Performance Analysis of Enhanced Inter-cell Interference Coordination in LTE-Advanced Heterogeneous Networks

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Abstract—**The performance of enhanced Inter-Cell Interference Coordination (eICIC) for Long Term Evolution (LTE)-Advanced with co-channel deployment of both macro and pico is analyzed. The use of pico-cell Range Extension (RE) and time domain eICIC (TDM muting) is combined. The performance is evaluated in the downlink by means of extensive system level simulations that follow the 3GPP guidelines. The overall network performance is analyzed for different number of pico-eNBs, transmit power levels, User Equipment (UE) distributions, and packet schedulers. Recommended settings of the RE offset and TDM muting ratio in different scenarios are identified. The presented performance results and findings can serve as input to guidelines for co-channel deployment of macro and pico-eNBs with eICIC.**

Index terms—**eICIC, heterogeneous network, LTE-Advanced, range extension, TDM muting.**

I. Introduction

Heterogeneous network (HetNet) deployment of Long Term Evolution (LTE)-Advanced has recently become a hot research topic [1]. HetNet consists of a mixture of different base station types such as high power macro base stations (called eNB for LTE) and low power pico-eNBs or home base stations (HeNB) [2]. The macro-eNBs are used to offer coverage over a wide area, while the low power eNBs are typically deployed in hotspots to offload traffic from the macro-layer [2][3]. HetNet is regarded as an efficient solution to boost the network capacity in order to be able to carry the forecasted increase of data traffic [4].

In order to fully benefit from HetNet deployments, there are several technical challenges related to mobility management, backhauling, interference management, etc. that needs to be addressed. The mobility within networks of the same or different Radio Access Technologies (RAT) has been addressed in [5][6]. The performance/cost of the pico-layer is evaluated in [7], taking backhauling into consideration. The potential of the relay nodes, which conceptually is similar to a pico-eNB, but with wireless backhauling, is investigated in [8]. Interference management has been studied using a variety of different techniques as well; interference cancellation/avoidance [9][10], power control [11], and resource partitioning [12]. A summary of possible interference management techniques is provided in [13].

In this paper we study enhanced Inter-Cell Interference Coordination (eICIC) for downlink co-channel deployment of macro and pico-eNBs by means of simulation. Thus, we consider a simple scenario with only a single carrier available for macro and pico. The network-centric eICIC technique with time domain (TDM) muting has also been extensively studied in the 3GPP community, and is now part of LTE Rel-10 – the first LTE-Advanced release. In our analysis, we combine the usage of TDM muting with pico-layer Range Extension (RE). The network performance is quantified for different densities of pico-eNBs, pico-eNB transmit power levels, packet scheduling methods, and spatial UE distributions. Thus, it presents a simple sensitivity analysis of how the eICIC performance depends on the most important network configuration and deployment parameters. Guidelines are presented on how to choose the proper configuration of eICIC and related critical network configuration parameters.

The rest of this paper is organized as follows: Section II discusses the eICIC related techniques under investigation. Section III outlines the simulation assumptions. The eICIC performance results are presented in Section VI. Finally, some concluding remarks are drawn in Section V.

II. Interference Coordination Techniques Under Investigation

A HetNet deployment with macro and pico-eNBs on the same carrier is depicted in Fig. 1. Each UE is served by only one cell, with the other cells generating interferences. The considered eICIC techniques are discussed in the following.

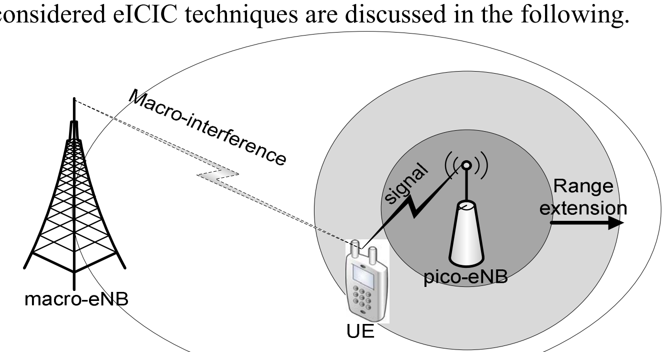

Fig. 1. A macro and pico heterogeneous network with range extension.

