Introducing Heterogeneous Networks in HSPA

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***Abstract* - In heterogeneous networks, low power nodes may be deployed within macro cells for coverage and capacity improvement. Due to transmit power difference between low power nodes and macro cells, downlink (DL) and uplink (UL) coverage of the low power nodes can be very different. This DL-UL coverage difference could negatively affect system performance on both the DL and the UL. We describe a few techniques to alleviate this problem in HSPA. We present simulation results to show the effectiveness of these techniques as well as the system performance improvement of heterogeneous networks over traditional macro cell only deployments in HSPA.**

I. Introduction

To accommodate the rapidly increasing demand for data on cellular networks, operators need to find solutions to improve system coverage as well as capacity. Over the last few years, cellular standards have explored link level optimizations (such as MIMO, Higher Order Modulation etc) to improve capacity, that have brought spectral efficiency close to theoretical limits. A promising approach to improve capacity further is that of Heterogeneous Networks (HetNets), in which low power nodes are deployed within macro cells.

In traditional homogeneous cellular systems, a network of base-stations (macro cells) is deployed in a planned layout with similar characteristics such as transmit power, antenna patterns, receiver noise floors etc. One way to increase network capacity may be to deploy more macro cells. However, in already dense deployments typically in urban areas, deploying more macro cells may provide diminishing returns due to higher inter-cell interference on the downlink. Another drawback may be the high site acquisition costs associated with macro deployments. An interesting alterative to deploying more macro cells may be to deploy low power nodes, which transmit at a lower power (typically ~ 100mW-5W) with lower antenna height, compared to macro cells (typically ~20W-40W). In this article, we refer to low power nodes as pico cells. When traffic is concentrated in so-called "hotspot" areas, deployment of picos near these hotspots may provide system capacity gains without significantly increasing interference on the downlink.

In this article, we focus on the co-channel deployment of low power pico cells in High Speed Packet Access (HSPA) networks. HSPA is the Code Division Multiple Access (CDMA) based packet-switched air-interface for cellular networks standardized by the 3rd Generation Partnership Project (3GPP) [1]. When deploying picos, we denote the UL coverage of the pico as the area in which the pico has the smallest path-loss to the user equipment (UE), assuming all macro and pico cells have the same noise figure. On the other hand, the DL coverage of the pico is determined by both the path loss as well as the pico's transmit power. Clearly, when pico transmits at a much lower power compared to the macro, pico has a smaller DL than UL coverage. Since serving cell selection is decided based on the DL received signal strength in HSPA, UEs within the UL coverage of a pico may be served by a macro cell that is stronger on the DL but weaker on the UL compared to the pico. This coverage imbalance, or DL-UL imbalance, poses additional challenges in terms of control channel (HS-DPCCH) [2] reliability as well as interference management between pico and macro cells.

We discuss a few solutions that mitigate the problems caused by a DL-UL imbalance between macros and picos. In the absence of such solutions, we show that deploying picos in the macro network may even result in performance degradation for a certain percentage of UEs. The solutions we describe not only ensure the decoding reliability of the control channel (HS-DPCCH), but also limit the UL interference caused by the UEs served by picos/macros to each other. Overall, these solutions ensure that picos can be deployed in a robust manner.

In Section II, we discuss potential problems that could arise from the pico deployment, and propose solutions for each problem. Section III provides recommendations for pico deployment in various configurations. In Section IV, we use simulations to show system throughput gains through introduction of picos. Section V presents our conclusions.

II. Potential Problems in Heterogeneous Networks

When deploying picos in macro networks, the transmit power difference between the picos and the macro cells is the source of potential issues. As serving cell selection is mainly based on DL received signal strength, the transmit power of each cell determines the area it covers as the serving cell. However, from the UL perspective, the strength of the signal received at each node does not depend on its DL transmit power. Thus, the introduction of picos could potentially cause DL-UL imbalance, in the sense that cells other than the serving cell could receive a stronger signal from the UE than the serving cell.

