the operator needs to adopt and implement new QoS management policies in order to ensure user satisfaction and avoid subscriber churns. To highlight the user point of view, a new metric was introduced, the quality of experience.

According to the International Telecommunication Union-Telecommunication Standardization Sector ITU-T P.10/G.100 Recommendation, the QoE can be defined as "*the overall acceptability of an application or service, as perceived subjectively by the end-user*." The European Network on QoE in Multimedia Systems and Services, Qualinet (COST Action IC 1003) is agreed on a new definition of QoE as in the following [5]: "*Degree of delight of the user of a service. In the context of communication services, it is influenced by content, network, device, application, user expectations and goals, and context of use.*" Therefore, the customer perception of the data services depends on the network infrastructure but also on the type of the UE (whose choice and performance are entirely beyond the control of individual mobile operators) and on the content providers accessibility (which is also completely independent of the goodness of the network).

Based on this definition, managing and measuring QoE becomes a complex task; therefore, the ITU-T G.1011 Recommendation provides a reference guide to QoE assessment methodologies [6]. Traditionally, QoE has been evaluated by qualitative methods that focus on voice perceptibility or applications usability and it is often obtained in laboratory environment. Subjective methods need user collaboration to provide mean opinion score (MOS) of the degree of satisfaction. These tests can be alterated by the typology of users group (experts or not in the use of applications) and do not consider the performance of the network providing the service. Other solutions are focused on including passive probes or network analyzers responsible for capturing the traffic measurements and for monitoring objective parameters like packet loss rate and latency. By using these traffic reports it is possible to define a mapping of QoS towards QoE values [7, 8],

Due to the growing number of new tablets and smartphones which increases the user expectations, it is important for the operators to know and to measure the UE performance. The users are accustomed to use an application on a PC-based platform and if the application is slower to run on the UE, they stop it because they are annoying to wait. By benchmarking the terminals performance and by analysing the cause for faults, it is possible to measure the QoE perceived from the user equipments perspective.

QoE toward 5G Perspective

The main challenges for 5G technology are the greatly increased amount of data generated by evolved applications, a massive number of devices to connect to different radio-access technologies (RATs), and the need for high quality services [2, 3, 9, 10]. These challenges are detailed as follows:

- High typical user data rate from 1 Gbps to 10 Gbps.
- Heterogeneous network architecture consisting of a mixed use of infrastucture elements such as macro-cells, micro-cells, and pico-femto-cells, and relays for interworking different cellular and wireless local area network standards.
- Ultra-low latency in the era of the tactile wireless Internet, with total end-to-end delay of less than 1 ms.
- Flexible use of spectrum, from spectrum refarming and spectrum sensing up to the use of millimeter wave frequencies (30 GHz to 300 GHz).
- A massive number of connected devices, from the few hundred devices per base station served in the current cellular systems to more than 104 connected devices required in some machine-to-machine (M2M) services.
- Devices that are smarter than 3G-4G devices.
- Ten times longer battery life for low-power massive machine communications.

In this section we discuss how the above 5G features should account for an improvement of QoE, highlighting the unique impact of 5G network design and the more active role user devices will play in user satisfaction.

The main challenges for 5G technology are the greatly increased amount of data generated by evolved applications, a massive number of devices to connect to different radio-access technologies, and the need for high quality services.

Data Rate

The current WiMax system can offer up to 128 Mbps downstream (56 Mbps upstream) and LTE has a theoretical peak capacity of 100 Mbps downstream (50 Mbps upstream) in ideal conditions. IMT-Advanced should be able to offer a nominal data rate of 100 Mbps downstream even at high speeds and a theoretical maximum of 1 Gbps for nomadic use. For 5G technology, the peak rate may be increased to 10 Gbps with user data rates greater than 100 Mbps even under high load conditions or at the cell edge. This high data rate is justified by the need for huge downloading of multimedia services, and it has also been traditionally envisaged to provide better satisfaction to the users. However, in recent years the growing number of tablets/smartphones and the new development of apps have changed the type of traffic. Smart phones have "always on" applications such as instant messaging, push email, and social networking, which are generally applications that require low data throughput.