A. Pico-cell range extension

Typically, UE cell selection is based on UE measurements of Reference Signal Received Power (RSRP). In traditional homogeneous networks, the eNB that offers the highest RSRP is selected as the serving eNB for the UE. Using the same

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method for the considered macro and pico scenario will result in potentially only few UEs being served by the pico-eNBs due to the much lower transmit power of pico-eNBs. In other words, the RSRP-based cell selection can lead to unbalanced cell load for HetNet scenarios. To properly balance the load between the macro and pico layers, a positive offset can be applied to the RSRP measured from pico-eNBs. Expressed mathematically as,

$$j_{selected} = \arg\max_{j}\{RSRP_{1\le j\le \#macro}, \\ RSRP_{\#macro+1\le j\le \#macro+\#pico} + RE_{offset}\} \quad (1)$$

where, #macro and #pico denotes the set of measured macro and pico cells, respectively. This approach is referred to as the pico-cell Range Extension (RE). By introducing this bias in the cell selection, more UEs are pushed to the pico-layer as shown in Fig. 1.

RE balances the network load at the cost of poor Signal to Interference and Noise Ratio (SINR) quality for pico-UEs if no eICIC technique is applied. This is mainly because these UEs will suffer from stronger macro interference and lower signal strength from their serving pico-eNB. This means that only moderate values of RE_{offset} are recommended to be used in co-channel cases without eICIC.

B. Resource partitioning

TDM eICIC offers resource partitioning between macro and pico, allowing use of larger values of RE_{offset} for further improving the offload of traffic to the pico-layer. The basic principle is to prevent the macro-eNBs from transmitting on certain subframes [3]. During these subframes, the pico-eNBs can schedule UEs that would otherwise experience too high interference from the macro-layer. This allows the use of higher RE_{offset} for the pico's. In LTE Rel-10, it is possible to coordinate the usage of pico RE and eICIC via the X2 interface.

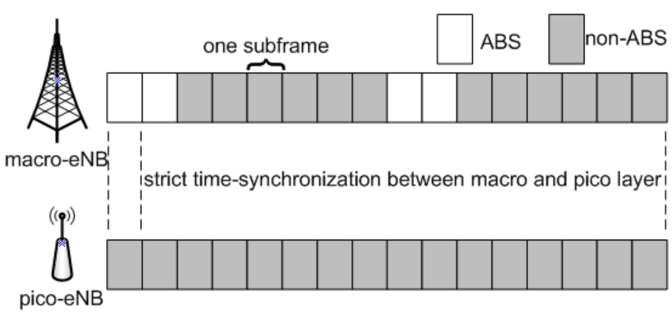

Fig. 2. TDM muting in HetNet with both macro- and pico-eNBs.

Fig. 2 shows a possible configuration of eICIC. The macro-eNBs are periodically muted at certain subframes. During these subframes, no data signal will be sent from the macro-eNBs. However, the macro-eNB should still transmit critical system information and Common Reference Signals (CRS) in order to provide support to the legacy UEs [3]. The muted subframes are therefore named the Almost Blank Subframes (ABS) [14]. The ABS pattern is periodical with 40 subframes for FDD mode. The periodicity of 40 subframes for FDD has been selected to maximize the protection of common channels, including uplink hybrid automatic repeat request (HARQ) performance. For maximum benefit from eICIC, base station nodes of the same type in a given local area are recommended to use the same ABS muting pattern.

