An Interference Coordination Scheme for Picocell Range Expansion in Heterogeneous Networks

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Abstract—**Through deploying additional low-power nodes (LPNs) under the coverage area of a macrocell, heterogeneous network (HetNet) or multi-layered network deployments could be critical for operators to boost system capacity (per unit area). In order to extent the coverage region of open access LPNs and hence offload more traffics from macrocells, cell range expansion (CRE) strategy is suggested to apply in HetNets. However, when macrocells and LPNs share the same spectrum, the total network throughput could actually decrease due to CRE if the inter-layer interference couldn't be effectively managed. In this paper, we propose an inter-layer interference coordination scheme on the downlink side for an OFDMA co-channel macro-pico HetNet that carries out CRE technique. The idea of the proposed method is to coordinate frequency and power resources among macrocells and picocells with a set of resource allocation rules. Simulation results show that the proposed method can bring a significant increase in overall system capacity as well as reduce the user outage rate in the system, especially when aggressive CRE is applied.**

Keywords- heterogeneous network; cell range expansion; inter-layer interference; interference coordination

I. INTRODUCTION

As the use of smart phones and other advanced mobile devices continues to explode, the amount of mobile data traffic has been increasing exponentially in recent years. As a result, the 3GPP (Third Generation Partnership Project) LTE-A (Long Term Evolution-Advanced) has started a work to investigate heterogeneous network (HetNet) or multi-layered network deployments as an efficient way to provide addition capacity needs. A HetNet refers to a network deployment in which a large number of low-power nodes (LPNs) or small cells are placed throughout a macrocell layout.

To overlay on top of the traditional macrocells (so called high power nodes), three different types of LPNs have been considered in 3GPP LTE-A for HetNet deployments, including picocells, femtocells, as well as relay stations [1]. These overlaid LPNs offload the macrocells, and more importantly, they provide a significant capacity gain via higher spatial spectrum reuse. Moreover, they can be used to enhance the receptions in poor coverage areas. In the subsequent discussions, we assume a basic HetNet deployment scenario with two cell layers, i.e. macro-layer and pico-layer, operating on the same set of frequencies (i.e. co-channel allocation).

With large power difference between the two layers and by using the conventional cell selection scheme, the load per picocell may be relatively low in a co-channel macro-pico HetNet. In order to extend the footprint of the picocells and thus increase the offload opportunities from macrocells to picocells, cell range expansion (CRE) technique [2][3] has recently been introduced in 3GPP LTE-A. However, user equipments (UEs) making use of CRE can experience severe interference conditions since the signal from the associated picocell is weaker than the signals from interfering macrocells. Therefore, in order to ensure robust operation in a co-channel macro-pico HetNet with CRE, the inter-layer (or cross-tier) interference must be effectively addressed.

In this paper, we introduce an inter-layer interference coordination scheme on the downlink side for an OFDMA co-channel macro-pico HetNet, and in particular we assume that the CRE technique is enabled in the system. The proposed scheme makes use of a combination of power and frequency coordination together with a set of resource allocation rules. The key idea of this scheme is to have a *protected* band for cell-edge pico users on which a reasonable signal quality can be obtained because of the relief of macro interference. We verify the suitability and the degree of performance improvement of the proposed scheme through simulation studies.

II. PICOCELL RANGE EXPANSION

In a traditional macro-only network, typically the cell selection (or cell association) is based on the criterion of maximal downlink (average) received signal strength (RSS). In other words, the UE is typically associated to the cell with the strongest downlink RSS and it can be further expressed as

$$Serving\ Cell = \arg\max_{\{i\}} \{RSS_i\}, \tag{1}$$

where the index i corresponds to the candidate cell index. This cell selection scheme is commonly adopted and identical to the existing cell section scheme used in LTE and WCDMA (Wideband Code Division Multiple Access) systems. Note that RSS is a long-term average measurement taking into account of transmit power, distance-dependent path loss, shadowing and antenna gain. In a macro-only deployment, since all the macrocells typically have similar transmission configurations (such as transmit power level, antenna patterns, etc.) and load

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conditions, the UE is typically best served by the cell which provides the largest downlink RSS.