Under this assumption, a new analysis of the degree of user satisfaction is necessary. For example, in a study of HSDPA data collected from network counters of the Telecom Italian Mobile (TIM) operator, two important regions may be associated with user satisfaction as shown in Fig. 1. The network operator aggregates the raw HSDPA data into specific key performance indicators (KPIs) to monitor the performance of

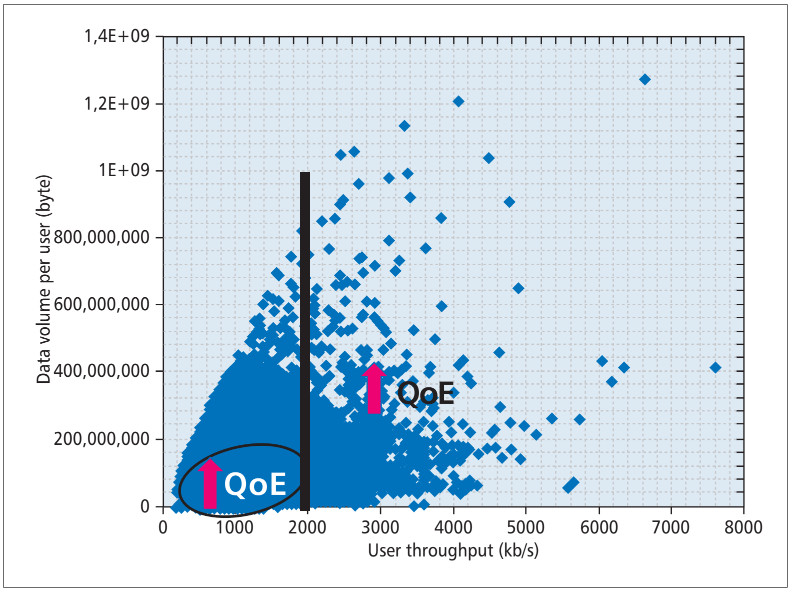

Figure 1. Data volume with respect to throughput regions with excellent QoE.

the telecommunication network in terms of warning status, traffic load, service quality, etc. KPIs are quantifiable metrics used to verify if the network could work well enough so that end-users' applications will be satisfied. Fig. 1 shows the data volume per user with respect to throughput, and according to the above discussion on user needs, we can assign an excellent QoE score for the two regions highlighted: the region to the right of the solid line where high data volume and high throughput are provided, and the region inside the circle where low throughput and low data volume per user can be envisaged due to the use of specific apps. Another example is on the following LTE data, shown in Fig. 2. In this case, we can also see that the requirements in terms of data volume are not so high due to the push applications used during the considered period. As a result, a low data rate does not imply a dissatisfaction for the user.

Heterogeneous Network Architectures

Networks will become much denser with many more cells with decreasing size from macro-cell to the most modern small cells as well as direct device-to-device communications. Small cells improve capacity and cellular coverage with lower cost compared to macrocells, and they are expected to carry the majority of traffic. Bringing the base station closer to the user, they can promote lower power use and more energy efficient communications. Due to the increasing volume of indoor traffic, approximately 80 percent of the volume of outdoor traffic, femtocells will always be more prevalent to cover houses, offices, etc., and will interact with existing networks. This *network densification*, as defined by Qualcomm [3], requires the need to minimize the interference toward macro (and vice versa) and to adjacent femtos. Consequently, new efficient schemes for interference coordination should be envisaged. Self-aware networks will be essential for the interaction of different equipment types and devices, for the coordination of resource use among nodes, and for the distribution of the traffic to the cells involved. Mobile small cells can be carried out if the devices are installed on cars and trains along with the idea of promoting M2M communications. From the point of view of users, small cells can limit QoE because the user could always stay *to reload the page continuosly* due to interference problems. The Internetworking of 5G systems with wireless local area networks (WLANs) influences QoS; therefore, we expect that such a choice will also influence QoE. This means that an eNodeB must service many different bands with different cell sites and sizes. Efficient inter-systems handover techniques should be envisaged to choose the most appropriate wireless access technologies to satisfy application requirements and, consequently, user expectations.

Ultra-Low Latency

Emerging monitor and control applications with very low wireless data rates combined with very low energy consumption and with *zero latency* (less than 1 ms) are expected to be components of 5G systems. The concept of zero latency will be a key aspect of 5G for games, augmented reality, or machine control in the era of the tactile Internet. In these ultra dense deployments, where many devices must be connected in a distributed manner, management is more challenging than content distribution, which is the salient factor for the 4G network of the Internet age. The new directions of smart grid, smart homes and cities, e-health applications such as remote surgery, and remotely-controlled robot applications, need low latency. Time critical delivery of alerts in M2M communications for traffic safety and also the new *social networks* (where devices can interconnect with each other and offer a cooperative exchange of information in case of emergencies or special events) draw support from the total end-to-end delays of less than 1 ms.