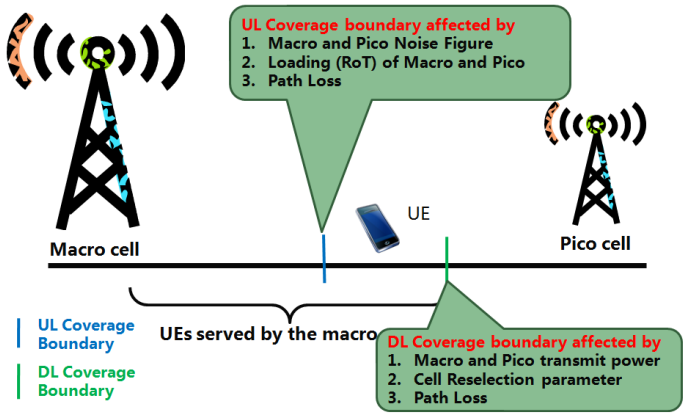

Figure 1 DL-UL Imbalance Scenario in Heterogeneous Network

Figure 1 illustrates the potential imbalance problem, i.e. UL and DL coverage boundary not being aligned for a given node. In a CDMA system, soft handover (SHO) can be supported such that the UE can be power controlled by the cells in the active set. Even with SHO support, DL-UL imbalance in HetNets could lead to the following key challenges:

1. Issues in decoding control channel (HS-DPCCH).
2. Excessive UL interference from UEs served by macros to picos.
3. Excessive UL interference from UEs served by picos to macros.

The magnitude of the above issues also depends on the architecture of deployment. From the architecture point of view, there may be two options for the deployment of picos, each of which brings different challenges:

- Shared RNC deployment where macros and picos share the same RNC. Under this deployment scenario, Soft Handover (SHO) is supported between macros and picos. Enabling SHO reduces interference issues between picos and macros since the transmit power of UEs in SHO can be controlled by both AGCH (serving cell) and RGCH (non-serving cell) as well as via power control. On the other hand, due to the DL-UL imbalance, serving cell may have problems decoding the HS-DPCCH channel.
- Dedicated RNC deployment where macros and picos are controlled by different RNCs. Under this scenario, SHO is not supported between macros and picos. On the positive side, there are no HS-DPCCH reliability issues. However, interference issues could be more severe.

A. *Excessive UL Interference from Macro UEs to Picos*

Excessive interference to picos may be caused by UEs who are served by the macro but do not have the victim pico in the Active Set (either pico is outside the Active Set threshold when considering DL EcpIo, or SHO is not possible due to the pico being controlled by a different RNC than the macro). In this case, due to the DL-UL imbalance, the UE could still have a better UL to the pico (compared to the macro). Without SHO, the pico is not able to power or rate control the UE, which could cause the pico to become a victim of large un-controllable interference from UEs served by the macro. In such a scenario, UEs served by the victim pico may experience low UL throughput.

We show simulation results for the case where picos have transmit power of 30dBm (1W), while macros have transmit power of 43dBm (20W). Figure 2 shows the UE UL throughput CDF for both the baseline and the HetNet cases. The baseline case contains only the macros, while the HetNet case has 4 picos uniformly dropped per macro. The rest of the simulation setup used Section II is the same as the setup described later in Section IV. In Figure 2, a very bad tail of the UL throughput can be seen for the HetNet case. Further insight on this tail comes from Figure 3, which separates UEs into two categories: UEs served by macros and UEs served by picos. Figure 3 shows that some UEs served by picos suffer from bad UL throughput. Figure 4 shows the average noise rise (RoT) of each cell. Cells with index 1 to 57 are macros while cells with index higher than 57 are picos. A proportional fair scheduler is used for the UL with a target RoT of 5.5dB. Since some macro UEs cause large interference to picos, several picos have RoT higher than the 5.5dB target. In this case, UEs served by these picos will receive very small grants. Also, due to the random dropping of UEs, some picos serve no or only a few UEs and have lower RoT than the target 5.5dB.

It should also be emphasized that this simulation assumes that SHO between macro cell and pico is allowed. When SHO between macro-cell and pico is NOT supported (for example, where the macro and pico are controlled by different RNCs or the pico is not added to the active set due to conservation active set threshold settings), the interference problem could be worse.

To control the excessive interference from macro to pico, our recommended solution is to apply padding at the pico. Padding attenuates the total UL received signal at the pico; effectively increase the pico noise figure. For example, if x dB padding is applied at the pico, it effectively makes the total out-cell interference received at the pico x dB weaker compared to the pico thermal noise. The use of padding helps to align pico DL and UL coverage.