However, in the deployments of macro-pico HetNets, under the conventional cell association rule of selecting the cell with the highest downlink received power, the number of UEs associated with picocells is very small. As a consequence, very few UEs benefit from the presence of the picocells and this may further leads to the case where the picocells serve only a few users while at the same time in the macrocells the competition for the available resources would remain high. The limited coverage of picocells is a result of lower transmit power, lower antenna gain and worse propagation conditions compared with macrocells. It is therefore beneficial to have an UE connect to a picocell even if it is not the cell which provides the strongest received power. Generally, such a cell selection scheme is referred as cell range expansion (CRE) of low power nodes.

Very recently, biased-RSS cell selection has been proposed and considered in 3GPP as a promising scheme for realizing CRE of picocells [3][4]. This scheme causes users to select a picocell by adding a cell selection bias to the RSS from picocells and it can be given as

$$Serving\ Cell = \arg\max_{\{i\}} \{RSS_i + bias_i\}, \tag{2}$$

in which the $bias_i$ (in dB) is chosen to be a positive, non-zero value whenever the candidate cell i corresponds to a picocell and is set to zero for all macrocells. As illustrated in Fig. 1, such a cell selection strategy would extend the area in which the picocell is selected. In our work, the CRE concept is fulfilled by using biased-RSS cell selection, and we further assume the same CRE bias setting for all picocells in the evaluation system.

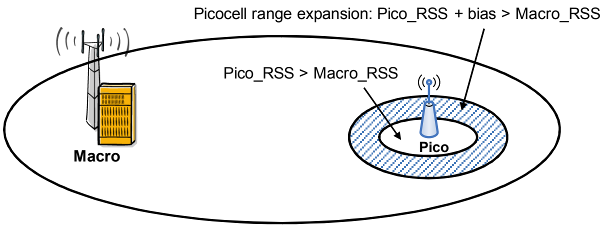

Figure 1. Simple illustration of picocell range expansion

III. PROPOSED INTER-LAYER INTERFERENCE COORDINATION SCHEME

Considering a macro-pico HetNet, inter-layer interference could be strong and varied significantly when the increased LPN footprint (i.e. CRE) technique is utilized. To overcome the interference issue, the picocell needs to perform interference coordination with the dominant macro interferers. In the following, the proposed inter-layer interference coordination (ILIC) scheme that applies restrictions to the frequency and power resources in a coordinated way between macro and pico cell layers is described. Herein, we call this method the *PF-ILIC* scheme.

For the rest of the paper, we use the following abbreviations for simplicity: Any UE served by the macrocell is referred to as a "*MUE*". The term "*PUE*" refers to a UE which is connected to a picocell. Furthermore, the term "*range expansion PUE*" (simply called *RE PUE* hereafter) refers to any PUE that is additionally served by a picocell due to CRE. More specifically, the RE PUEs are those UEs who are originally attached to macrocells, but now are served by picocells via the utilization of CRE.

The PF-ILIC scheme consists of three key components; they are frequency-power arrangement, band scheduling, and adaptive frequency partition.

A. *Frequency-Power Arrangement*

A typical interference-limited case when adopting CRE is that a noticeable fraction of cell-edge PUEs will suffer from macrocell interference. In order to make those PUEs work properly, it is fairly reasonable that one part of the frequency resources is reserved for cell-edge PUEs, on which the corresponding transmission power of the macrocells (or macro-layer) is reduced. Figure 2 shows the frequency-power arrangement of the PF-ILIC method. As depicted in Fig. 2, the available spectrum is divided into two distinct subbands in every cell. One subband is named *normal band* (*NB*) and the other subband is termed as *platinum band* (*PB*). Let P_{macro}^{tx} and P_{pico}^{tx} be the maximum transmission power level for macrocell and picocell, respectively. For each picocell, both normal band and platinum band are transmitted with maximum power level. However, for each macrocell, only the normal band has maximum transmission power level while the platinum band is restricted in power. In such arrangement, we can have "protected band" (i.e. platinum band) for PUEs on which the significant interference from macrocells is alleviated.

Referring to Fig. 2, a parameter η, called *power reduction factor*, is introduced to represent the power ratio of normal band to platinum band. This factor is chosen to be a value greater than one for macrocells while it equals one for picocells. In this study, the power reduction factor (η) corresponding to macrocells is set to 10 dB for the proposed method. In other words, the transmission power on platinum band for each macrocell is 10 times less than that on normal band.

