The Need for QoE-driven Interference Management in Femtocell-Overlaid Cellular Networks

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Abstract. Under the current requirements for mobile, ubiquitous and highly reliable communications, internet and mobile communication technologies have converged to an all-Internet Protocol (IP) packet network. This technological evolution is followed by a major change in the cellular networks' architecture, where the traditional wide-range cells (macrocells) coexist with indoor small-sized cells (femtocells). A key challenge for the evolved heterogeneous cellular networks is the mitigation of the generated interferences. In the literature, this problem has been thoroughly studied from the Quality of Service (QoS) point of view, while a study from the user's satisfaction perspective, described under the term "Quality of Experience (QoE)", has not received enough attention yet. In this paper, we study the QoE performance of VoIP calls in a femto-overlaid Long Term Evolution – Advanced (LTE-A) network and we examine how QoE can drive a power controlled interference management scheme.

Keywords: QoE · VoIP · Femtocells · LTE-A · E-model · Power control

1 Introduction

The International Telecommunication Union (ITU) has defined the fundamental requirements for the next generation (4G) telecommunication systems as described in International Mobile Telecommunications-Advanced (IMT-Advanced) [1]. Systems that fulfill the IMT-Advanced requirements promise an all packet-switched wireless network with data rates similar to those provided by wired communication networks, while all services are implemented over the Internet Protocol (IP). The first packet-based cellular system that is expected to deal with IMT-Advanced requirements is the Long Term Evolution - Advanced (LTE-A) [2]. LTE-A introduces a heterogeneous architecture where the conventional wide-range cells (macrocells) coexist with indoor small-sized cells, called femtocells [3].

Femtocells are low-power, small base stations connected to the operator's network via broadband lines, and they provide usually indoor coverage typically for a range of 10 m, for instance at the home or office. They are expected to be the most energy-efficient and cost-effective solution for improving the spatial spectrum utilization and

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for amplifying the indoor coverage, providing ubiquitous and seamless access to static or mobile end-users. More precisely, femtocells are an easy option to cover any communication gaps inside a certain area, caused either due to bad coverage (e.g., in the interior of a building) or due to low network capacity (e.g., in very crowded places). However, femtocell-overlaid networks define a highly interfered environment putting in priority the design of efficient Interference Management (IM) schemes [4].

The majority of IM approaches focus on guaranteeing the provided Quality of Service (QoS), promising mainly a high Signal to Interference plus Noise Ratio (SINR) at interfered (victim) users. However, a more attractive and suitable way to evaluate the quality of a provided service (especially for real-time services) is by measuring the end-users' satisfaction. Currently, the connection between network performance and end-users' satisfaction is not strictly defined. To give an example, the same throughput value may result to differently perceived data rates, giving in that way totally different impressions of the same provided service [5].

Recognizing the importance of quantifying the end-users' satisfaction, ITU has suggested the term Quality of Experience (QoE) as "*the overall acceptability of an application or service, as perceived subjectively by the end-user*" [6]. QoE is the most important factor for a user's decision on retaining a service or giving it up and this fact explains the emergence of shifting from QoS to QoE network management. Moreover, since interference is one of the key quality-deteriorating factors and has a direct impact on the users' perceived QoE, the design of QoE-driven IM mechanisms seems very appealing.

In this paper, we examine whether and in what extent the interferences in a femtocell-overlaid network are reflected as variations in the end-users' satisfaction. Firstly, we focus on Voice over IP (VoIP) services in an LTE-A network, and quantify the QoE deterioration of macrocell VoIP users due to the interference from femtocells. Sequentially, we examine the relation between the SINR and the perceived QoE at an interference-victim. Finally, we exploit these results to compare the basic Power Control (PC) IM scheme proposed by 3GPP [7] and a simple QoE-aware PC scheme, revealing the importance of involving QoE in the IM process.

The remainder of this paper is organized as follows. Section 2 presents the interference problem in the LTE-A heterogeneous networks. Afterwards, Sect. 3 describes the potential role of QoE in the interference management process, exploiting a quantitative relationship between the QoS and QoE terms. Section 4 summarizes the fundamental evaluation methods for VoIP quality and describes the adopted QoE estimation method. Finally, Sect. 5 provides the evaluation of the QoE values in the femto-overlaid LTE-A network, while Sect. 6 concludes the paper.

