Mitigating the Impact of Cross-Tier Interference on Quality in Heterogeneous Cellular Networks

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Abstract—**Recently, the use of heterogeneous small-cell networks to offload traffic from existing cellular systems has attracted considerable attention. One of the significant challenges in heterogeneous networks (HetNet) is cross-tier interference, which becomes significant when macro-cell users (MUE) are in the vicinity of femtocell base stations (FBS). Indeed, the femtocell will cause significant interference to MUEs on the macrocell downlink (DL) while MUEs will induce hefty interference to the femtocell on the macrocell uplink (UL). Substantial work has focused on offloading and interference mitigation in HetNets; yet, none of them has considered the impact of cross-tier interference on quality of service (QoS), quality of experience (QoE). This paper proposes the Quality Efficient Femtocell Offloading Scheme (QEFOS) that selects the users most affected by the interference encountered and offloads them to nearby FBSs. QEFOS testing shows substantial improvements in terms of QoS and QoE perceived by users in heavy cross-tier interference scenarios in comparison with alternative approaches. In particular QEFOS's impact on throughput, packet loss ratio (PLR), peak-to-signal-noise ratio (PSNR), and structural similarity identity matrix (SSIM) was assessed.**

Index Terms—**Offloading, femtocell, macrocell, QoS, QoE, PSNR, SSIM**

I. INTRODUCTION

The introduction of heterogeneous LTE-A networks enabled coping with increasing number of mobile broadband data subscribers and bandwidth-intensive services competing for restricted radio resources [1]. As discussed in [2], the wireless capacity has increased around one million times over the last 50 years due to three reasons: better transmitter/receiver performance, greater bandwidth, and greater number of cells. As a single macrocell cannot satisfy mobile users' QoS and QoE specifications, a HetNet architecture is used. It consists of different types of Radio Access Networks (RANs) or cells, such as for instance: a collocated macrocell, picocells (i.e. another type of small cells that can support up to 32 users), femtocells, and relay nodes.

Femtocell networks, also known as home base stations, have received considerable attention from industry and academia recently due to their tremendous capacity enhancement potential for the next generation wireless systems.

Femtocell networks do not face challenges related to site availability or management; they are deployed by the users themselves, and use the existing user broadband connection to introduce very little overhead on the operators. In our work, we focus on the combined presence of femtocells and macrocells as a case study. This is because the co-channel deployment of Macrocell Base Station (MBS) and Femtocell Base Station (FBS) cause a severe cross-tier interference. However, the ultimate goal is to improve the satisfaction of users. Today assessing user satisfaction can be performed in terms of Quality of Service (QoS) and/or Quality of Experience (QoE). These two similar terms have different definitions and different purposes. On one hand, QoS measures the networks' transport performance related to a service, whereas on the other hand, QoE is a measure of the pleasure or frustration of the experience a customer has with a service. To be more specific, QoS is generally not linked to a client but to content delivery or network support, whereas QoE is a strictly subjective indicator from the point of view of the consumer.

This paper focuses on the effect of cross-tier interference when FBSs for Femtocell User Equipment (FUE) cause severe interference to Macrocell Users Equipment (MUE), resulting in poor signal-to-interference noise ratio (SINR) and affecting the service quality as received by MUEs. A novel Quality-Efficient Femtocell Offloading Scheme (QEFOS), which mitigates the effect of interferences and improves QoS and QoE in a macro/femto two-tier network environment is proposed. QEFOS selects the macrocell users most affected by interference and offloads their services to FBS. Testing has compared QEFOSs' performance with that experienced by Ideal (with no interference) and heavy cross-tier interference (HCI) schemes. The HCI scheme corresponds to the worst-case condition situation in which randomly placed MUEs experience hefty cross-tier interference from the nearby FBSs while these are on. The performance was assessed in terms of QoS metrics such as throughput, Packet Loss Ratio (PLR), PSNR and SSIM, which estimate user QoE.