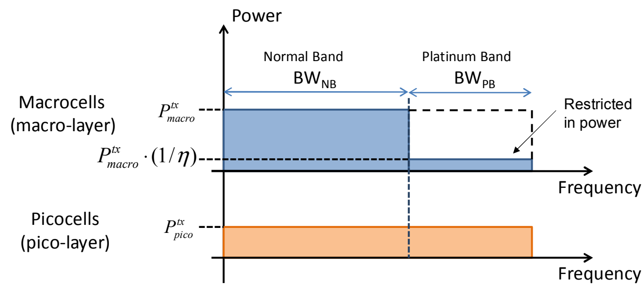

Figure 2. The proposed frequency-power arrangement for co-channel macro-pico HetNet

B. *Band Scheduling*

With the proposed frequency-power arrangement, it is useful for picocells to serve the UEs at cell borders by using platinum band since the interference is significant lower due to the power reduction at macrocells. Therefore, in the PF-ILIC scheme, the picocell primarily schedules cell-edge users to use the platinum band, whereas the users closer to the picocell (i.e. cell-interior users) have exclusive access to the normal band and nevertheless, they may be granted with the frequency resources of platinum band if it is not taken by the cell-edge users. Considering the macrocells, it is better to only serve central users (i.e. cell-interior users) on the platinum band since they are more insensitive to power reduction. By doing this, the frequency resources on platinum band could be effective utilized in macrocells. On the other hand, the normal band in macrocells can be applied to all the users, including edge and central users. We note that cell central users in a macrocell are allowed to access both platinum band and normal band since the inferior frequency resources (i.e., platinum band) might not be enough to supply these users and hence it would further lead to a loss on overall system capacity.

The proposed band scheduling method work together with the split of users into cell-interior users (CIUs) which have low probability to be interfered by neighbor cells and cell-edge users (CEUs) which have high probability to be interfered by neighbor cells. A widely accepted approach to classify UEs is based on the geometry factor (G-factor). The G-factor is the wideband average SINR measured by an UE in a fully-loaded network with universal frequency reuse and uniform power allocation. In the proposed method, the G-factor can be obtained from measuring reference signals (or pilot signals) over the normal band. The G-factor is then compared with a predefined threshold to determine whether the UE is a cell-interior user or a cell-edge user [5][6]. In this paper, we consider an UE as a cell-edge user if the G-factor measured at the UE is smaller than a threshold of 0 dB [5][6]; otherwise, the UE is regarded as a cell-interior user.

Assuming a fully loaded system, it becomes unlikely that cell-interior PUEs would be able to access the platinum band, and they would thus be confined to the normal band. This causes a separation of user groups for which the cell-interior PUEs occupy the normal band only while the cell-edge PUEs use the platinum band. As a result, in the case of a fully loaded system, the proposed band scheduling method can be summarized in Table 1.

TABLE I. THE PROPOSED BAND SCHEDULING MOTHED UNDER A FULLY LOADED SYSTEM

	Macrocell	Picocell
Normal Band	CIUs and CEUs	CIUs
Platinum Band	CIUs	CEUs

C. Adaptive Frequency Partitions

Herein, we introduce the *frequency partition ratio* (β) of the PF-ILIC scheme as

$$\beta \equiv \frac{BW_{PB}}{BW_{all}} = \frac{BW_{PB}}{BW_{NB} + BW_{PB}} \ (<1), \qquad (3)$$

where BW_{PB} and BW_{NB} are the configured bandwidth of platinum band and normal band, respectively. Recall that the main purpose for us to have a platinum band is to create protected zone for PUEs who have a low geometry factor (G-factor), and this is especially important for RE PUEs. With the user grouping threshold of 0 dB, a PUE will always be treated as a cell-edge PUE if its received signal power from the macrocell is higher than that of serving picocell. As a rule of thumb, it can be assumed that the amount of protected frequency resources should be approximately proportional to the number of cell-edge PUEs which have to operate at a low SINR. Accordingly, we set the frequency partition ratio (β) as the ratio of the number of cell-edge PUEs to the number of total users (including PUEs and MUEs), and it can be expressed by

$$\beta = \frac{N_{cell\text{-}edge\ PUEs}}{N_{total\ UEs}}, \qquad (4)$$

where $N_{cell\text{-}edge\ PUEs}$ and $N_{total\ UEs}$ denote the number of cell-edge PUEs and total users, respectively. The frequency partition ratio (β) can be adaptively configured according to the cell-edge PUEs' distribution in the system.