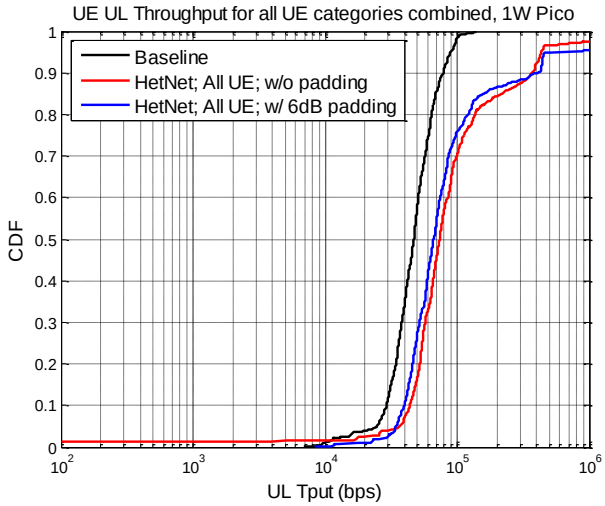

Figure 2 CDF of UL Throughput Assuming 1W Pico

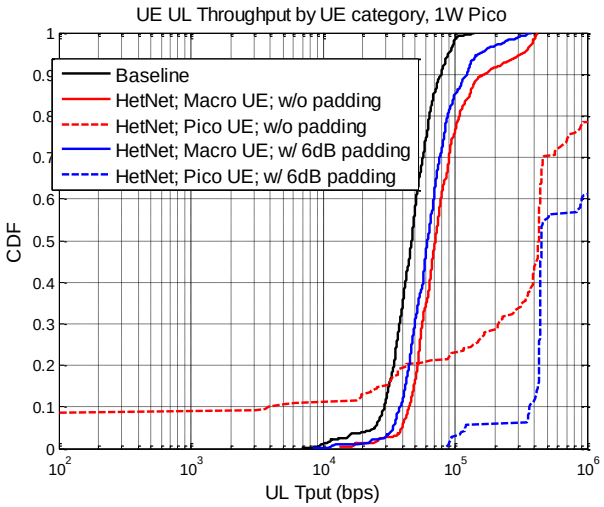

Figure 3 CDF of UL Throughput Assuming 1W Pico

Through simulations, we show the performance with 6dB padding at the pico. As can be seen in Figure 4, 6dB padding limits the interference from macro to pico, thereby stabilizing the

RoT at the pico. Furthermore, Figure 2 and Figure 3 show that the bad UL throughput tail has been removed. Without padding, we show that there are around 2% of UEs who suffer from significant UL throughput loss under HetNets deployment compared with the macro only scenario. With appropriate 6dB padding, statistically speaking, every UE in the system enjoys UL throughput improvement with HetNets deployment. Note that cell biasing [5] could also be used to reduce the DL-UL imbalance as well as offload more UEs to the pico. We will discuss the use of cell biasing in more detail in Section III.

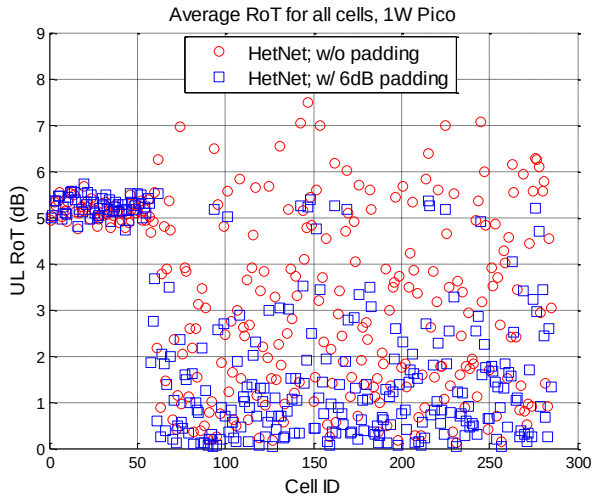

Figure 4 CDF of RoT Assuming 1W Pico

B. *Excessive UL Interference from Pico UEs to Macros*

In this section, we focus on excessive UL interference from UEs served by picos to macros, which mainly arises from uneven loading in HetNets. Consider a case where the pico serves a small number of UEs compared to the macro; in this case, UEs served by the pico may receive large grants and hence, transmit at high power. Such UEs could cause large interference to neighboring macro cells and degrade the UL throughput of the UEs served by the victim macro cell.