It is generally accepted that latency must decrease in line with the rising of data rates. Many sub-networks can be created to manage a proportional part of the traffic load to decrease the radio round trip time (RTT) for lower latency. Therefore, the optimized RAT in small cells, must provide a latency lower than 1 ms. From the point of view of user expectation, especially for highly interactive mobile applications, the delivery delay is a key factor. If the loading of a web page is slow, the user simply stops the application or changes to another provider. The content providers, the mobile network infrastructure, as wellas the type of the equipment, all affect delivery delay. Figure 3 shows an example of network latency and UE latency for several models of terminals [11]. The network and the UE latency are obtained by monitoring RTT associated with whatever data service is based on transport control protocol (TCP) (e.g. web browsing, HTTP, YouTube progressive downloading). The TCP connection establishment uses a three-way handshake so when a UE sends a TCP/IP packet with the bit SYN (synchronize sequence numbers) active, a timer starts for computing the RTT. When it receives a TCP/IP packet from the server with the bit SYN ACK (synchronize acknowledgement) active, the counter provides the measure of the latency of the server response to the request of the client (called in the following NW_latency). This measurement considers the load conditions of the external network and the content server response time. Finally, when the ACK message from the UE to the server is received, the end-to-end RTT will be completed, and this measurement provides information to the latency related to the network infrastructure and to the type of terminal (called UE_latency) providing the way to analyze QoE. The network latency is mostly dependent on the content server response time, and the NW_latency values are similar for all the mobile devices, as shown in Fig. 3. The UE_latency, instead, depends on the network but even on the behavior of the devices.

Smart phones have "always on" applications that rely on keep alive messages, for which smart devices send eight times more signalling for the dedicated radio resource allocation than laptops. The other factor that influences the UE_latency is the response time of the apps to the servers. Not all apps behave the same way in different types of terminals. Starting from 4G technologies, the evolved packet core network defined by 3GPP is based on IP. By reducing the number of hops in the network infrastructure, data travels faster between the end points, greatly reducing the latency to support real time applications. The goal of *zero latency* in 5G smooths the impact of the network infrastructure on QoE, and the problem of low latency will be moved toward the characteristics of the terminals for the customer perception of the services.

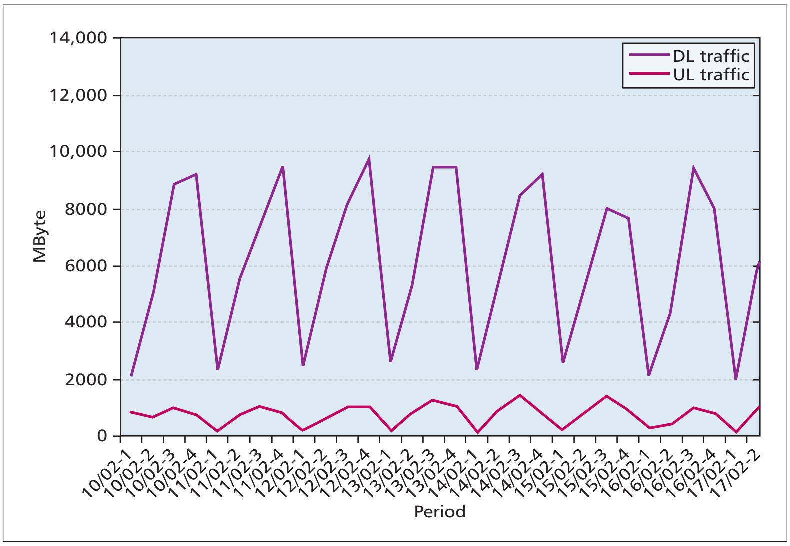

Figure 2. DL and UL traffic in LTE over a week.