IV. System Model and Assumptions

A. Heterogeneous Network Layout

The considered system model of macro-pico HetNet in a tri-sector cellular layout is illustrated in Fig. 3. As shown in the figure, each cell site (base station) controls three 120-degree sectors (macrocells) and two picocells are evenly placed in each sector (macrocell) at a distance of (2/3)r from base station, where r is the cell radius.

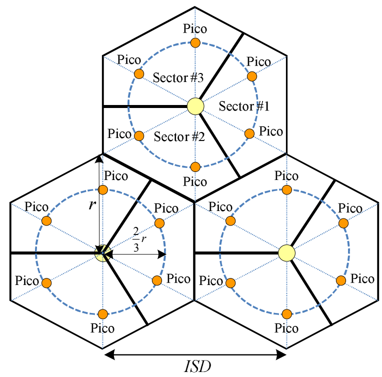

Figure 3. Macro-pico heterogeneous network layout

B. Average SINR Modeling

In this study, we do not consider fast fading and assume radio link is subject to propagation loss and log-normally distributed shadowing. To start with, we consider the average SINR for a MUE on the normal band and it can be expressed as

$$\gamma_{I,NB}^{MUE} = \gamma_{E,NB}^{MUE} = \frac{P_{macro}^{tx} \cdot A_s \cdot L_s \cdot S_s}{\sum_{i \in \{\Phi_{macro} - s\}} P_{macro}^{tx} \cdot A_i \cdot L_i \cdot S_i + \sum_{j \in \Phi_{pico}} P_{pico}^{tx} \cdot A_j \cdot L_j \cdot S_j + P_N}, \qquad (5)$$

where A_k, L_k and S_k are the antenna gain, path loss and shadow fading loss from the cell k to the MUE, respectively; the subscripts I and E stand for the CIUs and CEUs, respectively; the subscripts s, i and j stand for the serving cell, the interfering macrocells and the interfering picocells, respectively; Φ_{macro} and Φ_{pico} are the sets of macrocells and picocells, respectively; P_N denotes the received noise power spectrum density. We recall that in the proposed method, the normal band is available to all MUEs, including cell-interior and cell-edge MUEs.

Next, considering a cell-interior MUE on the platinum band, its average SINR can be written as

$$\gamma_{I,PB}^{MUE} = \frac{P_{macro}^{tx} \cdot (1/\eta) \cdot A_s \cdot L_s \cdot S_s}{\sum_{i \in \{\Phi_{macro} - s\}} P_{macro}^{tx} \cdot (1/\eta) \cdot A_i \cdot L_i \cdot S_i + \sum_{j \in \Phi_{pico}} P_{pico}^{tx} \cdot A_j \cdot L_j \cdot S_j + P_N}. \quad (6)$$

We remind that η is the power reduction factor and also note that according to our band scheduling method, only cell-interior MUEs are qualified to use the platinum band. Similarly, the average SINR for a cell-interior PUE on the normal band and a cell-edge PUE on the platinum band are given by (7) and (8), respectively.

$$\gamma_{I,NB}^{PUE} = \frac{P_{pico}^{tx} \cdot A_s \cdot L_s \cdot S_s}{\sum_{i \in \Phi_{macro}} P_{macro}^{tx} \cdot A_i \cdot L_i \cdot S_i + \sum_{j \in \{\Phi_{pico} - s\}} P_{pico}^{tx} \cdot A_j \cdot L_j \cdot S_j + P_N} \quad (7)$$

$$\gamma_{E,PB}^{PUE} = \frac{P_{pico}^{tx} \cdot A_s \cdot L_s \cdot S_s}{\sum_{i \in \Phi_{macro}} P_{macro}^{tx} \cdot (1/\eta) \cdot A_i \cdot L_i \cdot S_i + \sum_{j \in \{\Phi_{pico} - s\}} P_{pico}^{tx} \cdot A_j \cdot L_j \cdot S_j + P_N} \quad (8)$$