The rest of the paper is organized as follows. Section II surveys existing work. Section III presents the proposed solution and describes the relevant algorithms. Section IV describes the scenarios used in the study and simulation-based testing and discusses the performance results. Finally, Section V concludes the paper and provides some future research directions.

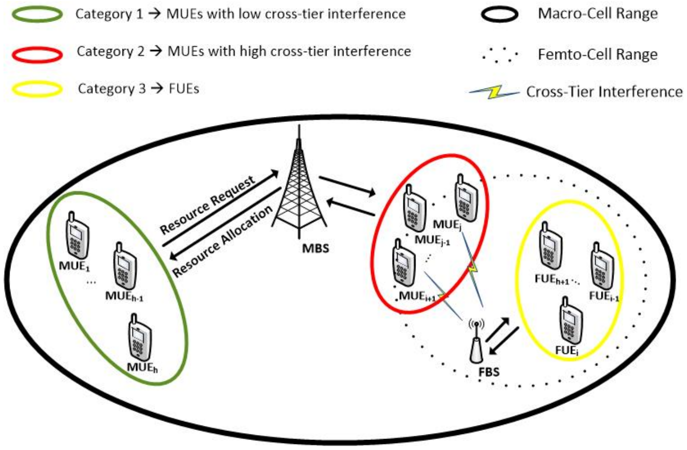

Fig. 1. A macro/femto two tier network

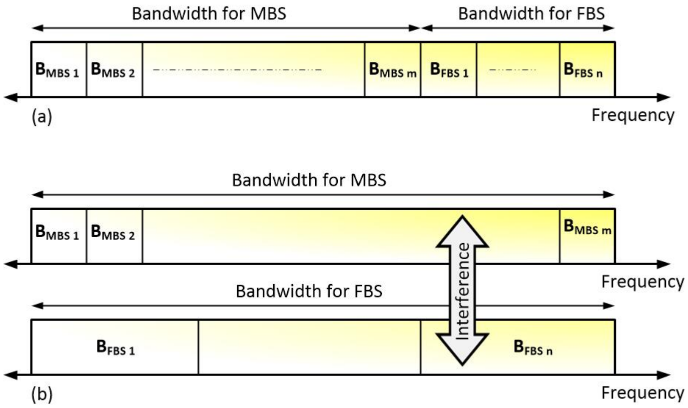

Fig. 2. (a) Dedicated channel operation, vs. (b) co-channel operation of femtocell and macrocell networks. Dedicated deployment of the channel offers lower bandwidth per femtocell user while co-channel deployment is subject to interference limitations [2], [5].

II. RELATED WORK

Offloading in mobile networks is expected to reduce macro cell traffic. According to Ericsson's mobile data traffic outlook studies, the global mobile data traffic will continue to increase and is forecasted to reach 131 exabytes (EB) per month by the end of 2024. The area of India has the highest monthly average usage per device, hitting 9.8 gigabytes by the end of 2018. During the forecast period, the Middle East and Africa regions are predicted to have the highest growth rate. Through offloading, nearly 800 million terabytes reduction could be achieved [3]. In [4], the authors presented a survey on existing architectures, access modes, resource allocation techniques as well as methods for improving coverage quality and handover techniques for efficient deployment of femtocells.

In [5], the authors showed how interference can directly affect the performance of systems linked to femtocell deployment settings. They considered three femtocell deployment configurations : a) Dedicated Channel vs co-channel, b) Open access and Closed Subscriber Group (CSG), and c) Fixed DL transmit power vs adaptive DL transmit power. As demonstrated in Fig. 2(a), femtocells are assigned a different spectrum for dedicated channel assignments than that of the macrocell. Even though this mostly eliminates potential interference from the macrocell, frequency resources are not efficiently utilized. Co-channel deployment of femtocells allows for more effective use of the usable spectrum. As illustrated in Fig. 2(b), both the macrocell and femtocell will have larger bandwidth available per user with co-channel deployments. In addition, the cell-search process for a MUE is more relaxed because it does not have to scan for cells in various frequency bands (e.g., for the purposes of handover). However, femtocells and the macrocell will observe co-channel interference from each other. In [6], the authors shows offloading in conjunction with interference mitigation (IM) but do not show the effect of cross-tier interference on the QoS, QoE.

