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Abstract— **Enhanced Inter Cell Interference Coordination (eICIC) for co-channel deployments of pico cells throughout a macro cell layout is studied. In particular, we analyze a scenario where only some macro cells have picos deployed, while other macro cells have no small cells. The challenge for such highly irregular scenarios is how to operate eICIC, and especially how to coordinate macro-cell muting. Our analysis shows that for eICIC to provide gain in such scenarios, it is recommended to use fully time aligned traditional Almost Blank Subframes (ABS) in the macro-cells with picos, while first tier surrounding macro cells shall use low-power ABS. For such cases, user throughput gains of 30%-40% are still achievable. Moreover, it is demonstrated that if macro muting patterns are not fully time aligned, it causes additional interference fluctuations in the network, resulting in less efficient link adaptation and radio-aware packet scheduling.**

I. INTRODUCTION

The co-channel deployment of outdoor pico cells throughout a macro cell layout has been attracting much attention in academia and the 3GPP standardization process of Heterogeneous Networks (HetNet) in Long Term Evolution (LTE)-Advanced systems [1][2][3]. Two main uses of such pico cells can be envisioned: pico cells located in areas with dense traffic (hotspots) or deployed to fill macro-layer coverage holes. The transition from homogeneous (LTE) to heterogeneous (LTE-Advanced) networks is expected to be smooth, with a gradual deployment of small cells. Even in fully working LTE-A deployments, very high traffic demands are typically concentrated in small geographical areas [4]. The heterogeneous nature of this kind of networks calls for the presence of different number of pico cells per macro aiming at fulfilling the specific traffic demand of the area.

Multiple studies in the literature have shown that downlink interference problems are likely to occur in co-channel deployment of macros and pico base stations (denoted eNB in LTE). Especially pico user equipments (UEs) are subject to severe interference from the macro-layer if using the so-called pico range expansion to increase the offload from the macro layer [1]. Enhanced Inter-Cell Interference Coordination (eICIC) is one of the solutions to mitigate the macro interference and improve the system and cell-edge throughput [2]. The time domain eICIC concept relies on the macro layer muting during certain subframes, which the pico layer will use to schedule UEs severely affected by inter-layer interference.

During the protected subframes, the macro layer can either completely stop the data transmission [5][6] or simply reduce the transmission power [7]. These two options are referred to as z-ABS (zero-Almost Blank Subframes) and LP-ABS (Low Power ABS), respectively. In order to gain from the protected subframes, the pico eNB needs to be aware of the applied muting patterns at the surrounding base stations.

The optimum muting pattern applied at the different macro-cells is closely related to the network topology, traffic conditions and other factors. For scenarios with the same number of pico cells in all macro cells, eICIC offers attractive downlink performance gains at high offered traffic if simply using the same muting pattern at all macro cells [8]. However, it is not worth using eICIC for cases where only a few pico cells are deployed. Previous contributions in the open literature have focused on *uniform* HetNets with picos deployed in all macros [5]-[8]. In this paper, we investigate the effectiveness of eICIC techniques in more realistic *non-uniform* HetNets, where picos are deployed only in some macro cells. It is an open research question how to best operate eICIC for such non-uniform cases – especially how to coordinate macro muting patterns. Our investigations reveal that coordinated use of z-ABS and LP-ABS is an attractive configuration to reach high system performance in this kind of topologies. It is also analyzed how the semi-static configuration of non-aligned (referring to the time-domain) macro muting patterns influences the overall system performance. Our priority is to study the performance of the derived proposals under realistic multiple user and multiple cell cases. In order to achieve this target, we use a system level simulator enabling statistical reliable results with high degree of accuracy.

The rest of the paper is organized as follows: Section II introduces the studied non-uniform scenarios and the different levels of macro coordination. In Section III some of the technical challenges associated to non-uniformities in the network are discussed as well as the inter-eNB interaction required to support the proposals. In Section IV we show the simulation results for the different considered scenarios. Results show the negative impact of non-uniformities and the benefits of the proposed z-ABS and LP-ABS macro coordination. Concluding remarks are given in Section V.