C. CSI management and packet scheduling for eICIC

With eICIC enabled, the pico-UEs may experience significantly different interference levels between ABS and normal subframes. It is therefore desirable to configure the pico-UEs to report separate Channel State Information (CSI) for ABS and normal subframes. The pico-eNB should use the proper CSI feedback that matches the current macro-eNB muting status when performing link adaptation and packet scheduling decisions. It is of vital importance that pico cell-edge UEs are prioritized in the scheduling process when macro-eNBs are muted. This can be achieved by using a channel aware packet scheduler, e.g., the Proportional Fair (PF) scheduler.

In this paper, we assume all pico-UEs are schedulable at all time. A frequency domain PF scheduler chooses a the UE that maximizes the metric of $M_k = r(k,m,t)/R(k,t)$ at each physical resource block group *m*, where *k* is the user index, *m* is the physical resource block group, $r(k,m,t)$ is the supported UE throughput at time *t*, estimated from the UE CSI report; $R(k,t)$ is the average UE throughput until time *t*. For a cell-edge pico-UE with strong macro-interference, a much higher supported throughput $r(k,m,t)$ is expected on macro-ABS than on normal subframes. Meanwhile, the UEs close to a pico-eNB are less affected by the macro-layer interference, and are therefore subject to smaller variations of supported throughput versus time. When the macro-cells use ABS, pico-UEs in the cell edge tend to have higher scheduling metric and are more likely to be scheduled. Similarly, when the macro-cells transmit normal subframes, more resources will be assigned to pico cell center UEs.

III. Simulation Methodology And Assumptions

A network layout with co-channel deployment of macro and pico-eNBs as defined in [15] is simulated. The network topology consists of a standard hexagonal grid of three-sector macro-eNBs, complemented with a set of low power pico-eNBs with omni-directional antennas. A quasi-dynamic system level simulator is used, including explicit modeling of major Radio Resource Management (RRM) algorithms such as packet scheduling, HARQ, link adaptation, 2x2 closed loop MIMO with precoding and rank adaptation [16]. For scenarios with eICIC enabled, we assume a perfectly synchronized network. According to the 3GPP simulation guidelines, one pico-eNB is deployed in each hotspot, and the hotspots have approximately the same amount of UEs [15]. Therefore, one common RE offset is suitable for all pico-eNBs. UEs are assumed to be LTE Rel-10 compliant, so they support separate reporting of CSI for ABS and non-ABS subframes. Furthermore, UEs are assumed to perfectly cancel CRS interference coming from ABS transmission, by estimating the CRS interference from neighbouring cells and subtracting it from the received signal [3]. The link to system mapping is based on the exponential effective metric model [17]. The default simulation parameters are summarized in Table I.

The following measures are used as performance indicators:

- 5%-ile and 50%-ile UE throughput: the UE throughput (both macro and pico UE) obtained at the 5% and 50% points of the Cumulative Distribution Function curve.

- Pico-layer offloading capacity: the percentage UEs that are offloaded to the pico-layer.

Table I: Summary of simulation assumptions [15][16].

Parameter	Setting
Network Layout	500m macro-layer Inter-Site Distance with 0~10 pico-eNBs per macro-cell
Cell layout	7 macro-sites (21 macro-cells), wrap-around
Number of UEs	630 in the whole network
UE placement	2/3 of UEs inside the hotspots (the area within 40 m radius of each pico-eNB); the remaining UEs are uniformly distributed within the macro-cell area.
Transmit power	Macro-eNB: 46 dBm; pico-eNB: 30 dBm
Sub-frame duration	1 ms (11 data plus 3 control symbols)
Modulation and coding schemes	QPSK (1/5 to 3/4), 16-QAM (2/5 to 5/6), 64-QAM (3/5 to 9/10)
HARQ modeling	Ideal chase combining with maximum 4 transmissions, 10% block error rate target
Bandwidth	10 MHz at 2 GHz carrier frequency
Antenna system	2 x 2 with rank adaptation and Interference rejection combining [18]
Antenna gain	Macro: 14 dBi; pico: 5 dBi; UE: 0 dBi
Antenna pattern	Macro: 3D [15]; Pico and UE: Omni
Traffic model	Full buffer, full load
Path loss	Macro-eNB to UE: *128.1+37.6·log10(R[km])* Pico-eNB to UE: *140.7+36.7·log10(R[km])*
Shadow fading	Lognormal. std=10 dB for pico-eNB to UE links, 8 dB for Macro-eNB to UE links
eNB packet scheduling	Proportional Fair (PF)
ABS muting ratio	Same for all macro-eNBs, 0/8 to 6/8