2 Interferences in the LTE-A Femtocell-Overlaid Network

2.1 Structure of the LTE-A Femtocell-Overlaid Network

The LTE-A system is divided into two basic subsystems (Fig. 1): the Evolved – Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC). This architecture has been adopted towards avoiding the hierarchical structures and providing increased scalability and efficiency. The EPC subsystem is a flat all-IP system designed to support high packet data rates and low latency in serving flows. The E-UTRAN subsystem implements the access network including large-sized base stations, called evolved NodeBs (eNBs), small-sized indoor base stations, called Home eNBs (HeNBs), and mobile terminals called User Equipments (UEs). In this paper, we refer to UEs served by the eNBs and HeNBs as Macrocell UEs (MUEs) and Femtocell UEs (FUEs) respectively.

Each (H)eNB has an IP address and is part of the all-IP network, while it is interconnected to other (H)eNBs through the X2 interface (Fig. 1). This interconnection allows collaboration among (H)eNBs in order to perform functions related to the resource, mobility and interference management. HeNBs are considered as low-power eNBs and realize the access network of the femtocells by spatially reusing the spectrum bands assigned to eNBs. HeNBs are closer to the end-users than the eNBs, improving in this way the indoor coverage, and thus users experience better channel conditions (higher QoE). However, HeNBs have the option to serve only a specific set of subscribed devices by adopting the so-called Closed Subscriber Group (CSG) mode, and they can be unpredictably switched on and off by the consumers, burdening in that way the received signals. Also, the spatial reuse of the spectrum amplifies the need for sophisticated interference management schemes, while the increased number of base stations with overlaying transmission ranges imposes the need for efficient control of the handovers. Under this heterogeneous environment, high quality services have to be delivered maximizing the end-user's experience. Since each type of service has different characteristics, requirements and restrictions, the end-user's experience strongly depends on the provided service. Nevertheless, real-time services, such as the VoIP, are the most suitable for QoE analysis, due to their high interaction with the end-user.

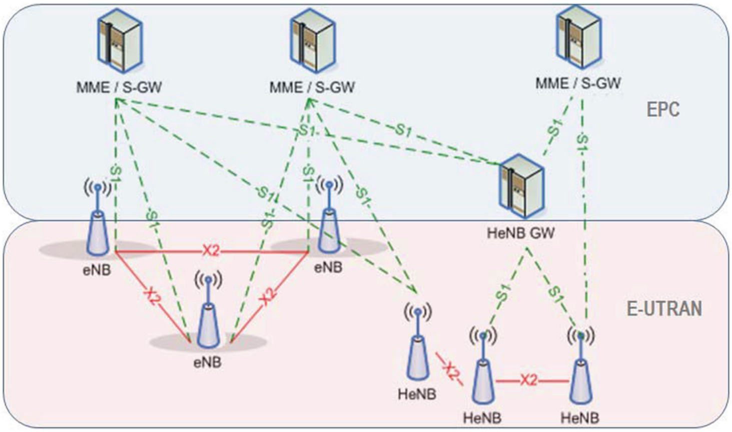

Fig. 1. LTE-A architecture

2.2 Interference Issues in the Femtocell-Overlaid LTE-A Network

We consider the network of Fig. 2, which represents a typical LTE-A heterogeneous network. We assume that macrocells and femtocells are synchronized, meaning that the uplink (UL) and downlink (DL) periods of both sub-networks have the exact same timing. In this kind of scenario, the parallel transmissions of eNBs and HeNBs during the DL, as well as of MUEs and FUEs during the UL may cause serious interference problems. To be more precise, during the UL, the MUEs may cause interference to the HeNBs, especially when MUEs are operating very close to a building where a HeNB is located. The same thing is valid during the DL, when transmitting HeNBs may also cause interference to closely located macro-receivers. In these two cases, the interference problem is locally present. However, the problem is much more severe during the DL regarding the eNB's transmissions, which may affect the femtocells' operation, since the eNB's signal is spread throughout the whole macrocell. As a consequence, such interference conditions are high likely to happen. The previously described interference scenario during the DL period is presented in Fig. 2.