In simulations, we observe such cases particularly when the pico transmit power is 37dBm (5W), with the macro transmit power being 43 dBm (20W), and SHO between macros and picos is NOT supported (this may be due to the pico being controlled by a different RNC than the macro). We also assume that picos have 3dB worse UL noise figure compared to macros, considering that picos may be a lower cost solution compared to macros. With the above settings, the pico has 6dB lower transmit power than the macro. Considering the 3dB UL noise figure difference, in the worst case, a pico UE could cause 3dB less RoT to the macro than the RoT it causes to the serving pico. Even though the macro is weaker than the pico by 3dB on UL, due to the loading difference, the whole RoT at the pico may be shared among only a few UEs and these UEs may cause large interference to the macro. Due to the lack of SHO, the macro may not be able to power control nor rate control such UEs. It is possible for some macros to become the victim of excessive UL interference from the neighboring picos.

Figure 5 shows the UL throughput CDF across all UEs. We observe a bad UL throughput tail for the HetNet case. Further insight can be derived from Figure 6, which separates UL throughputs of UEs served by macros and picos. We observe a bad throughput tail for UEs being served by macros, which suggests macros may see high interference from UEs served by picos. Figure 7 shows the average RoT of each cell, which illustrates that some of the macros have RoT much higher than the target of 5.5dB.

In order to control interference from UEs served by picos to macros, one technique is to limit the maximum transmit power of UEs served by picos that could cause a large interference to the macros. This procedure would work as follows:

- If the UE is served by a pico, the UE measures and reports the following information to the RNC: the path loss to the strongest macro cell $\mathrm{PL}_{\mathrm{Macro}}$, the path loss to the serving pico $\mathrm{PL}_{\mathrm{Pico}}$(one way for the UE to differentiate macros from picos is through network configuration). The RNC also has the information of the thermal noise level at the Macro ($\mathrm{No}_{\mathrm{Macro}}$) and at the pico ($\mathrm{No}_{\mathrm{Pico}}$) Techniques for estimating thermal noise level have been covered in the literature [3][4]).
- The RNC triggers the limitation of the maximum transmit power for a particular UE if the following condition is met: $\mathrm{PL}_{\mathrm{Macro}} + \mathrm{No}_{\mathrm{Macro}} < \mathrm{PL}_{\mathrm{Pico}} + \mathrm{No}_{\mathrm{Pico}} + \mathrm{Threshold}$. The Threshold is a design parameter.
- For the UE whose maximum transmit power is limited by the RNC, the maximum power is set to $\mathrm{PL}_{\mathrm{Macro}} + \mathrm{No}_{\mathrm{Macro}} - \Delta$.