In [7], the authors suggested a scheme for addressing the interference problem by offloading and formulating it as a mixed integer linear programming, but offloading alone is not just the solution to avoid interference. The authors of [11], [12], [13] talks about the QoE and energy consumption in HetNets in terms of video delivery but none of them use evalvid framework for video quality estimation in HetNets. The authors of [8] developed Evalvid, a framework and tool-set for the assessment of the quality of the transmitted video over a real or simulated communication network. This framework along with FFMPEG (Fast Forward MPEG) is used for calculating PSNR and SSIM in HetNets for QoE (i.e. see Fig. 5).

Although much research has been done in HetNets specifically for macro/femto two-tier networks, none of the existing studies has both assessed and mitigated the impact of cross-tier interference on QoS and user QoE.

III. QEFOS

QEFOS is a heuristic scheme which tries to reduce the effects of interference experienced by users in HetNets. Fig. 1 illustrates a combined macro-femto two-tier network architecture. In such an environment, QEFOS categorizes the users into three categories: MUEs which experience low cross-tier interference (category 1), MUEs which experience high cross-tier interference (category 2), and FUEs (category 3). The proposed QEFOS mainly focuses on the users most affected by interference (category 2 users) and brings a significant improvement in terms of both QoS and QoE in relation to the services consumed by them.

QEFOS classifies the randomly distributed HetNet users into the three categories based on the degree of interference they encounter, and their association with either MBSs or FBSs. Following the categorization, the users who experience interference above a certain threshold (Υ) are offloaded to nearby FBSs.

QEFOS has three phases, as shown in Algorithm 1: *Computation*, *Categorization* and *Offloading*. In the *Computation* phase, U denotes the set of participating UEs, with $U = C1 \cup C2 \cup C3$= $\{u_1, u_2, ..., u_j, ..., u_{|U|}\}$ and C1 denotes the set of category 1 users, C2 - the set of category 2 users and C3 - the set of category 3 users. If N_m is the number of MBSs and N_f - the number of FBSs, the set of all BSs is *B* = $\{B_1, ..., B_{Nm}, B_{Nm+1}, ..., B_l, ..., B_L\}$, where L = $N_m + N_f$. Let R be the set of available resource blocks that each BS *l* ∈ *B* can use. These R= $\{r_1, r_2, ..., r_k, ..., r_{|R|}\}$ resource blocks are further divided into sub-channels and allocated to the UEs associated with each BS *l*. Next in the *Computation* phase, different matrices and vectors are computed as follows:

$$V_{|U|X|R|} = \begin{pmatrix} v_{1,1} & v_{1,2} & \cdots & v_{1,|R|} \\ v_{2,1} & v_{2,2} & \cdots & v_{2,|R|} \\ \vdots & \vdots & \ddots & \vdots \\ v_{|U|,1} & v_{|U|,2} & \cdots & v_{|U|,|R|} \end{pmatrix} \qquad (1)$$

In eq. (1) V denotes the matrix of interference experienced by all UEs from U on each resource block from R. $v[j,k]$ indicates the interference experienced by UE u_j on resource block r_k.

In eq. (2) A denotes the matrix of UE association with MBSs or FBSs. In this paper $a[j,l]$ is a binary decision variable used for user association as follows: $a[j,l]$ = 1 if UE u_j is associated with MBS and $a[j,l]$ = 0 if u_j is associated with FBS. Matrix A is updated after Phase 3 (*Offloading*).

$$A_{|U|X|B|} = \begin{pmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,|B|} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,|B|} \\ \vdots & \vdots & \ddots & \vdots \\ a_{|U|,1} & a_{|U|,2} & \cdots & a_{|U|,|B|} \end{pmatrix} \qquad (2)$$

In the *Categorization* phase we classify the users and identify those which experience the worst interference from FBS. If UE u_j has an association with MBS and experiences interference above the defined threshold, it will be categorized as a category 2 user. Otherwise, it will be categorized as category 1 user. On the other hand, if UE u_j has an association with FBS, it will be categorized as a category 3 user. In the *Offloading* phase, the category 2 users who experience worst interference in their services, get offloaded to the nearby FBS. Our proposed algorithm runs for each FBS and UEs surrounding it, so no need to select FBS. In this model we consider that any UE can only be associated with one BS at any time instance.