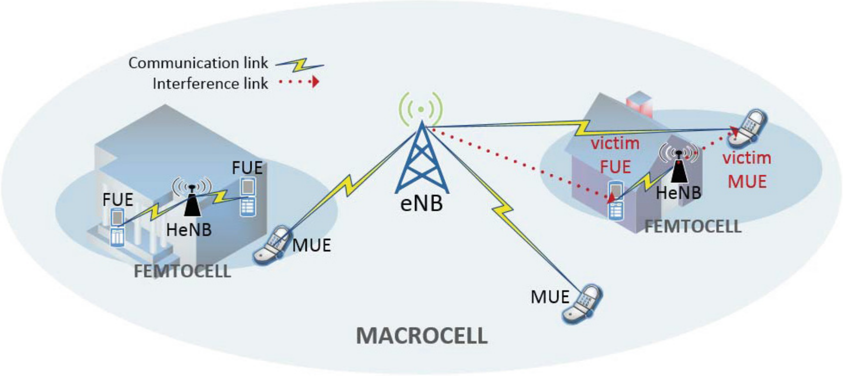

Fig. 2. Interference-scenario in the heterogeneous network under study (DL)

It is made clear that the DL period is very challenging in terms of interference, and mechanisms need to be deployed in order to avoid, reduce or manage it. One more reason that the DL is very challenging is that it concerns the perceived quality of communication from all the receiving mobile users, who may have various types of devices, may be communicating at different environments (open area, car, home, etc.), or may even have different expectations of the offered service. Even though UL interference problems may still be very severe, these are handled by the technologically-advanced base stations and are not directly revealed to the users. Since the acceptability of a service, however, is determined by the end-users and not the operators, we focus on DL IM, and we incorporate the user's perception in this process.

3 The Role of QoE in Interference Management

3.1 QoE and QoS Relationship

The “Quality of Service (QoS)” term was originally defined by ITU as “*the collective effect of service performance which determines the degree of satisfaction of a user of the service*” [8]. However, during the years, the study of QoS has lost this user-oriented approach and these days it is considered as just a subset of the more general QoE notion. Hence, QoS is no longer considered sufficient for the thorough characterization of a product or service as opposed to the most appealing QoE notion.

The reason to differentiate between QoS and QoE and to adopt QoE as the most suitable criterion for quality evaluation is twofold: First of all, QoS handles purely technical aspects regarding a service and does not incorporate any kind of human-related quality-affecting factors. This means that the same QoS level might not guarantee the same QoE level for two different users. Apart from the system’s technical characteristics, other factors such as the context of use, the user-specific characteristics such as users’ experiences and expectations, the delivered content and the pricing of a service make a significant impact on the finally perceived QoE as well [9]. The second reason for this differentiation is that, QoS does not reflect the impact that the technical factors have on the user’s quality perception, since there is no straightforward connection defined. This implies that, for instance, the constant amelioration of one technical parameter does not linearly and infinitely improve the user’s experience. Actually, this observation alone justifies why the need for the QoE notion has arisen. Based on this gap between the QoS and QoE, some formulas have emerged recently trying to map QoS parameters to the overall QoE value. Two different approaches have dominated in the literature: the perception-centric and the stimulus-centric one.

The stimulus-centric approach is based on the “WQL hypothesis” inspired by the so-called “Weber-Fechner Law (WFL)” [10], which describes the effect of a physical stimulus on the human perception according to the principles of psychophysics. This law claims that the relationship between stimulus and perception is logarithmic, which drives the conclusion that in order for a stimulus’ change to be reliably detected by an observer, this has to differ from its original value by a constant fraction. From this law, the notion of “just noticeable differences” emerges, which describes the smallest detectable difference between two sequential levels of a particular stimulus.

Regarding the perception-centric QoS-QoE mapping, the so-called “IQX hypothesis” [11] has been proposed. According to this approach, the relationship between the QoE and one QoS degrading parameter is negative exponential and the change of QoE actually depends on the current level of QoE. The mapping curve between the QoE and the QoS disturbance consists of three clearly distinguishable regions, as shown in Fig. 3. The first one is the *constant optimal* region (Region 1 in Fig. 3), where the QoE is always excellent, regardless some initial impairments of one technical quality-affecting parameter. To be more precise, the QoE is not affected inside this region at all, either because some mechanisms inside the system provide some kind of tolerance to such impairments or simply because the human perception (e.g., vision or hearing) is not capable of distinguishing such changes. The second region of the QoS-QoE curve is characterized by *sinking* QoE in an exponential way (so that QoS disturbances are