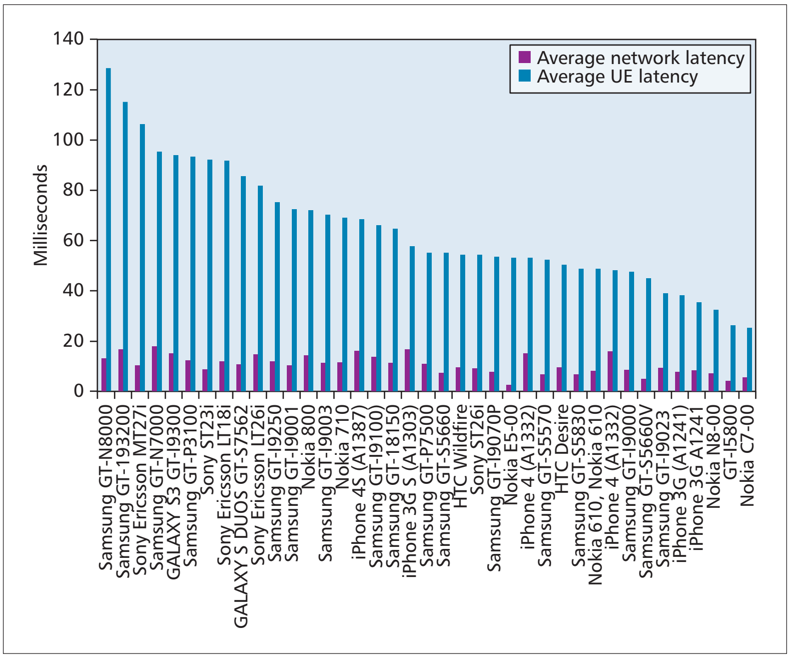

Figure 3. NW latency and UE latency with respect to different UEs.

D2D/M2M

In the context of IoT, the direct connections between end-user devices enables the creation of dynamic networks that will coexist with the access infrastructure. In the D2D concept, the devices can interchange information or help neighbors deliver data. Therefore, smart management is an important task to control these devices, to distribute the traffic load, and to prevent congestion in the access points. This massive number of connected devices requires high link reliability and low latency. Multiple information flows will be managed independently by the nodes in the D2D or M2M vision by implying a redesign at the level of network architecture. If data can be shared between devices and, for example, the device with better radio link propagation is in charge of delivering data to the access point, some resources of that device are exploited for other devices by decreasing its own battery life. Lifetimes of batteries need to be improved, and more smart devices should be exploited, even using smart caching technology to handle frequently used applications and data automatically and dynamically, so that battery life does not act on perceived QoE.

Smart Devices

The 2G-3G-4G cellular network infrastructures are designed to have complete control and management of the network and of UEs in a hierarchical scheme. For example, in the case of handovers, even if the need is originated by the channel measurements carried out by the terminal, the eNodeB has the responsibility and, on the basis of the measurements themselves, decides whether to start a handover or not. Moreover, resource allocation is determined by the network starting with a request of the mobile. In 5G systems, the above highlighted D2D connectivity requires more intelligence at the mobile side, which also implies a change in the architectural design. In addition, the different wireless technologies (e.g. 2.5G, 3G, 4G, 5G or Wi-Fi, WPAN) to which the terminal can access at the same time and move between them (vertical handovers), require radio access to different licensed or unlicensed bands. The devices' fragmentation in terms of handsets, operating

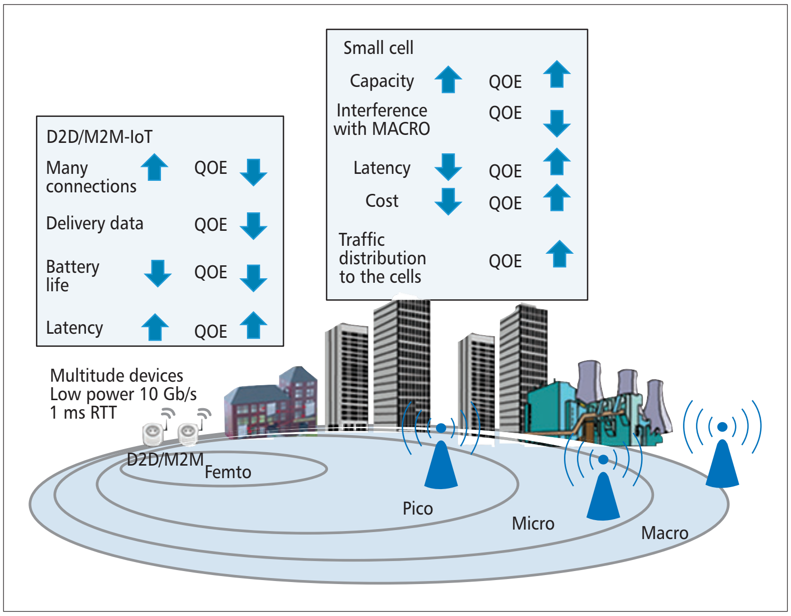

Figure 4. Small cells and D2D/M2M toward QoE.