C. Throughput Calculation

To evaluate the achievable throughput as a function of the average received SINR while using AMC (adaptive modulation and coding), a modified form of the Shannon bound was proposed in a 3GPP technical report [7] to calculate link capacity in an LTE system, and it is given by

$$C(\gamma) = \begin{cases} 0 & : \text{for } \gamma \le \gamma_{\min} \\ \xi \cdot S(\gamma) & : \text{for } \gamma_{\min} < \gamma < \gamma_{\max} \\ C_{\max} & : \text{for } \gamma \ge \gamma_{\max} \end{cases}, \text{(bps/Hz)} \quad (9)$$

in which γ denotes the given SINR and ξ is the attenuation factor applied to the Shannon bound given by $S(\gamma) = \log_2(1+\gamma)$ which achieves C_{max} at $\gamma_{\max}$ or beyond and 0 at $\gamma_{\min}$ or lower. In this study, we adopt this modified form of the Shannon bound with the values recommended in [7] to evaluate the link spectral efficiency.

We assume that the users are uniformly distributed within cell coverage and that each user has unlimited traffic to transmit on the downlink and hence all frequency resources designated for each cell are fully utilized (a fully loaded system). Under a fair scheduler (equal resource sharing between users), the average throughput T can be calculated as

$$T = BW \cdot \nu \cdot \int C(\gamma) f_\gamma(\gamma) d\gamma, \quad (10)$$

where ν is a loss factor that accounts for the system overhead, $f_\gamma(\gamma)$ is the probability density function of SINR γ, and BW denotes the allocated bandwidth. In this paper, the loss factor ν is set to 1; this yields optimistic results, but is deemed acceptable for relative comparison purposes. Accordingly, let T_{NB} and T_{PB} be the average throughputs on the normal band and platinum band, respectively. The average macrocell/picocell throughput ($T_{Cell}^{macro} / T_{Cell}^{pico}$) can be obtained by summing T_{NB} and T_{PB}.

Then, the metric of average *macrocell area throughput* is introduced herein to evaluate the system throughput per single-macrocell coverage area, and it is described as

$$T^{area} = T_{Cell}^{macro} + N_p \cdot T_{Cell}^{pico}, \quad (11)$$

where N_p denotes the number of picocells within each macro geographical area. Note that the value of N_p equals 2 in this study.

D. Simulation Parameters

Static snapshot simulations have been used. The average SINR distribution (i.e. $f_\gamma(\gamma)$) is obtained through Monte Carlo simulations involving 1000 random placement of users geographically. Simulation assumptions and parameters basically follow the 3GPP evaluation criteria [1] for HetNet. Table 2 summarizes the main simulation parameters.

TABLE II. SIMULATION PARAMETERS

Parameters	Macro	Pico
Cellular layout	19 cell sites, 3 sectors per site	2 pico cells per sector
Minimum distance	35m (between UE and cell site)	10m (between UE and pico)
Distance-dependent path loss	128.1+37.6log$_{10}$(R), R in km	140.7+37.6log$_{10}$(R), R in km
Shadowing standard deviation	8 dB	10 dB
Shadowing correlation	0.5 (between cell site) 1 (between sectors)	0.5
Antenna pattern	3D antenna as described in [1]	Omi-directional (horizontal)
Total Tx power	46 dBm	30 dBm
Antenna gain	14 dBi	5 dBi
Inter-site distance (ISD)	500 m	
Carrier frequency	2 GHz	
System bandwidth	10 MHz	
UE antenna gain	0 dBi	
UE noise figure	9 dB	
Penetration loss	20 dB	
Macrocell/UE antenna height	32 m/1.5 m	
Correlation distance of shadowing	50 m	

V. NUMBERICAL RESULTS AND DISCUSSIONS

For comparison, we consider a reference system, i.e. the macro-pico HetNet with conventional reuse one (reuse-1) scheme, in which no inter-layer interference mitigation scheme between macro-layer and pico-layer is performed. All macrocells and picocells transmit with its maximum power level over the entire bandwidth. In addition, there is no resource allocation restriction applied to different user groups (i.e. CIUs and CEUs) in each cell.