Algorithm 1: QEFOS

```
Goals: Increase → Throughput, PSNR, SSIM
       Decrease → Packet Loss Ratio
PHASE 1 : Computation
  $U$, ∀ $u_j \in U$
  B = $\{B_1, ..., B_l, ..., B_L\}$ , L = $N_m + N_f$
  C1 = {} , C2 = {} , C3 = {}
  Set threshold ϒ
  Interference Matrix V
  Association Matrix A
PHASE 2: Categorization
  foreach $u_j \in U$ do
      foreach $r_k \in R$ && $B_l \in B$ do
          if v[j,k] >= ϒ && a[j,l] = 1 then
              C2 ← C2 ∪ $\{u_j\}$
          else
          if v[j,k] < ϒ && a[j,l] = 1 then
              C1 ← C1 ∪ $\{u_j\}$
          else
              if v[j,k] < ϒ && a[j,l] = 0 then
                  C3 ← C3 ∪ $\{u_j\}$
      j++
PHASE 3: Offloading
  foreach $u_j \in C2$ do
      Offload $u_j$ to FBS
      a[j,l] = 0 (Update Matrix A)
```

TABLE I
CONSTANT PARAMETERS

Parameter	Value
No. of MBSs (N_m)	1
MBSs and FBSs DL Frequency	2120 MHz
MBSs and FBSs UL Frequency	1930 MHz
# of resource blocks ($\|R\|$)	100
# of sub-channels	12 x 100
bandwidth of each sub-channel	15 KHz
MBSs Tx Power	46 dbm (39.8 watts)
FBSs Tx Power	26 dbm (.398 watts)
Mobility Model	Constant Position Mobility Model
LTE Mode	FDD
Packet Size	1500 Bytes

IV. PERFORMANCE EVALUATION

Two scenarios are considered and the performance is assessed in terms of QoS parameters such as throughput and PLR and QoE estimation using PSNR and SSIM. A macro/femto LTE two-tier network as illustrated in Fig. 1 is considered. All UEs and FBSs are randomly placed within the MBS area. Table. I indicates the simulation parameters used in all scenarios. Some parameters are varied in different scenarios, as indicated.

A. *QoS Assessment*

The two scenarios considered are as follows.

Scenario A: In this scenario only one MBS and one FBS are deployed ($N_m = 1$, $N_f = 1$). The number of UEs $|U|$ is increased linearly from 10, 20, 30 to 40. Fig. 3 shows the average user throughput (Kbps) and PLR(%) achieved under