system, and network technologies has to be overcome, and a unique reconfigurable, multi-mode and cognitive radio-enabled UE will be the future 5G smart device. Software defined radio (SDR) is the enabling technology for making this reconfigurability easy, and to develop multiband, multi-standard terminals. In the SDR concept, the radio communication system has a dynamic behavior according to the operative scenario by changing bandwidth, modulation, coding rate, etc., which can also be modified during runtime through the software and by leaving to hardware only the implementation of the RF front-end. The same terminal will adapt the air interface to the radio access technologies available in that context, simply through software downloading, and will select among the surrounding RATs those that guarantee to fulfill its QoS requirements. The onerous task of multi-mode, multi-band, multi-standard choices will be delegated to the efficiency of SDR technology and should be transparent to the user with real-time reconfiguration of the terminal so there is no negative impact on user satisfaction.

Flexible Spectrum Management

The evolution of mobile systems requires backward compatibility to the older standards to guarantee support to the users who have not yet migrated to the new standards. For example, in 3GPP standardization, LTE-system architecture evolution (LTE-SAE) integrates GSM and WCDMA/HSPA systems through a common anchor point and gateway node (serving gateway-GW) providing intra-3GPP mobility and also assures through the packet data network (PSDN) gateway the access for all technologies based on IP (as WLAN) but also to non-3GPP technologies such as WiMAX and 3GPP2 (CDMA 1X and EV-DO). The spectrum is a scarce resource for wireless communication and this *scarcity* requires a policy of spectrum management of unused and underutilized frequency bands. Solutions such as refarming spectrum of the terrestrial TV spectrum lead to free not so much spectrum and at high cost. Recently, the use of flexible spectrum allocation is envisaged. The proposal to allow the use of licensed band (primary users (PU)) to unlicensed users (secondary users) through cognitive radio technology, can significantly alleviate spectrum scarcity. The transmission of secondary users (also called cognitive radio (CR)) should not cause interference to PU, and so each CR must accurately monitor the presence of PU over a particular spectrum. If the CR is utilizing a band and a PU is detected, the CR should immediately free the band. For example, the IEEE 802.22 standard finds white spaces in the television (TV) frequency spectrum to provide broadband access in rural enviroments. As an alternative, the use of mmWave spectrum could be considered to provide larger bandwith and consequently higher data rates for 5G cellular. Recently research by [10] and a Samsung team show that propagation in mmWave frequencies can work. The limited range of coverage (around 200 meters) can be combated by using an array of multiple elements to steer the narrow beam in a particular direction. Adaptive array processing can also be used to change the spatial beam direction to avoid signal blocking/absorption, typical of mmWave frequencies, from various objects in the environment and provide high data rates. The mmWave frequencies allow a large number of tiny antennas in a device, but unfortunatly they have other hardware constraints.

Efficient management of flexible spectrum allocation is in charge of terminals, which can reduce the impact of multi-band selection on QoE by using SDR and multiantenna techniques. The above enabling technologies of 5G systems and their impact on QoE are summarized in Fig. 4 and Fig. 5. Historically, cellular systems had a "*network centric*" vision where the eNodeB controls device admission and connections to a service and the data traffic into the cell. In 5G systems the vision moves toward the terminal in a "*device-centric*" architecture [2]. The device will be more and more intelligent, autonomous and dynamically adaptive in managing parallel information flows in heterogeneous networks. As a result, the terminal will handle most of the burdensome tasks of ensuring user satisfaction. Only improved performance of smart devices can improve QoE, as highlighted in Fig. 5.

QoE Estimation Model

Traditionally, operators monitor network performance to optimize coverage and capacity in their 3G networks and to have feedback information to assess service quality. The data of millions of users are collected for a certain time period (daily or weekly) and for different services and from different cells through counters available on the radio network and statistically analyzed providing KPIs. Currently, the configuration of network equipment and the optimization of radio network resources is manual, and as mobile networks produce a huge amount of spatio-temporal data, the analysis of warnings and faults is not a trivial job for the engineers. Evolving toward 4G LTE networks, self-organizing networks (SONs), self-configuring, self-optimizing, and self-healing mechanisms are introduced to minimize operational efforts.