IV. PERFORMANCE OF EICIC

A. *Baseline performance of eICIC*

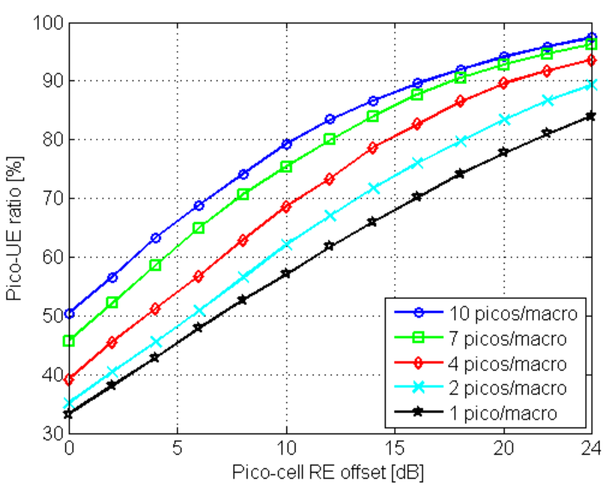

Fig. 3. Pico-cell offloading capability at different RE offsets and different number of pico-eNBs per macro-cell.

The baseline performance is first presented under default assumptions of 30 dBm pico-eNB transmit power, 2/3 of UEs placed in hotspots around the picos, and use of PF scheduling. Fig. 3 shows the ratio of UEs that are offloaded to the pico-layer versus RE_{offset}. Increasing RE_{offset} significantly increases the number of UEs that are connected to the pico-layer. In a case with 4 picos per macro-cell area, 70% of the UEs are offloaded by the pico-layer with 10 dB RE_{offset}, whereas only 40% without RE. The offloading also improves as the number of pico-eNBs is increased. Fig. 3 can be used to map from RE offset values to offloading ratios in results presented in the rest of the paper.

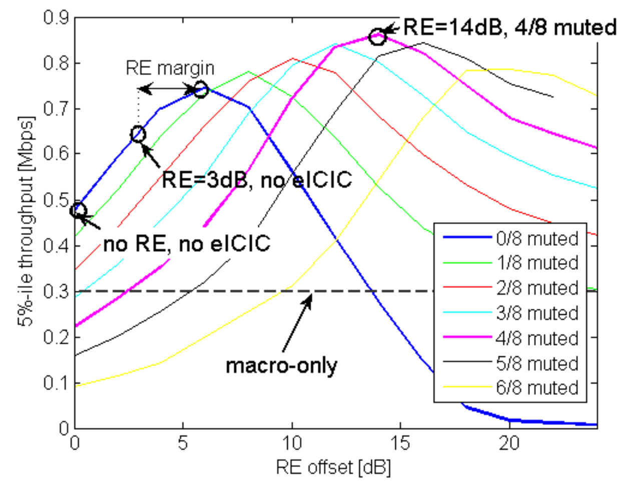

Fig. 4. 5%-ile UE throughput with 4 pico-eNBs per macro-cell. Results are shown with various pico-layer RE offsets and macro-layer muting ratios.

The 5%-ile UE throughput for a scenario with 4 pico-eNBs per macro-cell area is shown in Fig. 4. The results are presented for different RE offsets and different macro-layer ABS muting ratios. For each muting ratio, RE offset values from 0 to 24 dB are simulated. Different muting ratios are also simulated to obtain the best performance of eICIC.