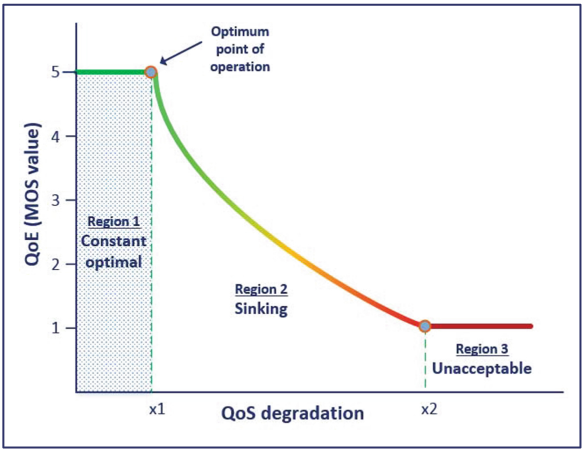

Fig. 3. The IQX hypothesis

more impactful when the QoE is higher), while the third and last region refers to *unacceptable* quality.

The clear discrimination among these three regions may be exploited by service providers not only for their own economic benefit but also for the common good. Regarding the providers' benefit perspective, since there can clearly be identified a region (Region 1) where the QoE is constantly excellent regardless some technical parameters' deterioration, the providers could deliberately deteriorate the performance of some technical parameters so that all users operate just on the turning point between Regions 1 and 2 (the point x_1 in Fig. 3, perhaps with some safety margin). This could be made possible by reducing resources such as spectrum resources or transmission power. As a result, all end-users will be pushed to operate on x_1 instead of any other "western" point of Region 1, since such a thing would not add to quality and also would consume resources for no reason. As a direct consequence, redundant resources could be released and saved to be provided to other users (for the common good) to who it would really make an impact on the perceived QoE (i.e., for users operating at Region 2 or 3, trying to "push" them towards Region 1's optimum point of operation).

3.2 QoE-aware Interference Management

As discussed in previous sections, the co-existence of femto- and macro-users operating on the same constrained resource pool causes interference problems in the network, while the study of the QoE could be beneficial for existing or future IM schemes.

The most common and direct way to mitigate the interferences is to adopt a PC-based IM scheme. However, an important trade-off is recognized when PC-based IM schemes are used; sufficient transmitted energy is required in order to ensure a specific QoS level at the receiver, but at the same time increasing the energy will cause higher interferences in the network and less battery life for the terminal. Consequently, the goal behind PC is to carefully limit the transmission power of the interference aggressor guaranteeing the required SINR at the target receiver. A simple yet efficient PC mechanism would be able to estimate the exact, minimum transmission power of the sender that would lead to the exactly sufficient SINR at the target receiver for faultless communication with guaranteed QoS level. In this way, interference would be smoothed, and in parallel, energy would be saved.

Taking this into account, we propose the introduction of QoE criteria to the estimation of this minimum transmission power, exploiting the operation inside the aforementioned Constant Optimal Region in terms of QoE (Region 1 in Fig. 3), abbreviated hereafter as COR. Although the existence of this region has been extensively discussed and widely accepted in the literature, to the best of the authors' knowledge, there have not been any studies yet that try to identify and measure the potential benefit of exploiting it for IM. We propose the decrease of the transmit power of all affecting base stations (eNBs and HeNBs) in order to cause the minimum sufficient SINR at the target device (MUEs and FUEs respectively) without any impact on the user perceived quality. Increasing the SINR further would lead to interference problems without any corresponding increase in the perceived quality, and thus, this is considered redundant and costly in terms of energy and resources.

The proposed QoE-aware scheme can be applied as an additional rule in any existing PC scheme. For instance, this rule may be applied on top of the PC scheme proposed by 3GPP [7]. The mathematic formula that describes this 3GPP-standardized scheme is as follows:

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min}) \tag{1}$$

where P_{Tx} and $P_{eNB-HeNB}$ represent the transmit power of the HeNB (interference aggressor) and the measured received power from the eNB, respectively, while $PL_{HeNB-MUE}$ depicts the pathloss between the HeNB and the victim MUE. P_{max} and P_{min} parameters refer to predefined maximum and minimum transmit power settings, respectively, and depend on the device type.