A. User Association Statistics

To begin with, we plot in Fig. 4 the cell association statistics as a function of the CRE bias, and the fractions of RE PUEs are also presented in the figure. One can see that under the cell selection algorithm of selecting the cell with the highest downlink RSS (i.e. without CRE), the number of UEs associated with picocells is small. As shown in Fig. 4, observing the case of CRE bias=0 dB, only 13% of UEs are associated with picocells, whereas 87% of UEs are still connected to macrocells. On the other hand, one can find that as the CRE bias value is increased, there are more UEs being attached to picocells. For example, considering the case that the CRE bias is equal to 8 dB, it is observed that 31% of UEs are now connected to picocells, and thus the corresponding percentage value for MUEs is reduced to 69%. It is clearly observed how the offload from macrocells to picocells is increased while applying the CRE technique.

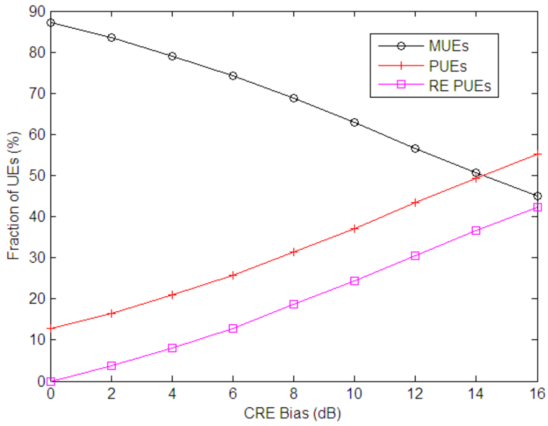

Figure 4. User association statistics for various CRE bias values

B. Link Quality Analysis

Although the CRE technique can further improve load balance between macro-layer and pico-layer, it generates RE PUEs which are significantly interfered by the macrocells. Therefore, when we consider a macro-pico HetNet with CRE, it is important to examine the link quality of the RE PUEs, i.e. the extremely-low SINR users. The average SINR CDFs (cumulative distributed functions) of RE PUEs are plotted in Fig. 5 for CRE bias=4, 8, and 12 dB. Note that as shown in Fig. 4, the percentages of RE PUEs in the cases of bias=4, 8, and 12 dB are, respectively, around 8%, 19%, and 31% in the evaluation system. One can observe from Fig. 5 that as compared with the conventional reuse-1 scheme, the PF-ILIC scheme yields a significant improvement in average SINR of the RE PUEs. For example, observing the 50%-tile of SINR CDFs in Fig. 5, the PF-ILIC scheme improves over the reuse-1 scheme by approximately 8 dB. This is because in the PF-ILIC scheme, the RE PUEs will operate on the "protected band", i.e. the platinum band, on which the macrocell interference is reduced significantly.

As a metric of network performance evaluation, the service outage probability is referred as the fraction of UEs for which the average SINR falls below the SINR threshold for the receiver to function appropriately. According to (9), the corresponding SINR threshold is set to -6.5 dB ($\gamma_{\min}$=-6.5dB [7]) in this study. Note that in LTE systems, the range of average SINR threshold for correctly decoding the control channels is between -6 and -7 dB [8]. Figure 6 illustrates the service outage probability with different CRE bias values. As expected, the PF-ILIC scheme gives much better results as compared with the conventional reuse-1 scheme. To exemplify this, using a CRE bias value of 8 dB would lead to nearly 10% of the users in the reuse-1 system experiencing coverage problems; however, the corresponding value is just about 0 in the PF-ILIC case. Moreover, considering the practical system deployment criterion of 5% outage probability [9], one can see from Fig. 7 that the CRE bias values less than about 6 dB are feasible in the reuse-1 system while the bias values up to approximately 15 dB can be tolerated for the system with the PF-ILIC scheme. From the above observations, we can conclude that the PF-ILIC scheme is an appropriate method to carry out the CRE concept even if a large CRE bias value is used.