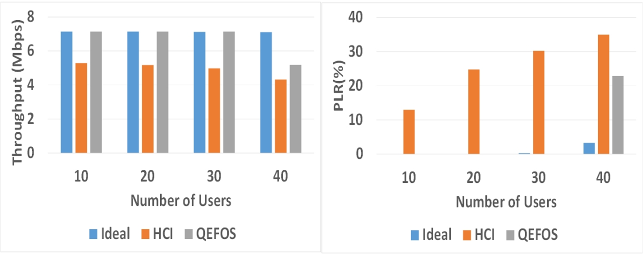

Fig. 3. Scenario A for QoS Assessment

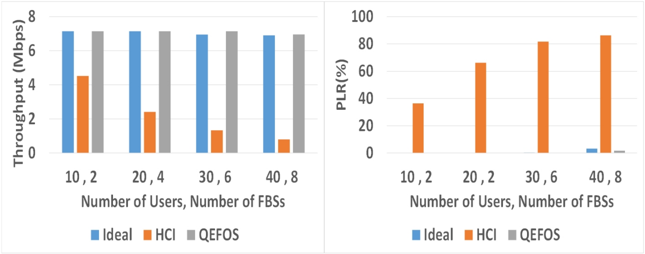

Fig. 4. Scenario B for QoS Assessment

different schemes. Fig. 3 results show how category 2 users achieve an average 7 Mbps throughput and almost negligible PLR when our proposed QEFOS scheme was employed. The QEFOS throughput is 30% higher than what was achieved when the HCI scheme is employed and similar with that of the Ideal scheme for up to 30 users. This result was obtained as the proposed QEFOS scheme has offloaded category 2 users to FBS, which provides good quality for their services. Fig. 3 also shows that when the number of UEs increased to 40, the QEFOS throughput is 37% lesser than what was achieved when the Ideal scheme is employed and 17% higher than what was achieved when the HCI scheme is employed. Also, QEFOS PLR is 85% higher than what was achieved when the Ideal scheme is employed, but 34% less than what was achieved when the HCI scheme is employed.

This slight degradation in performance perceived by the category 2 users is due to the limited availability of FBS resources which supports the deployment of more FBSs. This is considered in the next scenario.

Scenario B: In this scenario only one MBS is deployed ($N_m = 1$), the number of FBSs N_f increased linearly from 2, 4, 6 to 8 and the number UEs is in turn 10, 20, 30 and 40, respectively. This addresses the performance limitation issue dues to the availability of a single FBS in *Scenario A*. Fig. 4 shows the average user throughput and PLR achieved when different schemes are used in turn. Fig. 4 results show that category 2 users achieve an average 7 Mbps throughput and almost negligible PLR when our proposed QEFOS scheme was employed. The QEFOS throughput is 88% higher than what was achieved when the HCI scheme is employed and similar with that of the Ideal scheme. It can also conclude from Fig. 4, that under our proposed scheme, when the number of UEs increased up to 40, users did not experience the drop in throughput and increase in PLR as experienced in *Scenario A*. The deployment of more FBSs helps us achieve the required performance, but the rollout should be done in a planned way. The random implementation of FBSs can degrade the performance of the other categories of users. In this paper, proper planning done for the deployment of the FBSs. The FBSs are deployed in a coordinated manner, with MBS to maximize the overall performance.

Both scenario results show how the proposed QEFOS scheme substantially improves users' performance in terms of throughput and PLR, outperforming the HCI scheme and being very close to those of the Ideal scheme.

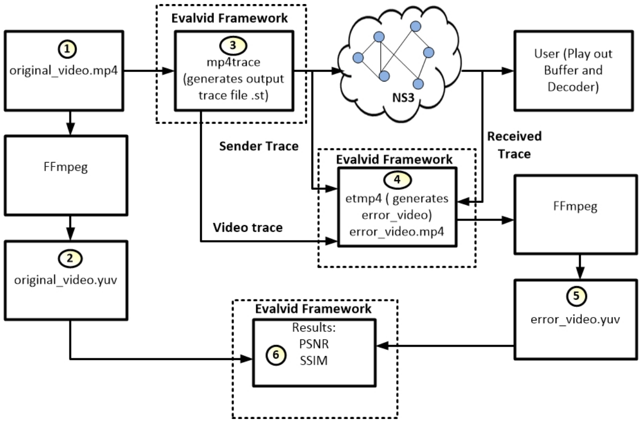

Fig. 5. Integration of FFMPEG with Evalvid Framework

B. QoE Estimation

Nowadays, multimedia communications are gaining increasing popularity [8]. Therefore, objective quality assessment of multimedia sequences (as perceived by a user) is really critical and this paper considers multimedia content delivery as one of the fundamental services in a HetNet environment. In order to estimate user QoE in a HetNet, PSNR and SSIM are considered [8], [10]. These are the most common user QoE estimation metrics found in scientific literature.