Having defined the already standardized PC scheme, we present the proposed QoE-aware PC rule: *"If the estimated transmission power of the PC scheme is higher than the threshold power that leads to the lowest SINR in the constant optimal QoE region (i.e., optimum point of operation of Fig.* 3*), reduce this power up to its threshold value, using a safety margin".*

This leads to an enhanced formula that incorporates the proposed QoE-aware rule on top of the 3GPP PC scheme, as follows:

$$P'_{Tx} = max\left(P_{min}, P_{Tx(3GPP)} - \Delta P_{COR,opt}\right), \quad if\ \Delta P_{COR,opt} > 0 \tag{2}$$

where $\Delta P_{COR,opt}$ is the decrease in transmission power that moves the SINR from the SINR point that the $P_{Tx(3GPP)}$ defines, up to the "eastern" optimum point in the constant optimal region (COR). This formula will be applied only if the $P_{Tx(3GPP)}$ scheme provides a QoE score inside the constant optimal region, so that the $\Delta P_{COR,opt}$ is positive, and thus makes sense. The QoE score is measured using the Mean Opinion Score (MOS) scale, which is presented in the next section.

In the following, we provide the background for QoE estimation in VoIP services towards estimating the constant optimal QoE region and the gain of applying the proposed QoE-aware PC rule to a femtocell-overlaid LTE-A network.

4 QoE of the VoIP Service

4.1 Measuring the QoE of the VoIP Service

VoIP is one of the dominant services that will be provided by the LTE-A network. The VoIP requirements for the E-UTRAN sub-system are described in [12]. Practically, the VoIP service must be realized completely in packet switched (PS) domain and perform at least as efficiently (in terms of latency and bit rate) as the VoIP over Universal Mobile Telecommunications System (UMTS) in the circuit switched (CS) domain. Moreover, according to ITU, a VoIP user is considered to be in outage if less than 98 % of its VoIP packets have been delivered successfully to the user within a permissible delay bound of 50 ms, while the percentage of users in outage must be less than 2 % [13]. However, these bounds do not reflect the level of end-users' satisfaction. The end-users' satisfaction measured in QoE is a strongly subjective term and also one of the dominant factors for assessing a provided service. The most common measure of the QoE is the Mean Opinion Score (MOS) scale recommended in [14]. The MOS ranges from 1 to 5, with 5 representing the best quality, and is commonly produced by averaging the results of a subjective test, where end-users are called under a controlled environment to rate their experience with a provided service. However, this subjective methodology (use of questionnaires) is cost-demanding and practically inapplicable for real-time monitoring of the VoIP performance.

On the other hand, objective methods have been proposed to measure the speech quality. These methods can be classified into intrusive and non-intrusive methods. Intrusive methods, such as the Perceptual Speech Quality Measure (PSQM) and the PESQ (Perceptual Evaluation of Speech Quality), estimate the distortion of a reference signal that travels through a network by mapping the quality deterioration of the received signal to MOS values. However, the need for a reference signal is a drawback for using intrusive methods for QoE monitoring. To this end, non-intrusive methods have been defined such as the E-model and the ITU P.563 [15]. Since the ITU P.563 method has increased computational requirements, making it inappropriate for monitoring in real-time basis, we adopt the easier to be applied E-model described in the next section.

4.2 The E-model

The E-model has been proposed by the ITU-T for measuring objectively the MOS of voice communications by estimating the mouth-to-ear conversational quality as perceived by the user at the receive side, both as listener and talker [16]. It is a parametric model that takes into account a variety of transmission impairments producing the so-called Transmission Rating factor (*R* factor) scaling from 0 (worst) to 100 (best). Then a mathematic formula is used to translate this to MOS values. In the case of the baseline scenario where no network or equipment impairments exist, the R factor is given by:

$$R = R_0 = 94.2. \tag{3}$$

However, delays and signal impairments are involved in a practical scenario and hence the R factor is given by:

$$R = R_0 - I_s - I_d - I_{ef} + A \tag{4}$$

where:
I_s: the impairments that are generated during the voice traveling into the network,
I_d: the delays introduced from end-to-end signal traveling,
I_{ef}: the impairments introduced by the equipment and also due to randomly distributed packet losses,
A: allows for compensation of impairment factors when there are other advantages of access to the user (Advantage Factor). It describes the tolerance of a user due to a certain advantage that he/she enjoys, e.g., not paying for the service or being mobile. Typical value for cellular networks: $A = 10$.