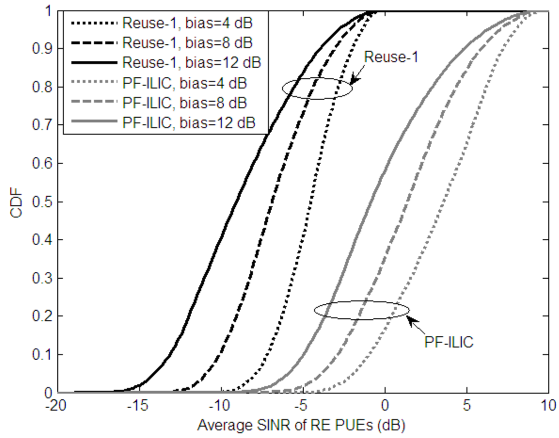

Figure 5. Average SINR distribution of RE PUEs

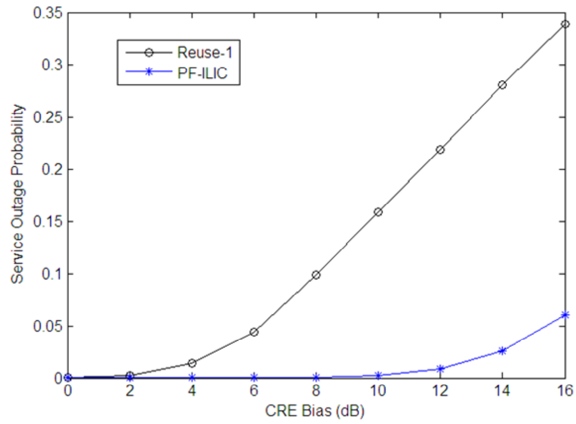

Figure 6. Service outage rate with different CRE bias values

C. Throughput Performance Analysis

Figure 7 shows the average macrocell throughput, picocell throughput and macrocell area throughput for the conventional reuse-1 scheme and the PF-ILIC scheme with different CRE bias values. Recall that the single-macrocell coverage area contains one macrocell and two picocells. From the figure, we have three observations. First, the PF-ILIC scheme provides a significant picocell throughput gain over the reuse-1 scheme and the gain is increased as the CRE bias increases. More specifically, approximately 200% and 300% average picocell throughput gain can be found at CRE bias of 6 dB and 12dB, respectively. This is reasonable since the number of service outage users can be greatly reduced through using the PF-ILIC scheme. As a fair scheduler is assumed in this study, the picocell throughput loss turns out to be proportional to the number of service outage users in the system. Second, the PF-ILIC scheme causes about 2-7% macrocell throughput loss as compared with the reuse-1 scheme. This is because in the proposed PF-ILIC scheme, the platinum band in each macrocell is used with reduced power (by 10 dB in this study), which favors PUEs while harms MUEs. Third, compared with the reuses-1 scheme, the PF-ILIC scheme improves the macrocell area throughput by 25-55%, and we further notice that the improvement becomes prominent when the CRE bias is getting larger. This shows that the decreased macrocell throughput caused by employing the PF-ILIC scheme can be regained from the greatly increased picocell throughput, and it turns out to be a considerable macrocell area throughput gain.

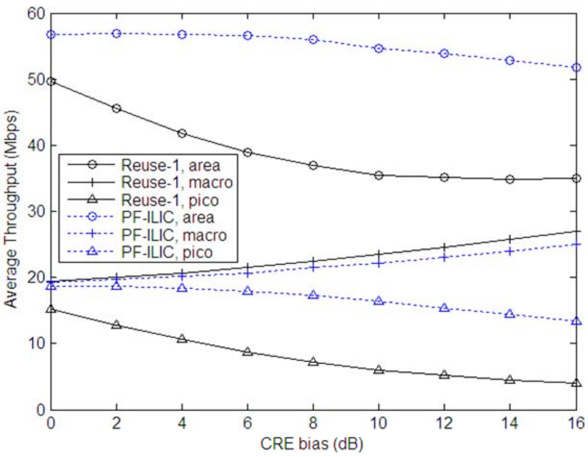

Figure 7. Average throughput performance with different CRE bias values

VI. CONCLUSIONS

In this paper, we present a downlink inter-layer interference coordination scheme for an OFDMA co-channel macro-pico HetNet where the CRE technique is used. The proposed scheme can be seen as a joint power and frequency coordination technique accompanied with a set of resource allocation rules. Our simulation results demonstrate that as compared with the reference reuse-1 scheme, the proposed scheme can greatly reduce the outage rate in the system. Moreover, even if there is a small loss in macrocell throughput, our approach provides a substantial total area throughput gain over the reuse-1 scheme. So we conclude that the proposed scheme is a competitive choice to enhance system capacity and mitigate user outage in macro-pico HetNets with CRE.

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