II. SCENARIOS AND MACRO MUTING CONFIGURATIONS

We focus on the network topology pictured in Figure 1 (a). Here four picos per macro cell are assumed in the central three macro cells, while all other macro cells have no picos

(a) Scenarios   (b) Macro transmission power
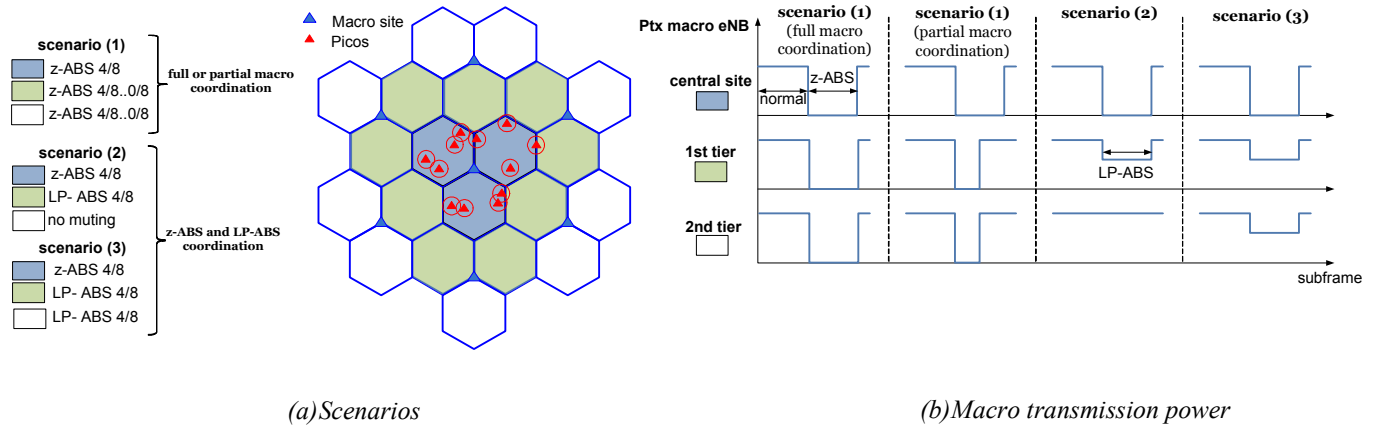
Figure 1. Non-uniform topologies

deployed. This models a realistic network layout where pico cells are irregularly spread throughout the network covering high traffic demand areas. Even though the relevance of this kind of topologies is clear, its performance and associated design problems have not been addressed in the eICIC literature yet.

It has been shown in previous studies that the load between the macro and pico layers can be balanced by adding a positive bias, denoted as Range Extension (RE) offset, to the Reference Signal Received Power (RSRP) measured from the pico cells [1]. With 4 picos per macro the best performance with full macro muting coordination is obtained with z-ABS, muting pattern of 4/8 and RE = 12dB [8], and hence this is the configuration applied in the central three macro cells. For the sake of simplicity, we consider zero interference from macros applying z-ABS, as we assume advanced terminal receivers capable of cancelling e.g. Common Reference Signals (CRS) that are still transmitted during z-ABS [8]. Thus, with this muting pattern (half of the available resources free of macro interference) the pico cell can comfortably serve the high percentage of users offloaded to the pico layer due to the application of the RE offset.

Figure 1 (b) further summarizes macro layer muting options considered in this study:

- **Full macro coordination**. The macro eNBs fully coordinate the eICIC configuration by using the exact same z-ABS muting pattern at all macro cells throughout the network, i.e. perfectly time-aligned.
- **Partial macro coordination**. The start of the muting period is perfectly aligned among macro eNBs (i.e. it starts in the same subframe); however, the length of this muting is not the same for all the macro cells.
- **z-ABS and LP-ABS macro coordination.** Coordinated so that macro cells with picos apply z-ABS while neighboring macros without picos use fully time-aligned LP-ABS patterns.

These different macro layer muting scenarios are further quantified in the following.

Macro muting scenario (1):
Scenario (1) in Figure 1 (b) models *full or partial macro coordination*. The start of the muting pattern (z-ABS in the whole network) is aligned in all cases. Macro cell neighbours that do not have picos apply the same muting pattern, but possibly with less muted subframes as compared to the central macro cells. With full macro coordination the beginning and duration of the protected subframes is identical throughout the network, as shown in Figure 1 (b). In the example of partial macro coordination, cells in the first and second tier are using a muting pattern that is half the duration of the one of the central site.