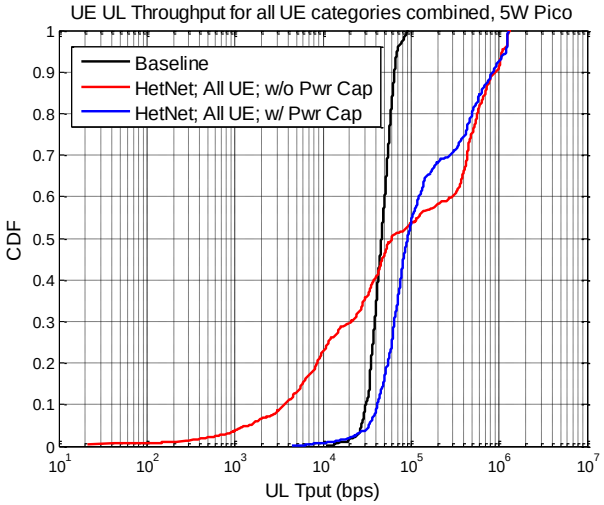

Figure 5 CDF of UL Throughput Assuming 5W Pico

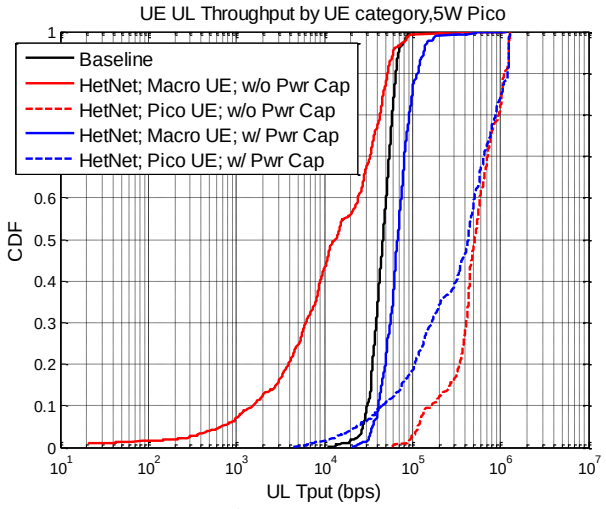

Figure 6 CDF of Throughput Assuming 5W Pico

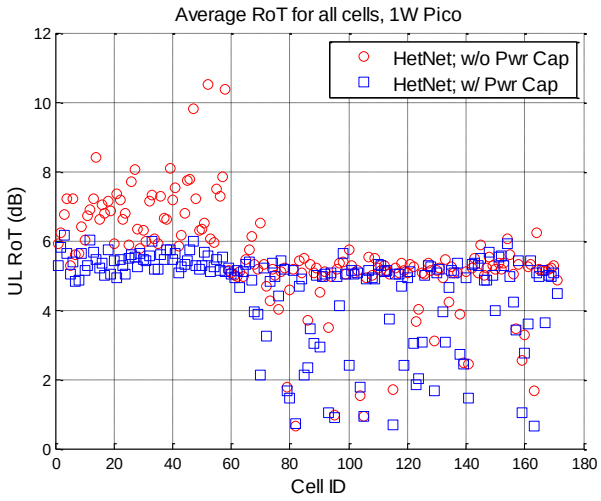

Figure 7 CDF of RoT Assuming 5W Pico

We choose Threshold = 6dB and Δ= 10dB . The effectiveness of the solution is demonstrated in Figure 5, Figure 6 and Figure 7. Clearly, with the UE transmit power limit, the interference from UEs served by picos to macros is significantly reduced. The RoT of macros can also be controlled close to the 5.5dB target. If we use 10% UE UL throughput as the performance metric, without power cap, we observe ~80% performance loss while with power cap, we observe ~30% performance gain with HetNet deployment.

C. *Control Channel (HS-DPCCH) Decoding Problem*

When a UE is in SHO between a macro and a pico with the macro being the serving cell, the UE may have a much better UL to the pico than to the macro. This causes the pico to power control the UE and the received signal strength at the macro to be very weak. This may result in the HS-DPCCH channel, which carries ACK/NAK and CQI for DL scheduling, being decoded unreliably. This could lead to NACK to ACK as well as ACK to DTX/NACK errors and trigger unnecessary retransmissions either at the RLC or PHY layers, thus degrading DL throughput.

We consider a case where the pico has transmit power of 30dBm (1W) while macro has transmit power of 43dBm (20w). There are 4 picos uniformly dropped in each Macro. We assume that the pico has the same UL noise figure (sensitivity) as the macro. In these simulations, the UE selects the cell with the strongest EcpIo as the serving cell. In Figure 8, we show that, without appropriate alleviating measures, HetNets could result in the ACK to DTX error probability for some of the UEs higher than 50%. Unreliable ACK/NACK detection could lead to very high percentage of unnecessary retransmissions.

To solve the HS-DPCCH reliability problem, a combination of the following two techniques can be considered:

1. Padding at the pico
   Padding has a negative impact such that UEs served by the pico have to transmit at a higher power, which increases interference in the system. Therefore, we do not recommend adding padding to perfectly align the DL and UL. Instead, we recommend handling some of the imbalance using padding, while handling the remaining imbalance using the second solution below.
2. HS-DPCCH C2P boosting
   To allow HS-DPCCH to be successfully decoded at the macro, we propose to dynamically increase the HS-DPCCH power offset (C2P). In HSPA, each field of HS-DPCCH (ACK/NACK, CQI) has a fixed C2P to the pilot channel, i.e. Δ_{ACK} , Δ_{NACK} and Δ_{CQI}. We propose to let RNC detect the DL-UL imbalance and appropriately boost the HS-DPCCH C2P by signaling the boost to the UE. The procedure would work as follows:

- Serving Node B reports the estimated UL EcpNt to the RNC
- RNC detects the DL-UL imbalance by comparing the serving Node B's reported UL EcpNt with the target EcpNt. Ideal C2P boost is computed as: $\text{C2P Boost Ideal} = \text{average}(\text{EcpNt}_{\text{target}} - \text{EcpNt}_{\text{serving}})$
- RNC signals the new HS-DPCCH C2P to the UE.