Recently researches have been working in the direction of estimating QoE from traffic measurements mapping the objective QoS parameters in subjective values such as those obtained by MOS subjective tests to quantify a relationship with QoE [7]. Even though QoS and QoE measurements are quite different, they have a high degree of correlation.

In [8] the well known neural networks are considered to be the main method to correlate QoS parameters and QoE values. In the literature, the use of NN was analyzed for radio planning as in [12], for prediction of traffic congestion, or specifically for an automatic QoE measurements tool for scalable video coding mechanism as proposed in [13], or for the pseudo-subjective quality assessement (PSQA) for the perceived quality of an audio or video communications [14]. In [8] selected KPIs (e.g. showing the channel quality indicator, the user throughput, the data volume, the modulation order, and coding) are used as features in input to the neural network. The NN provides in output the correspondence to one of the values of QoE according to the MOS method [15]. For example, if user throughput is high and the channel quality indicator is good (range (0–15) in LTE), the eNB can use a higher modulation scheme (from QPSK to 64QAM) and coding rate to achieve higher efficiency. Therefore, if the related KPIs report this favorable situation, the NN classifies as excellent the quality of experience perceived by the users.

A simple multi layer perception (MLP) neural network presents stability performance in the classification as demonstrated during tests on real KPIs collected from the HSPA network of TIM. An example is shown in Table 1. The MLP is made up of multiple layers of nodes where each layer is connected to the next and only the last produces the output of the network. In our MLP network, two hidden layers are used, and the number of neurons into the hidden layers is respectively four and seven. After a targeted training process, the MLP network fails to properly classify about 1 percent of the total data. The adoption of the NN method allows the easy adaption of the classification to the changes of the values of KPIs due to various levels in the standards (e.g. HSPA, LTE, LTE-A) or due to the aggregation of raw data in cells with different characteristics. A simple updating of the training data of NN can provide the new classification of user expectations.

The use of NN can also ensure replicability of QoE estimates regardless of user involvement, which is the main drawback in the subjective tests based on MOS. Starting from the above considerations, the use of neural networks can become a convincing proposal for an adaptive estimation and automatic classification of the quality perceived by the user in 5G systems.

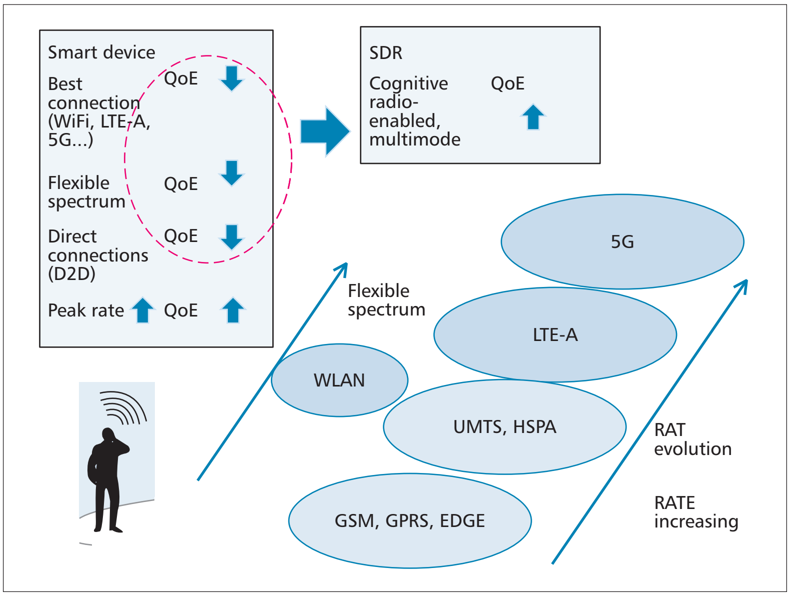

Figure 5. Smart device toward QoE.

MOS			
5 Excellent	4 Good	3/2 Fair/Poor	1 Bad
28.3%	36.9%	22.5%	11.0%
NN classification			

Table 1. NN classification and QoE.