Macro muting scenarios (2) and (3):
Scenarios (2) and (3) in Figure 1 (b) are representative examples of *z-ABS and LP-ABS macro coordination*. Non-uniform HetNet topologies can benefit from efficient cooperation among macro eNBs, taking into account that only some cells (central site in our case) can gain from eICIC. With the introduction of LP-ABS, several options for the transmission power will be available at the macro cell. Thus, a macro eNB can choose between using normal full transmission power (i.e. normal transmission), reducing the data channel transmission power during certain subframes (LP-ABS), or completely muting the data channel during certain subframes (z-ABS) [7]. By applying LP-ABS in a neighboring macro cell without picos, the interference suffered by victim pico UEs is mitigated and, at the same time, the performance of macro UEs in the neighboring cells will not degrade much as the experienced SINR will not be significantly affected since the centre macros are assumed to use z-ABS. The z-ABS and LP-ABS patterns are assumed to be perfectly time aligned as pictured in Figure 1 (b). Note that for scenario (2), LP-ABS is only applied in the first tier whereas scenario (3) assumes also LP-ABS in the second macro layer tier surrounding the center site. Thus, the first tier cells have the same behavior in scenarios (2) and (3), whereas the second tier cells transmit with constant or variable power as illustrated in the example in Figure 1 (b).

III. TECHNICAL CHALLENGES AND SIGNALING SUPPORT

(A) Impact of not having full macro coordination

The motivation for using z-ABS is to provide the pico layer with some interference protected resources during which UEs severely affected by inter-layer interference can be scheduled. The optimal RE (and consequently muting ratio) depends on several factors, among others the cell topology and the traffic conditions. As a rule of thumb, it is convenient to decrease the muting ratio as the load decreases and/or the offloading decreases, the latter due to a low number of small cells and/or a small RE offset [8]. In practice, the muting ratio among macros will not be (network wide) fully coordinated, due to irregular pico density and offloading. The main problem of that is precisely the increase of interference as seen by users in the extended area. In cases like scenario (1) pico users experience significant interference fluctuations due to neighbor macros applying different muting patterns. In scenario (2), even though the muting patterns are identical in the centre site and first tier, the experienced interference for a pico UE depends on whether the macros around apply z-ABS, LP-ABS or no muting, and similarly for scenario (3) where all the macros are muting.

(B) UE measurement restrictions

In general, the use of ABS muting patterns results in more severe interference fluctuations in the network, and those have to be captured in the Channel Quality Indicator (CQI) report, which maps the measured SINR at the terminal. The 3GPP standard provides mechanisms to report different CQI measurements corresponding to normal and ABS subframes in the overlaying macro [8]. However, in non-uniform scenarios, with surrounding cells using a different muting pattern, the reported CQI during protected subframes is capturing the frame pattern of the overlaying macro (which is the main interferer in most cases), but does not necessarily match the frame pattern of surrounding macros, being underestimated or overestimated depending on whether the neighbor macros are muting or not in a given subframe. This is illustrated in Figure 2, where a sketch of the SINR and reported CQI at the pico UE in scenario (1) is plotted. It is assumed that the overlaying macro is muting half of the time, but the surrounding cells are only muting 25% of the time. When both the overlaying macro and the surrounding cells use ABS, the maximum SINR is perceived. However, when neighbor cells use normal subframes while the overlaying macro is still applying ABS, then the SINR experienced by pico UEs decreases, but this degradation is not captured in the reported CQI, which strictly refers to the ABS in the overlaying macro. Consequently the eICIC performance gain is expected to be lower.

Notice that the mismatch between real channel conditions and reported CQI is more critical depending on whether the protected subframes are z-ABS or LP-ABS. Thus, in the case of LP-ABS the interference fluctuations are smaller (i.e. smaller changes in the SINR during normal and protected subframes), and therefore the reported CQI gets closer to the experienced SINR condition. Finally, it is worth mentioning that for cases with time-aligned muting ratios (scenarios (2) and (3)) the separate CQI measures for normal and protected subframes supported in the 3GPP standard are sufficient, and
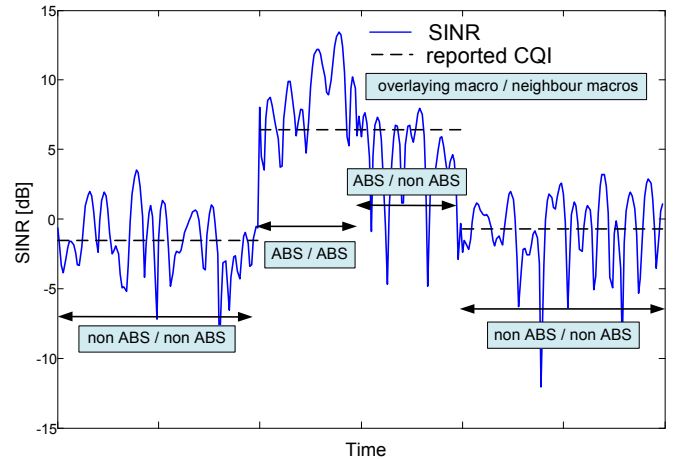