Figure 8 illustrates the effectiveness of the combination of these two techniques. For the HetNet scenario considered in this section, pico transmit power is 13dB lower than the macro transmit power which is the maximum DL-UL imbalance. We apply 6dB padding at the pico, which reduces the potential DL-UL imbalance to 7dB. We apply HS-DPCCH C2P boosting to handle the remaining imbalance. By combining 6dB padding with HS-DPCCH C2P boosting, the reliability of HS-DPCCH improves significantly.

Figure 9 shows the impact of the HS-DPCCH decoding reliability on the DL throughput. We focus on the lower percentile UE DL throughput, which shows the most impact from HS-DPCCH decoding. Simulation results demonstrate around 10% performance gain in terms of 10^{th} percentile UE DL throughput, comparing the HetNets deployment with 6dB padding and C2P boost over the HetNets deployment with neither padding nor C2P boost.

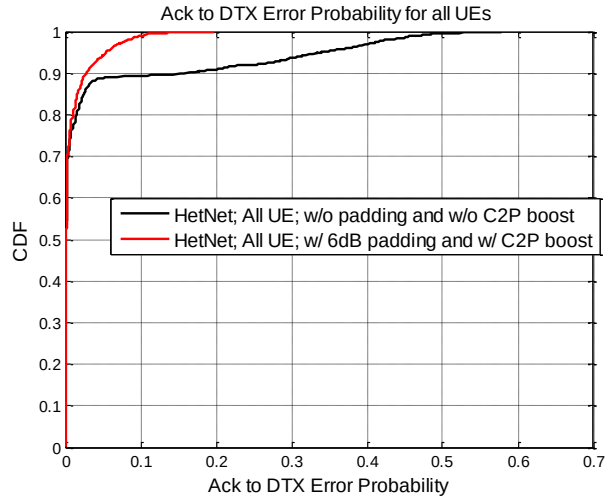

Figure 8 CDF of HS-DPCCH ACK to DTX Error Probability 1W Pico

In summary, Table 1 lists the potential problems that may be caused by the introduction of picos as well as the magnitude of the problem, as a function of the pico transmit power and whether SHO can be supported between the pico and the macro.

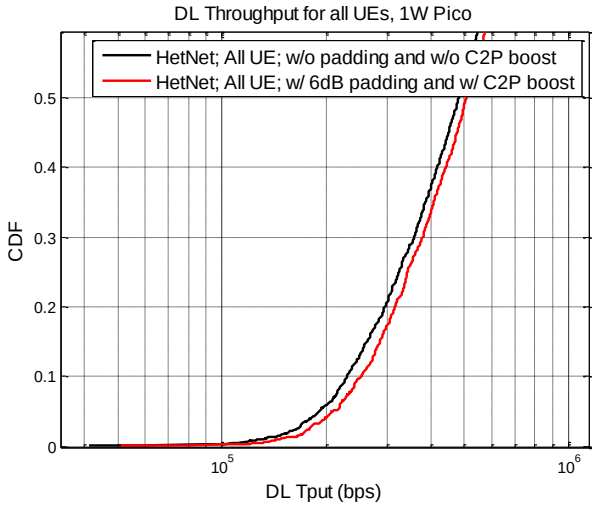

Figure 9 CDF of DL Throughput 1W Pico

Table 1 Potential problem from deployment of picos

SHO Between Pico and Macro	Pico Tx Power	HS-DPCCH Reliability	UL Interference Macro UE -> Pico	UL Interference Pico UE -> Macro
Allowed	5W	Minimum	Minimum	Medium
	1W	Medium	Medium	Minimum
	0.25W	Severe	Severe	Minimum
NOT Allowed	5W	NA	Minimum	Medium
	1W		Medium	Minimum
	0.25W		Severe	Minimum

III. Recommended Settings

In addition to the issues discussed in the previous section, another consideration is that due to the small transmit power of picos, their DL coverage is limited. Since picos are usually less loaded than macros (due to their smaller coverage area), it is desirable to extend their coverage through cell biasing. The UMTS specifications allow cell biasing using the Cell Individual Offset (CIO) [5], which biases cell selection by the CIO amount. Note that the use of CIO for picos also helps to reduce DL-UL imbalance.