Conclusions

The key innovations of 5G technologies, e.g. heterogeneous networks, mmWave, native support of D2D/M2M, smart devices and their impact (positive or negative) on QoE, are highlighted. Only a combination of improvements together with new and efficient cognitive radio devices will enrich the overall user satisfaction to a high level in 5G systems.

The article proposes the use of NN techniques as an efficient technique for adaptive estimation and self-optimization of the quality perceived by the user in the 5G perspective. Mapping the relationship between QoS and QoE is an extremely challenging task and the network will increasingly learn from data and will use automatic teaching between expert nodes to accelerate the QoE needs. Finally, as a result of our QoE analysis, user equipment will be delegated to handle most of the burdensome tasks of ensuring fully user satisfaction.

Acknowledgment

The author would like to thank Dr. Davide Micheli (by TIM) for his helpful discussion and support for parts of this work.

References

[1] Ericsson, http://www.ericsson.com/res/docs/2012/ericsson-mobilityreport-november-2012.pdf.

[2] F. Boccardi *et al.*, "Five Disruptive Technology Directions for 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 74–80.
[3] N. Bhushan *et al.*, "Network DENSIFICATion: The Dominant Theme for Wireless Evolution into 5G," *IEEE Commun. Mag.*, vol. 52, no. 2, Feb. 2014, pp. 82–89.
[4] 3GPP Technical Specification TS 23.107 V11.0.0, "Quality of Services (QoS) Concept and Architecture," June 2012.
[5] P. L. Callet, S. Moller, and A. Perkis, "Qualinet White Paper on Definitions of Quality of Experience (QoE)," http://www.qualinet.eu/, 2012.
[6] "ITU-T G.1011: Reference Guide to Quality of Experience Assessment Methodologies," http://www.itu.int/rec/T-REC-G.1011-201305-I/en.
[7] G. Gomez *et al.*, "Towards a QoE-Driven Resource Control in LTE and LTE-A Networks," *J. Computer Networks and Commun.,* 2013.
[8] L. Pierucci *et al.*, "An Optimized Neural Network for Monitoring Key Performance Indicators in HSDPA," *2010 IEEE 21st Int'l. Symp. Personal Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2010, pp. 2041–45.
[9] P. Demestichas *et al.*, "5G on the Horizon: Key Challenges for the Radio-Access Network," *IEEE Vehic. Tech. Mag.*, vol. 8, no. 3, Sept. 2013, pp. 47–53.
[10] T. Rappaport *et al.*,, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, 2013, pp. 335–49.
[11] D. Micheli *et al.*, "Handset and Network Quality Performance Benchmarking for QoE Improvement," 2013 *IEEE Globecom Wksps. (GC Wksps.)*, Dec 2013, pp. 1145–50.
[12] T. Binzer and F. Landstorfer, "Radio Network Planning with Neural Networks," *IEEE-VTS Fall VTC 2000 Vehic. Tech. Conf.*, 2000,, vol. 2, 2000, pp. 811–17.
[13] K. Singh, A. Ksentini, and B. Marienval, "Quality of Experience Measurement Tool for SVC Video Coding," *2011 IEEE Int'l. Conf. Commun. (ICC)*, June 2011, pp. 1–5.
[14] G. Rubino, P. Tirilly, and M. Varela, "Evaluating Users Satisfaction in Packet Networks Using Random Neural Networks," *Int'l. Conf. Artificial Neural Networks-ICANN 2006*, S. Kollias *et al.*, Eds., vol. 4131, Springer Berlin Heidelberg, 2006, pp. 303–12.
[15] ITU-T Recommendation P.800.1, "Mean Opinion Score Terminology," July 2006.

Biography

Laura Pierucci [SM'14] (laura.pierucci@unifi.it) received the degree in electronics engineering from the University of Florence, Italy, in 1987. Since 2000 she has been an assistant professor in the Department of Information Engineering (DINFO), University of Florence. Her main research interests include digital signal processing, neural networks, wireless communication systems especially in the topics of 4G/5G systems, multiple-input multiple-output (MIMO) antenna systems, cooperative communications, communication systems for emergency applications, and green ICT. She co-invented a patent on the use of RFID for health applications. She has been involved in several national and European research projects on satellite communications, tele-medicine systems, wireless systems, and radar signal processing. She has been the scientific coordinator of the EU COST Action 252, and she has served as an expert for the European Committee in the area of satellite communications. She is currently serving as associate technical editor for *Telecommunication Systems* and *IEEE Communications Magazine*.