Figure 2. SINR and reported CQI in non-uniform topologies

the problem illustrated in Figure 2 does not apply.

(C) Inter-eNB signaling support

The standard enables all levels of macro-coordination considered in this paper by means of X2 signaling support. Thus, eNBs can exchange and request information on ABS patterns, and dynamically change and ask for changes in the configuration of surrounding cells. For z-ABS and LP-ABS coordination, we recommend the addition of the power reduction to the existing exchanged messages between eNBs, in order to facilitate the LP-ABS operation [7]. Thus, the joint use of LP-ABS and ABS could be configured as follows. A macro with deployed picos would get the ABS information from all surrounding macro cells and, on detection of one macro not applying ABS, it would inform of its own ABS configuration and suggest reducing the power in order to minimize the interference caused to pico UEs. If the aggressor neighbor cell decides to reduce the power, then it would confirm the new configuration by reporting the actual power reduction level and muting pattern. Moreover, for the decision of reducing the power or muting, it is important to match up the muting ratio with the configuration of neighbor cells as much as possible (getting closer to full macro coordination), in order to avoid significant system performance degradation as shown in the simulation results in Section III.

IV. PERFORMANCE RESULTS

(A) Simulation assumptions

The network layout is as defined in Figure 1 [9]. The network topology consists of a standard hexagonal grid of three-sector macro eNBs with a number of outdoor low power pico-eNBs (Figure 1). Macros and picos share the same 10MHz of bandwidth at a carrier frequency of 2GHz. There are a total of 7 macro sites (21 macro cells) with wrap around to simulate the interference effect of a larger network.

The macro intersite distance is 500m, and the minimum distance among pico eNBs is 40m. The system-level simulator follows the LTE specifications, including modeling of major radio resource management functionalities such as packet scheduling, hybrid ARQ, link adaptation, 2x2 closed loop MIMO with pre-coding and rank adaptation and UEs using an

Interference Rejection Combining (IRC) receiver with cancellation of Common Reference Signals interference during the protected subframes [8]. Macros and picos are transmitting at 46dBm and 30dBm, respectively, with 3D directional macro antenna pattern as defined in [9] and picos with omni-directional antennas. The propagation model consists of a deterministic distance dependent component, as well as two independent stochastic components for shadow fading and fast fading [9], with different path loss exponent and shadow fading standard deviation for macro and small cell radio links. In the case of LP-ABS, the macro power reduction is set to 3dB or 6dB (higher values not viable in the current release of LTE-Advanced [7]). For simplicity, the range extension bias in pico cells is fixed and set to 12dB. There are 10 users uniformly placed in each macro cell and 5 users per pico eNB, all outdoor. Thus, a macro with 4 picos will have a total number of 30 users, whereas a macro without picos has 10 users. With 4 picos per macro and 12dB of range extension, 80% of the users are offloaded to the pico layer. Proportional Fair packet scheduler and full buffer traffic are assumed. The primary performance metrics reported are the 5%-ile (coverage) and 50%-ile (median) downlink experienced user throughput. To have a better understanding of the origin of the gain, we study not only the whole network throughput but also separately in the central site, the first tier and the second tier as defined in Figure 1.