While use of CIO for picos allows for improved HetNet system performance by offloading more UEs to picos (which are, in general, less loaded than macros), there are constraints on how large CIO values can be chosen:

- If CIO chosen is too large, UEs offloaded to the pico via CIO may see very strong interference on the DL, and consequently, have low geometries. This is the reason that we recommend a value of 3dB for CIO. It should be noted, though, that with more advanced UE receivers capable of interference cancelation (not considered in this paper), it may be possible to allow larger CIO values without much impact to the geometry of UEs offloaded to picos.
- With a larger number of UEs being served by picos, pico UEs may cause large UL interference to the neighboring macro. This is another reason to not pick a high CIO value.

In Table 2, we summarize some recommended settings depending on the pico transmit power and whether SHO is allowed between picos and macros. These settings are chosen mainly to ensure that both UL and DL observe robust gains (i.e., gains without any impact to tail performance).

It should be noted that when SHO is not allowed between pico and macro, we choose to assign CIO of 0dB instead of 3dB. This choice results in less number of UEs being offloaded to picos; however, the UL interference caused by UEs served by picos to macros is better controlled. Note that the interference from UEs served by picos and macros could be better controlled if Node Bs were equipped with advanced receivers, for example, receivers capable of inter-cell interference cancellation (ICIC). With such receivers, more aggressive values of CIO could also be chosen. Other techniques can also be used to control UL interference from UEs served by macros and picos. One example would be to introduce a new common RGCH (Relative Grant Channel) to send relative grants to other cell UEs. When the neighboring cell detects that out-of-cell interference has crossed a threshold, it begins to send down commands on this common RGCH.

In this paper, we focus on the case where Node Bs are not capable of advanced receivers, nor are techniques such as common RGCH employed. Under such systems, with the parameter settings in Table 2, the DL-UL imbalance can be completely handled with the combination of CIO, padding and adaptive HS-DPCCH C2P boosting up to 8dB.

Table 2 Recommended Setting for Heterogeneous Network Deployment

	SHO Allowed Between Pico and Macro			SHO NOT Allowed Between Pico and Macro		
Pico Tx Power	**5W**	**1W**	**0.25W**	**5W**	**1W**	**0.25W**
CIO at Pico (Macro CIO 0dB)	3dB	3dB	3dB	0dB	0dB	0dB
Padding at Pico	0dB	6dB	12dB	0dB	6dB	12dB

IV. System Simulation Results

In this section, through simulation results, we show the improvement in user throughput in HetNets compared to macro-only deployments. The performance metrics we use are:

mean user throughput and 10% tail user throughput. We also show the percentage of UEs offloaded to picos.

We consider a 57-cell deployment with wrap-around and inter-site distance of 500m. The macro Node Bs are sectorized into 3 cells, and the pico Node B's are omni-directional. There are 4 or 8 pico cells uniformly dropped in each macro cell area, with the minimum distance between a macro and a pico being 75m. The minimum distance from a macro or a pico to a UE is 35m and 10m respectively. The propagation loss models are based on the model 1 in evaluation methodology [6]. The UE population is 16 UEs per geographic area of each macro cell. The channel model is Pedestrian A 3km/hr (In this paper, we focused on the evaluation of performance benefit from HetNet deployment as well as the solutions to the potential issues that could arise from the deployment of small power node. Our conclusion should be insensitive to the choice of channel mode. The benefit from HetNet mainly comes from the cell splitting gain while the main issues arise from the DL_UL imbalance. Both of them are not directly impacted by the channel modes we choose). The traffic model is assumed to be full buffer for both DL and UL. Proportional fair scheduler is used for both DL and UL. Two ways of dropping UEs in the system are considered:

- Uniform dropping: UEs are uniformly dropped in the geographic area of each macro cell.
- 50% Clustered dropping: This mimics the pico deployment in hotspots. 50% of UEs are uniformly dropped within a 40 meter radius from each pico. Each pico has the same number of UEs clustered around it. The remaining 50% UEs are uniformly dropped in the geographic area of each macro cell.