By examining frames of both received and reference video files, PSNR computes the signal-to-noise ratio in order to extract the differences between the two images. SSIM takes into account the characteristics of the Human Visual System (HVS) to extract the structural information of an image [10]. SSIM values range from 0 to 1; bigger values represent better quality, with values from 0.9 upwards reflecting a gap almost impossible for the human eye to perceive.

For the evaluation of PSNR, SSIM we re-designed the Evalvid framework [8] and integrate FFMPEG with it Fig. 5. The terminal commands that were used to estimate the metrics are presented in TABLE II. This terminal commands are required for generating the video trace, PSNR, SSIM, and the erroneous video both in *mp4* and *yuv* format. The intention of offering such commands is to assist the researchers in their work, as there is no work defining all these commands.

Video streaming is considered in the HetNet environment illustrated in Fig. 1. Our objective is to use the simulated network to transmit the video file and then compare the receiver-side perceived output under three different schemes. For this, first we have increased the number of FBSs (same as in *scenario B*) and reported the packet loss for a video defined in TABLE III. The video that we selected is H.264 encoded and consists of 300 frames, and the total number of IP packets that form the data flow is approximately equal to 2100 (see TABLE III for more details).

Fig. 6 presents the PLR for video streaming in HetNets. We observe that as the number of FBSs increases in the vicinity

TABLE II
TERMINAL COMMANDS

Stages(**From** → **to**)	**Command**
Generation of yuv Format of Original Video (1 → 2)	ffmpeg -i original_video.mp4 original_video.yuv
Trace File Generation(1 → 3)	./mp4trace -f -s ufbr.br 12346 original_video.mp4 > st_original_video.st
Error Video Generation (4)	./etmp4 -f -0 sender_trace received_trace st_original_video original_video.mp4 error_video.mp4 200
Generation of yuv Format of Error Video (4 → 5)	ffmpeg -i error_video.mp4 error_video.yuv
PSNR and SSIM Generation(2 and 5 → 6)	./psnr 352 288 420 original_video.yuv error_video.yuv > psnr.txt ./psnr 352 288 420 original_video.yuv error_video.yuv ssim

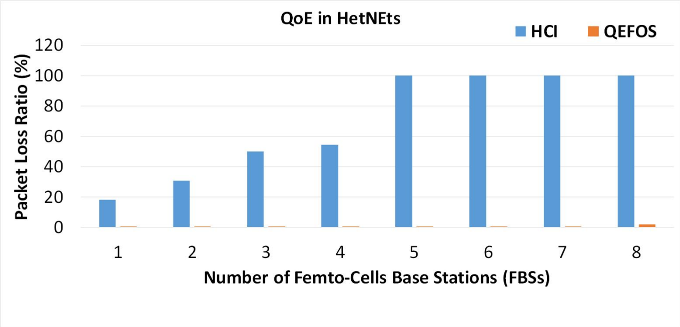

Fig. 6. PLR for QoE Estimation

of MUEs, PLR increases. After deployment of five or more FBSs, MUEs are not able to make requests due to substantial cross-tier interference and experience 100% PLR. On the other hand, experience almost negligible PLR when our proposed QEFOS scheme was employed, thus improving QoE.

TABLE III
PROPERTIES OF VIDEO USED FOR QOE ESTIMATION

Properties	Value
Frame Width	352
Frame Height	288
Data rate	1028 Kbps
Total Bitrate	1028 Kbps
Frame Rate	30 frames/second