(B) Full and partial macro coordination

The performance results of scenario (1) with full and partial macro muting time alignment are plotted in Figure 3. The muting ratio of neighbour cells varies from 4/8 (full macro coordination) to 0/8 (no eICIC in neighbour cells). The 5%-ile and 50%-ile end user throughput in the center site and in the whole network is shown. The first blue bar plots the full macro coordination case, while the next four bars correspond to partial macro coordination with 3/8, 2/8, 1/8 and 0/8 muting ratio. Focusing on the central site, when surrounding cells apply the same muting ratio (full macro coordination) the optimal coverage and median gain is achieved: 0.92 Mbps in coverage and 3.13 Mbps in median. If the muting ratio in surrounding cells is only reduced to 3 over 8 subframes, then a loss of 11% in 5%-ile and 4% in 50%-ile is observed. This is mainly due to the increased interference conditions suffered by pico UEs during z-ABS and the wrong CQI reporting (Figure 2). Finally, if surrounding cells do not apply any muting ratio, the performance loss goes up to 60% for the coverage and 25% for the median. More specific link adaptation mechanisms and packet schedulers able to alleviate the impact of the mismatch among eNBs are for further study. For example, the eNB has the information of the muting ratios of neighbor cells, which could be used to get a more accurate estimation by properly scaling the received CSI report. If we observe the overall network performance, it is observed that the maximum coverage is obtained when the neighbouring cells mute 3/8 of the time, being the performance for 4/8 and 3/8 very close both in coverage and median terms. If we do not use eICIC in the first and second tier the loss goes up to 40% in 5%-ile and 8% in median.

From Figure 3 we conclude that the level of macro coordination has a significant impact on the eICIC
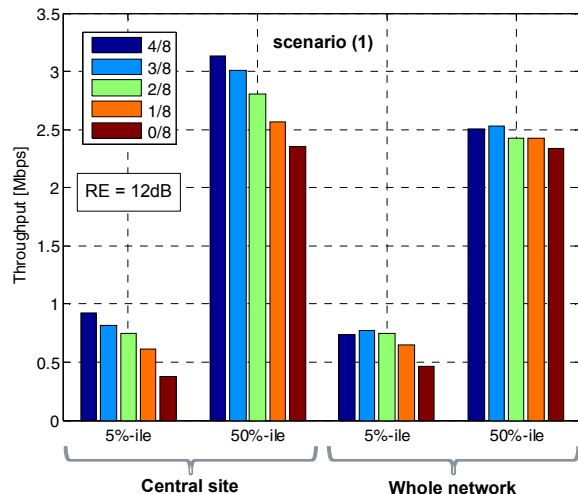

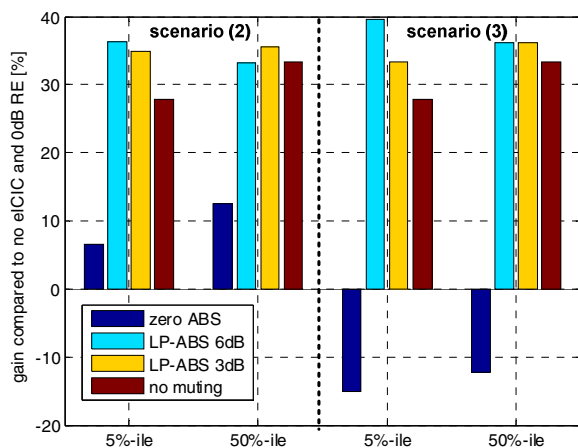Figure 3. Throughput performance with partial macro-coordination

Figure 4. Performance gain with joint use of LP-ABS and z-ABS with reduced power in the first tier (scenario (2)) and the first and second tier (scenario (3))

performance. For a cell with deployed picos but neighbours not applying eICIC (or applying a very small muting ratio), the RE offset and correspondingly the muting period should be reduced. On the other hand, for a macro cell with no picos but surrounding cells with deployed picos, it is better to operate eICIC with a moderate muting period in order to provide some interference free resources to pico users. In high density networks and high load conditions (as is the case of the central site), muting ratios up to 4/8-5/8 are recommended. Higher values of muting ratio do not provide extra performance gains.