Focusing on parameters which depend on the wireless part of the communication (transmissions between (H)eNB and UEs) it holds that [17]:

$$I_d = 0.024d + 0.11(d - 177.3)H(d - 177.3) \tag{5}$$

where:

$$H(x) = \begin{cases} 0, & x < 0 \\ 1, & x \geq 0 \end{cases} \tag{6}$$

and d is the average packet delivery delay. Also, assuming that the codec G.729a is used, the packet loss rate, referred here as p, affects the parameter I_{ef} as follows [17]:

$$I_{ef} = 11 + 40\ln(1 + 10p). \tag{7}$$

The R factor can be used as an assessment value; however, we transform it to MOS values to retrieve results comparable with results provided by subjective methods. The transformation formula is as follows:

$$MOS = \begin{cases} 1, & \text{if } R < 0, \\ 1 + 0.035R + R(R - 60)(100 - R) \cdot 7 \cdot 10^{-6}, & \text{if } 0 \leq R \leq 100, \\ 4.5, & \text{if } R > 100\,. \end{cases} \tag{8}$$

In the next section, we focus on the deterioration caused in parameters d and p in a femto-overlaid LTE-A network and on the resulting user perceived quality.

5 Simulation Model and Results

Towards quantifying the need for QoE-aware IM schemes, we first evaluate the impact of macrocell-femtocell coexistence on VoIP users' QoE. We assume an LTE-A network that consists of a target hexagonal macrocell with 6 neighboring cells and multiple femtocells inside the target cell area. Each femtocell is deployed with some probability inside a 10 m × 10 m apartment, while 25 apartments define a 50 m × 50 m square building block. Multiple building blocks are uniformly distributed inside the target cell area, while the femtocells reuse the licensed spectrum of the target macrocell, exacerbating the interference problem. For this scenario, we have expanded the open source system level simulator described in [18] to derive the QoS fluctuations, and used the E-model to translate them to MOS. The main simulation parameters are shown in Table 1:

Table 1. Simulation Parameters

Parameter	Value
Number of eNBs	7
Macrocell radius	500 m
eNBs TX power	43 dBm
Femtocell building block	3GPP based 5 × 5 building block
Apartment side	10 m
Number of HeNBs/building	Scalable
HeNBs TX power	20 dBm
HeNBs deployment	Co-channel
MUEs placement	Random (inside the macrocell area)
FUEs placement	Random (inside the apartments)
UEs in the system	Scalable
Traffic load per user	1 VoIP call
VoIP codec	G.729a
Duplex mode	FDD (focus on downlink)
Channel bandwidth/cell	10 MHz
Scheduling algorithm	Proportional fair
Flow duration	5 s
QoE model	E-model

At first, we examine the impact of femtocell deployment on the QoE performance of all types of end-users (MUEs and FUEs), assuming an increasing number of concurrent VoIP calls inside a target macrocell area. More specifically, 10 building blocks are uniformly distributed inside the target macrocell area, while each HeNB is located with 50 % probability into an apartment of a building block. We consider that the HeNBs operate in CSG mode and also that the 50 % of VoIP flows are originated indoors, while the rest of them outdoors. The results concerning the QoE of the users, represented using the MOS scale, are shown in Fig. 4.

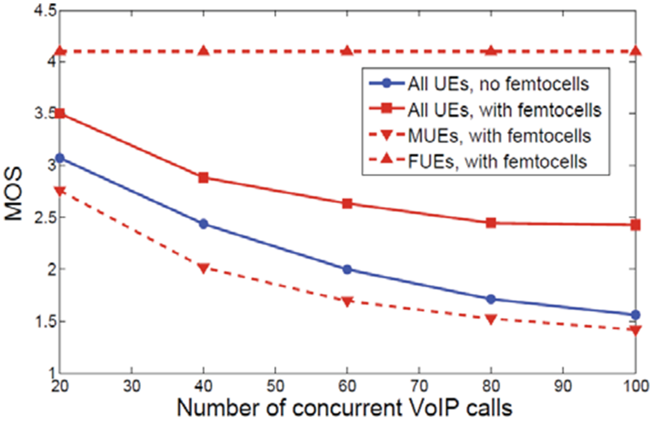

Fig. 4. Impact of the number of VoIP calls on QoE

As shown in this figure, on average, the femtocell proliferation improves the QoE experienced by VoIP users (the “All UEs, no femtocells” case has lower performance than the “All UEs, with femtocells” case). Nevertheless, this improvement is mainly caused due to the high QoE performance of VoIP calls served by femtocells, reaping femtocell benefits such as the proximity gain (“FUEs, with femtocells” case). Note that since each femtocell serves a low number of VoIP calls (practically 1 or 2) the increase on the total number of VoIP calls has negligible impact on FUEs’ QoE, maintaining the high QoE performance. On the contrary, the QoE of MUEs seems to deteriorate due to the interference caused by the HeNBs (“MUEs, with femtocells” case). This observation validates the need for more investigation on how to mitigate the interferences caused to MUEs.