Based on the results in Fig. 4, it is observed that simple co-channel deployment of macro and pico-eNBs without RE and eICIC results in a gain of 59% over macro-only case. With 6 dB RE offset and no eICIC, the gain is further increased to 150%. However, it should be noted that applying RE will decrease the pico-UE SINR and reduce the control channel reliability if no eICIC is enabled [19]. Hence, typically the RE offset for cases without eICIC is recommended to be maximum on the order of 3 dB, and in many cases lower depending on the mobility parameter settings [20]. When eICIC is enabled, higher RE offsets can used, resulting in a gain of 190% of the 5%-ile user throughput by using 14 dB RE offset and a muting ratio of 4/8.

Fig. 5 and Fig. 6 summarize the eICIC performance with different numbers of pico-eNBs per macro-cell area. Three curves are plotted in each figure; (i) no RE without eICIC, (ii) 3dB RE offset without eICIC, (iii) optimized RE with eICIC. For (iii), the performance is optimized by simulating different RE offsets and muting ratios, and selecting the configuration that maximizes the 5%-ile UE throughput, which is summarized in Table II.

Fig. 5 shows the performance of the 5%-ile UE throughput. By deploying one pico-eNB per macro-cell without RE or eICIC, the 5%-ile UE throughput is increased by 68% as compared to the macro-only case. When the number of pico-eNBs increases to 10, a performance gain of 12% is achieved. This is observed because the additional pico-eNBs also lead to high interference. The use of 3 dB RE (as compared to no RE) with 10 pico-eNBs results in 61% gain. By enabling eICIC, the gain is further increased to 1.61*1.50-1=142% for 10 pico-eNBs, as compared to no RE or eICIC.

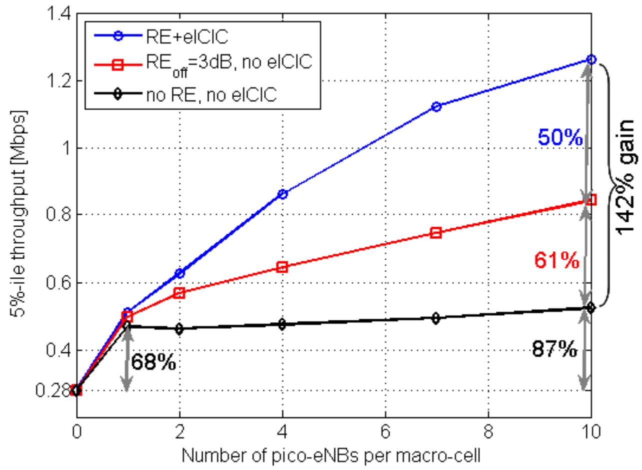

Fig. 5. 5%-ile UE throughput with different number of pico-eNBs and eICIC related techniques.

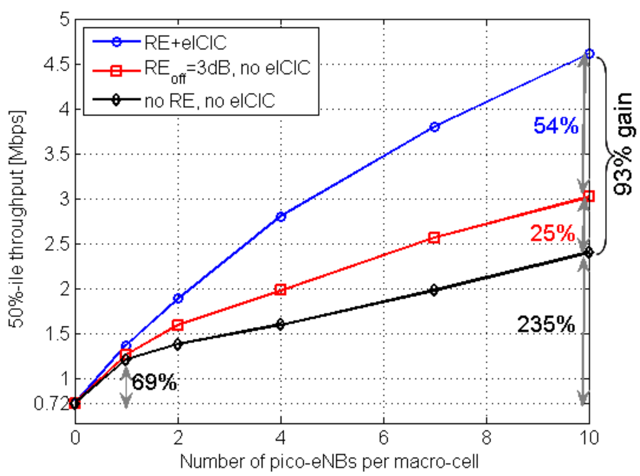

Fig. 6. 50%-ile UE throughput with different number of pico-eNBs and eICIC related techniques.