(C) z-ABS and LP-ABS coordination

The performance of the proposed z-ABS and LP-ABS macro coordination is investigated next. Figure 4 shows the eICIC performance gain for scenarios (2) and (3), compared to the case with no eICIC and no RE. In the case of scenario (3), even though macro cells in the second tier are not pointing to center macros, the center site can also benefit from extra interference reduction due to shadowing and wrap around. The performance gain is computed accounting for the users in the three center cells and those in the surrounding cells. Thus, it includes both the gain of center macro cells being able to
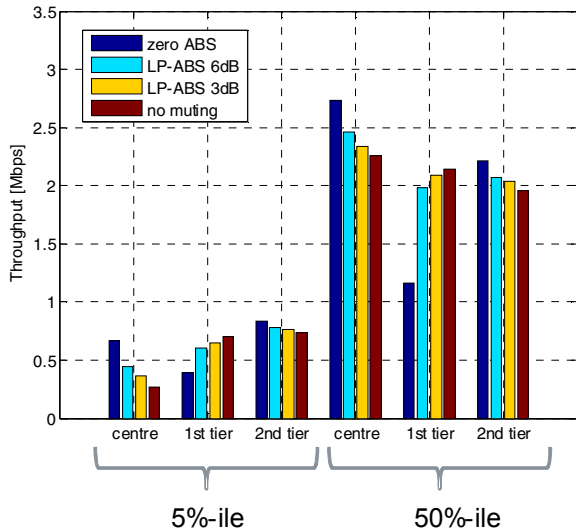
Figure 5. Detailed throughput performance of scenario (2) with joint use of LP-ABS and z-ABS with reduced power only in the first tier
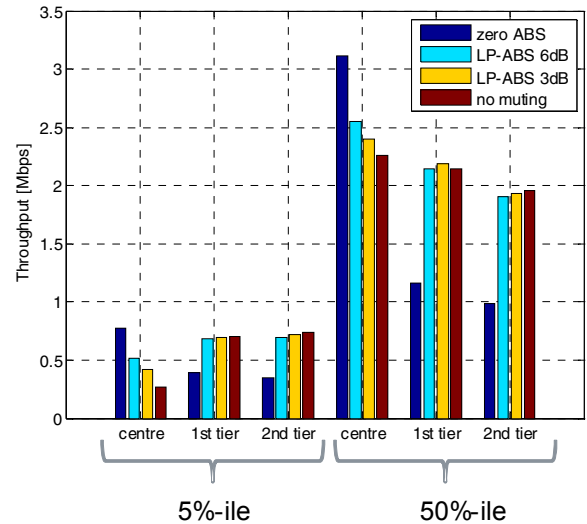

Figure 6. Detailed throughput performance of scenario (3) with joint use of LP-ABS and z-ABS with reduced power in the first and second tier

offload more users to the picos and the potential degradation in surrounding macros from using LP-ABS. The two power reduction LP-ABS values in the neighbor cells are simulated, namely 3dB and 6dB, as well as the cases with zero-ABS (matching up with scenario (1)) and no muting as baseline results. Notice that the legend refers to the power policy applied in surrounding cells, being only the first tier in scenario (2) and the first and second tier in scenario (3).

As expected, it is not worth muting cells without picos, resulting in a very low gain (scenario (2)) or even a loss (scenario (3)). With our proposal, eICIC performance gains in the order of approximately 30%-40% are achieved with the power reductions of 3dB and 6dB, illustrating a promising use case for applying LP-ABS in macro cells without picos. Moreover, comparing scenario (2) and (3) it can be seen that reducing the power not only in the first tier but also in the second tier provides an extra gain both in coverage and median user for a power reduction of 6dB.

The contributors to this gain are further investigated in Figures 5 and 6. Here, we plot the 5%-ile and 50%-ile user throughput of the center site, the first tier and the second tier separately, and for both scenarios. Comparing the two Figures, the same trends are observed in the coverage and median user. When the power reduction is extended to the second tier, center cells and first tier benefit from the interference reduction and their throughput increases. On the other hand, throughput in the second tier gets worse due to the reduction in available resources.

V. CONCLUSION

We consider a representative HetNet topology where a centre area with high traffic density and a number of hotspots and pico cells is surrounded by a less populated area with no deployed small cells. The performance of such irregular pico densities and different levels of macro coordination is investigated. We propose a promising use case of LP-ABS to fully benefit from eICIC in this kind of non- uniform topologies. Using z-ABS and LP-ABS coordination among macro eNBs, z-ABS is applied in macros with deployed picos, while LP-ABS is kept for only-macro cells, providing user throughput gains in the order 30%-40% compared to the case with no-eICIC. A low pico density in neighbor cells irremediably affects the throughput performance when the muting ratio is reduced accordingly. The increase in interference when not having full-macro coordination and the scope of the CQI measurement restrictions were discussed, with a significant loss when neighbor cells do not apply fully time aligned muting patterns.

VI. ACKNOWLEDGEMENTS

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