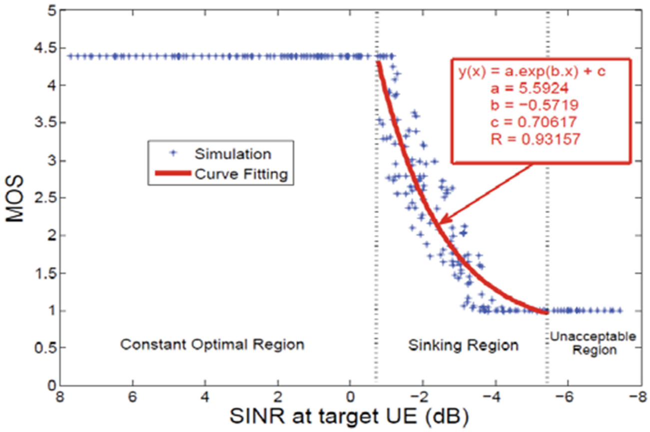

Fig. 5. Impact of SINR degradation on QoE

Moving one step further, in Fig. 5, we prove the existence of the constant optimal region discussed in Sect. 3 for any UE. To this end, we focus on a single building block and we monitor the performance of the VoIP call of a single user located close to a femtocell-overlaid building block, while the SINR at this user is constantly degraded. The reason of the SINR deterioration might be lower transmitted power from the serving base station or higher interferences imposed or even worse channel conditions, without any loss of generality. We depict the results in MOS (y axis) and SINR degradation (x axis) and perform curve fitting to define the function that best describes the simulated data. We observe that the IQX hypothesis is indeed validated, while there is a quite large COR available for exploitation. The optimum point of operation is identified for an SINR threshold value of around −0.8 dB for this scenario.

Having defined the constant optimal region for our scenario, we apply the proposed QoE-aware PC rule on top of the PC scheme proposed by the 3GPP, using the formulas of Sect. 3.2. In Fig. 6, we compare these two formulas depicting the resulting transmission power by each one of them, for constant and guaranteed QoE at FUEs. This means that all resulting plots have been derived ensuring the same maximum MOS value, both for the 3GPP scheme and for the QoE-aware PC scheme (blue & red curves in Fig. 6 respectively). As shown in this figure, the QoE-aware PC rule significantly reduces the required transmission power and thus the interference perceived by victim MUEs, maintaining in parallel the required high QoE level at the served FUEs.

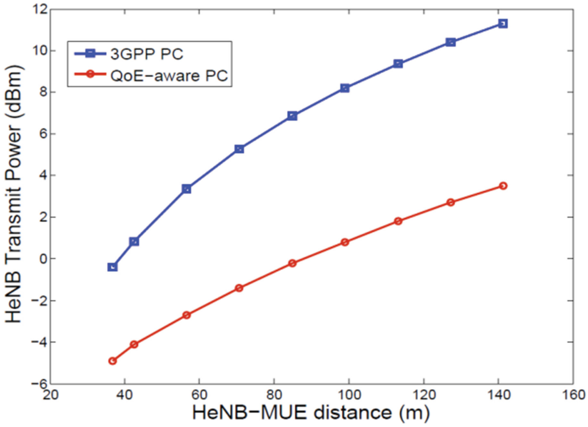

Fig. 6. Performance of QoE-enhanced 3GPP PC

6 Conclusions

In this paper, we focused on VoIP services in an LTE-A network, and quantified the QoE deterioration of macrocell users due to the interference from femtocells. Sequentially, we examined the relation between the QoE and the perceived SINR at an interference victim, defining the constant optimal region for the SINR. For all SINR values in this region the QoE is constant and in high level, making room for reducing the transmission power with no impact on the service perception of end-users. Finally, we exploited these results to compare the basic power control (PC) interference management (IM) scheme proposed by 3GPP and a simple QoE-aware PC scheme, revealing the importance of involving the QoE notion in the IM process.

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