The performance of the 50%-ile UE throughput is summarized in Fig. 6. Here it is observed that even without RE or eICIC the performance steadily increases as more pico-eNBs are installed. With 10 pico-eNBs per macro-cell, the gain is 235%. The use of RE and eICIC offers additional gains of 25% and 54%, respectively. Correspondingly, the total gain of using eICIC and high RE offset in 50%-ile UE throughput equals 93% with 10 pico-eNBs per macro-cell.

Table II. Optimal configuration with different number of pico-eNBs per macro-cell.

Deployment scenarios		Number of pico-eNBs per macro-cell				
		1	2	4	7	10
No eICIC	Pico-UE ratio	33%	35%	39%	46%	50%
With eICIC	RE_{offset} [dB]	8	10	14	16	22
	Muting ratio	2/8	3/8	4/8	5/8	6/8
	Pico-UE ratio	53%	62%	79%	88%	96%

Finally, the RE offset, TDM muting ratio, and the corresponding pico-layer offloading ratios that maximize the 5%-ile user throughput are summarized in Table II. This can be used as guidelines for the heterogeneous network deployment. It clearly shows that with eICIC, more UEs can be offloaded to the pico-layer and hence results in better overall network performance. If more pico-eNBs are to be deployed in a network, they have higher offloading capability and benefit more from TDM muting of the macro-layer. Therefore, both the RE offset and the TDM muting ratio should be increased accordingly.

B. eICIC gain vs. pico-eNB power and packet scheduler

Having determined the optimal settings with the default scenario assumptions, it is also important to note that the gains are impacted by many other factors, including the pico-eNB transmit power, the packet scheduler and the spatial distribution of the UEs.

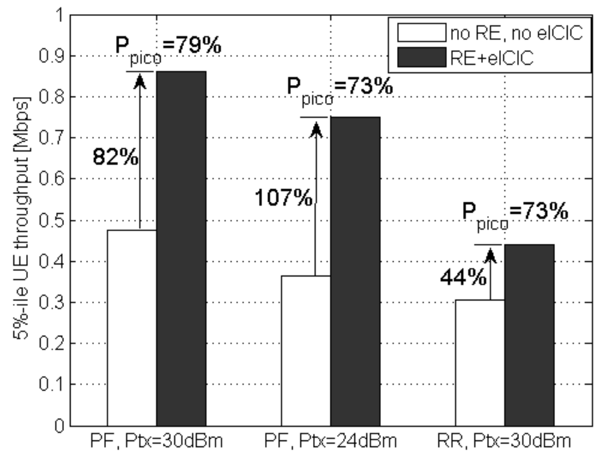

Fig. 7. 5%-ile UE throughput with pico-eNB tx power levels and different packet schedulers. There are 4 pico-eNBs per macro-cell area.

Fig. 7 summarizes the 5%-ile UE throughput for two different pico-eNB transmit power levels of 30 dBm and 24 dBm. The performance is evaluated for cases with/without eICIC, assuming 4 pico-eNBs per macro-cell. The performance with eICIC is obtained with a muting ratio of 4/8, which achieves the highest 5%-ile user throughput. The pico-layer offloading ratio (P_{pico}) when eICIC is enabled is also shown in the figure, and the corresponding RE offset can be obtained from Fig. 3.

In general, the throughput is reduced if the pico-eNB transmit power is reduced. The pico-layer offloading capability with eICIC also decreases from 79% to 73%. However, it is worth noticing that the total gain of eICIC and RE increases if the pico-eNB transmit power is reduced. This is because the macro-layer interference becomes relatively stronger as compared to experienced pico-eNB signal strength. The gain equals 82% when the pico-eNB transmit power is 30 dBm, and 107% at a lower power level of 24 dBm.