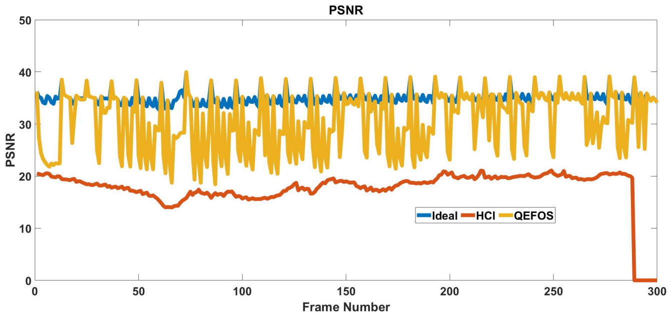

Fig. 7. PSNR for QoE Estimation

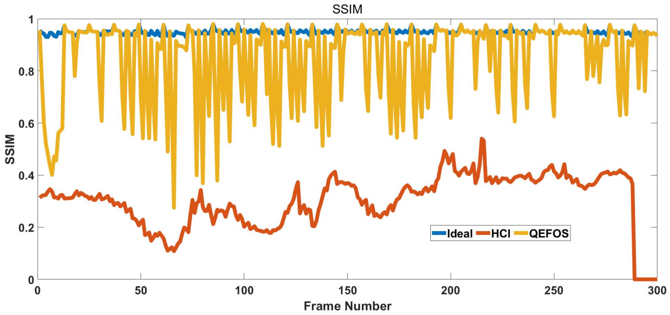

Fig. 8. SSIM for QoE Estimation

The main simulation outcomes are presented in Fig. 7 and 8. As can be seen, PSNR and SSIM profiles are different for all three schemes, which clearly shows that the users of category 2 experienced much better QoE under our proposed QEFOS scheme with respect to the HCI scheme, but experience more fluctuations with respect to the Ideal scheme.

In more detail, considering Fig. 7 and 8 again, it is possible to perceptually notice that, for the QEFOS scheme, the frame quality is high, and there is no loss of frames. In contrast, for the HCI scheme, image degradation grows, and after 288 frame numbers, all frames are lost.

Please note that even though the PSNR graph differs from the SSIM one, both the trends are quite similar.

Fig. 9 shows the mean and standard deviation of PSNR and SSIM achieved when different schemes are used in turn. Fig. 9 results shows that the mean value of QEFOS PSNR and SSIM is 42% and 63% higher than what was achieved when the HCI scheme is employed and 13% and 11% lower than what was achieved when the Ideal scheme is used. Fig. 9 results also show that higher quality variations are observed under our proposed QEFOS scheme. Increases of 30% and 33% in the standard deviation value of QEFOS PSNR and SSIM in relation to the HCI scheme and 77% and 93% in relation to the Ideal scheme were recorded.

The numerical results, obtained show how the proposed QEFOS scheme substantially improves users' perceived quality in terms of PSNR and SSIM, outperforming the HCI scheme and being very close to those of the Ideal scheme.

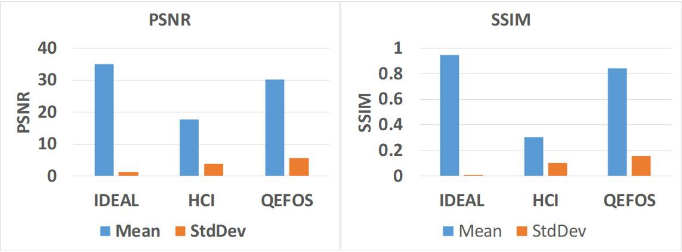

Fig. 9. Mean and Standard deviation

V. CONCLUSION

The deployment of femtocells in the LTE networks enhances data rates for users, effectively extends and improves system coverage, increases the entire network throughput, and brings users closer to the network. However, some important problems have to be addressed for the large scale and high density deployment of femtocells, namely femtocell-to-macrocell and macrocell-to-femtocell interference which affects the performance perceived by the users in such high density HetNets networks.

To address the problems mentioned above, we propose the QEFOS scheme, which classifies the randomly distributed HetNet users into the three categories based on the degree of interference they encounter, and their association with either MBSs or FBSs. Following the categorization, the users most affected by interference are offloaded to nearby FBSs. QEFOS shows substantial improvements in terms of QoS metrics and estimated QoE perceived by the users in heavy cross-tier interference scenarios in comparison with alternative solutions.

Future work includes integration of the proposed scheme with dynamic interference management to address the offloading in HetNets in a more coordinated way. This refers to coordination between interference mitigation, user association, and resource allocation. Finding a solution for decreasing of the quality variation of is also targeted.

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