A. *HetNets Performance Gain: Uniform dropping*

In Table 3, Table 4 and Table 5, we show the performance improvement with the deployment of picos in the coverage area of macros given uniform dropping. The baseline for comparison is the macro-only system.

From the results, we show that even with uniform dropping, significant gains are seen in most cases with deployment of picos. The DL throughput gain ranges from 20%-120% for mean throughput and up to 36% for 10% throughput. The UL throughput gain ranges from 80%-450% for mean throughput and up to 40% for 10% throughput.

B. *HetNets Performance Gain: 50% clustered dropping*

In Table 6, Table 7 and Table 8, we show the performance improvement with the deployment of picos in the coverage area of macros given 50% clustered UE dropping. Compared with uniform dropping, we expect to see a larger number of UEs being offloaded to picos, hence, more performance improvement. It is also interesting to note that, with larger pico transmit power, more UEs can be offloaded to picos, and therefore, the performance improvement is also larger. Moreover, gains are larger, particularly on the uplink, when SHO is allowed between macros and picos. For the DL, we observe 50-240% gains for the average throughput and 10-100% gains for the 10% UE throughput with HetNets deployment. For the UL, we observe 300-800% gains for the average throughput and up to 120% gain for the 10% UE throughput.

V. Conclusions

In this article, we discussed potential problems that could arise from the deployment of low power nodes in HSPA within the macro cell layout. These problems, which mainly arise from the DL-UL imbalance caused by the transmit power difference between the low power nodes and the macro cells, results in (1) unreliable HS-DPCCH decoding at the serving cell, (2) excessive UL interference from the UE served by the macro cells to the low power nodes, and (3) excessive UL interference from the UEs served by low power nodes to the macro cells. We proposed solutions to each of these issues, and demonstrated through simulations that these solutions can mitigate the issues. With these solutions in place, we also showed that significant DL and UL throughput gains are possible with deployment of low power nodes.

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[6] 3GPP 36.814, "Further advancements for E-UTRA physical layer aspects"

Table 3 HetNets Gain: uniform dropping and 5W Pico

5W Pico		DL		UL		
SHO Between Pico and Macro	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico
Allowed	2	71%	16%	250%	14%	20%
	4	129%	36%	456%	42%	37%
NOT Allowed	2	69%	7%	198%	12%	14%
	4	123%	18%	375%	21%	27%

Table 4 HetNets Gain: uniform dropping and 1W Pico

1W Pico		DL		UL		
SHO Between Pico and Macro	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico
Allowed	2	37%	5%	146%	16%	9%
	4	65%	15%	266%	27%	17%
NOT Allowed	2	33%	0%	107%	11%	6%
	4	57%	5%	187%	20%	11%

Table 5 HetNets Gain: uniform dropping and 0.25W Pico

0.25W Pico		DL		UL		
SHO Between Pico and Macro	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico
Allowed	4	27%	6%	133%	9%	8%
	8	55%	15%	260%	28%	15%
NOT Allowed	4	21%	1%	84%	8%	5%
	8	39%	2%	88%	14%	9%

Table 6 HetNets Gain: 50% clustering dropping and 5W Pico

5W Pico		DL		UL		
SHO Between Pico and	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico

Macro						
Allowed	2	153%	81%	518%	93%	47%
	4	244%	101%	818%	129%	55%
NOT Allowed	2	153%	62%	427%	47%	39%
	4	236%	68%	710%	72%	44%

Table 7 HetNets Gain: 50% clustering dropping and 1W Pico

1W Pico		DL		UL		
SHO Between Pico and Macro	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico
Allowed	2	93%	46%	407%	41%	29%
	4	139%	49%	576%	59%	32%
NOT Allowed	2	86%	29%	340%	4%	22%
	4	129%	29%	503%	18%	25%

Table 8 HetNets Gain: 50% clustering dropping and 0.25W Pico

0.25W Pico		DL		UL		
SHO Between Pico and Macro	#Pico per macro	Mean Tput Gain	10% Tput Gain	Mean Tput Gain	10% Tput Gain	% UE Served By Pico
Allowed	4	65%	23%	333%	25%	18%
	8	87%	26%	391%	50%	22%
NOT Allowed	4	54%	12%	285%	1%	12%
	8	67%	7%	333%	9%	14%