To verify the benefit of PF together with eICIC, we compare its performance with a channel blind Round Robin (RR) scheduler. With RR, UEs of the same cell get an equal amount of resources, irrespective of their channel qualities. As can be seen from the right-most bar in Fig. 7, the eICIC gain (with the help of RE) with a RR scheduler is only 44%, which is much lower than the case with a channel aware PF scheduler. When eICIC is enabled, PF doubles the performance of a RR scheduler. Therefore, in order for RR to benefit from TDM eICIC, a time domain scheduler that prioritizes the cell-edge pico-UEs on ABS should be applied. PF does not require such a time domain scheduler because it inherently prioritizes cell-edge pico-UEs on ABS.

C. eICIC gain vs. the spatial UE distribution

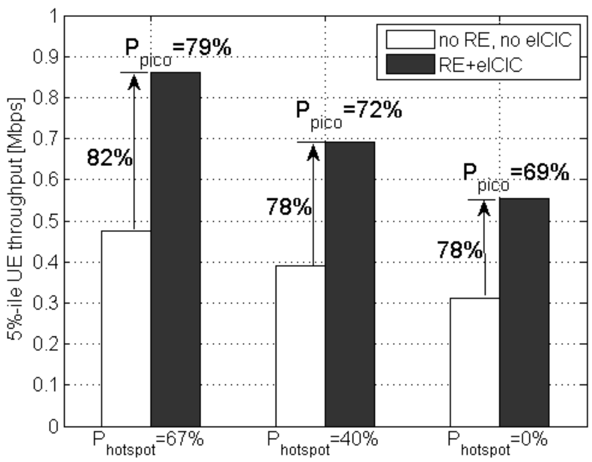

Fig. 8. 5%-ile UE throughput with different ratios of hotspot UEs, assuming 4 pico-eNBs per macro-cell, with 30 dBm transmit power and PF scheduling.

The performance of HetNet depends significantly on the spatial UE distribution. The 5%-ile UE throughput performance is therefore summarized in Fig. 8 for three different UE distributions, each characterized by the percentage of UEs that are assumed to be placed in the immediate surroundings of the pico-eNBs, denoted by $P_{hotspot}$. The case with 0% hotspot corresponds to simple uniform spatial distribution of UEs in the entire simulated network. The presented results in Fig. 8 are for 4 pico-eNBs per macro-cell with 30 dBm transmit power and PF scheduling.

It is observed that as the ratio of UEs within the hotspot area decreases, less UEs are offloaded to the pico-layer, and the system performance gets worse. Changing the percentage of hotspot UEs affects both the performance with and without eICIC. As a consequence, the relative gain of applying eICIC and RE is hardly affected, and is stable at approximately 80% in this case.

V. Conclusion

In this paper we have analyzed the downlink co-channel performance of macro and pico-eNBs using both RE and eICIC. Using RE for pico-eNBs helps increase the percentage of UEs offloaded to the pico-layer. However, if eICIC is not enabled, only marginal RE offsets can be used as the macro-cell interference will otherwise cause significant problems for the pico connected UEs. Enabling eICIC allows the use of higher RE offsets for the pico-cells. With 10 pico-eNBs per macro-cell area, the gain of eICIC with RE equals 93% for the 50%-ile UE throughput.

The benefit of eICIC naturally depends on the HetNet deployment scenario and various network parameters. Based on the presented performance results, the following additional main findings are worth highlighting; the relative eICIC gain increases for lower pico-eNB transmit power levels, but is less sensitive to the spatial distribution of UEs. However, the overall system performance decreases if too low pico-eNB transmit power is used, so lowering the pico transmit power is not recommended. The optimal RE offset and eICIC ABS muting ratio were found to depend on many factors, such as the number of deployed pico-eNBs, and thus call for careful optimization to gain the most from these techniques. The signaling of the eICIC parameter settings is supported via X2 between network nodes. Finally, it should be emphasized that all the results presented assumed LTE Rel-10 UEs supporting configuration of restricted CSI measurements and cancellation of CRS interference from ABS. Without such UE support, the gain of eICIC will naturally decline.

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