QoS-aware Interference Control in OFDMA Femtocell Networks

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***Abstract*—In this paper, we present a Quality-of-Service (QoS)-aware interference control scheme in femtocell networks. The proposed scheme dynamically adjusts the transmission power of Home Evolved Node B (HeNB) based on its "troubling" property and "servicing" property so as to balance the provisioning of QoS for users and the avoidance of interference to neighboring HeNBs. The simulation results illustrate that our approach can effectively improve the efficiency of resource utilization and aggregate throughput of the femtocell networks in comparison with other schemes.**

Keywords-3GPP Long Term Evolution (LTE); femtocell; interference mitigation; power control

I. INTRODUCTION

The Long Term Evolution (LTE) access technologies developed by the Third Generation Partnership Project (3GPP) group [1][2] are promising Broadband Wireless Access (BWA) solutions of providing high data-rate transmissions, extensive-area coverage, and high-speed mobility for a variety of wireless applications. However, with the growing number of mobile devices and various application demands, the traffic congestion problem will still be inevitable due to limited frequency spectrums even with the BWA technology. Frequency reuse might be the most suitable solution to increase the total capacity of an area. Moreover, once mobile users enter into a building, the radio signal strength can drop tremendously due to a large path loss especially when the building is made up of the concrete and steel. Therefore, Home Evolved Node B (HeNB), also called femtocell is expected to prevail in the LTE networks in the future because of certain large amounts of indoor users and further for its capability to solve the problem of spectrum insufficiency by frequency reuse.

In femtocell networks, the interference problem can be severe if no proper power control or resource management scheme is presented. As a matter of fact, the interferences in femtocell networks can be classified as cross-tiered and co-tiered interferences. When the macrocell and femtocell have an overlap area and use both the same frequency spectrum and time slot for data deliveries, the cross-tiered interference would be incurred. On the other hand, if a number of HeNBs are deployed close to each other, the interference between neighboring HeNBs is so called the co-tiered interference [3]-[10].

In this paper, we tackle the co-tiered interference problem between neighboring HeNBs in the LTE networks and propose simple and practical interference control and resource allocation schemes in a distributed manner. The proposed scheme dynamically adjusts the power of HeNBs according to its "troubling" property and "servicing" property to simultaneously reduce the interference to neighboring HeNBs and improve the overall transmission efficiency of the femtocell networks. Our key idea is based on the observation that each HeNB simultaneously acts as a "servicing node" for data deliveries to the associated users, and acts as a "troubling node" with respect to the neighboring HeNBs. Thus the power control of each HeNB should simultaneously consider the two roles so as to improve its individual transmission efficiency, as well as to lessen the interference in femtocell networks. We conducted simulations to compare the performance of our proposed power control algorithm with that of other approaches. The results demonstrate that our approach can effectively improve the efficiency of resource utilization and aggregate throughput of the femtocell networks in comparison with other schemes.

The rest of this paper is organized as follows. Section 2 introduces the existing studies of interference mitigation in wireless networks. The problem description is presented in Section 3. Section 4 illustrates the proposed power control algorithms. Section 5 explains the simulation setup and results. Finally, the conclusion is given in Section 6.

II. RELATED WORK

There have been many efforts on the mitigation of interferences and/or the cooperation of resource allocation in previous studies [4]-[10]. Sun et al. [4] proposed a subcarrier allocation scheme based on the auction algorithm for solving the cross-tiered interference between macrocells and femtocells. Hoteit et al. [7] proposed a game-theoretic resource allocation scheme in cooperative femtocell OFDMA networks. From the evaluation results, it is shown that their proposed game-theoretic scheme outperforms other proposals in terms of throughput, fairness, and computation time. The studies in [8] proposed a cognitive-radio based scheme which uses cognitive relays to improve the cross-tier interference performance between macrocells and femtocells. However, these centralized schemes can be complex and unpractical. When the femtocell networks are expected to deployed in indoor environments such as home and enterprise buildings, it is hard to adopt a centralized management scheme for resource allocation or power control because the femtocell management system will maintain a growing data base for global interference information with the growth of femtocell deployment, and the computational complexity will dramatically increase and remain a challenge issue.

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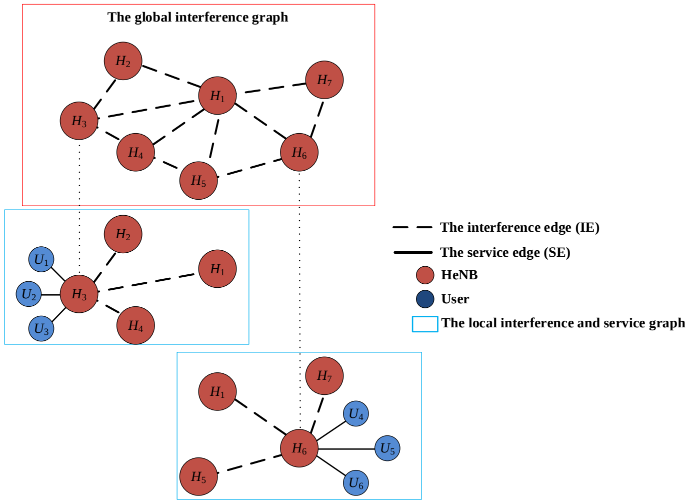

Figure 1. Example of network model in a co-tier interference scenario

III. PROBLEM DESCRIPTION

To solve the optimization problems of interference control and resource allocation, we model the service and interference scenarios in the downlink of femtocell networks as a graph $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$, where $\boldsymbol{V}$ is the set of vertices and $\boldsymbol{E}$ is the set of edges. Figure 1 shows an example of the modeled graph. There are two types of vertices, namely, the HeNB and UE vertices. The HeNB vertex is connected with two kinds of edges including Service Edges (SE) and Interference Edges (IE), which represent the connection with the served users and interfered neighboring femtocells, respectively. For HeNB H_i, let $\boldsymbol{S_i}$ denote the set of served users and $|\boldsymbol{S_i}|$ is the number of served users; let $\boldsymbol{I_i}$ denote the set of interfered neighboring femtocells and $|\boldsymbol{I_i}|$ is the number of interfered femtocells. In the downlink transmission scenario, $\boldsymbol{I_i}$ consists of the femtocells which have users being interfered by HeNB H_i. Thus, if $H_j \in \boldsymbol{I_i}$, we have

$$\frac{RSS(H_j, U_k)}{RSS(H_i, U_k)} < SINR_{th}, U_k \in \boldsymbol{S_j}, \tag{1}$$

where $RSS(H_i, U_h)$ denotes the Received Signal Strength (RSS) of UE U_h from the serving HeNB H_i; $SINR_{th}$ is the threshold of Signal to Interference plus Noise Ratio (SINR) for data transmission.

For HeNB H_i, let $SE_{H_i U_h}, U_h \in \boldsymbol{S_i}$ denotes the weight edge between HeNB H_i and user U_h, representing the degree of service for U_k given by H_i. In this paper, we adopt the QoS class identifiers (QCIs) specified in 3GPP [2] to quantify the service degree $SE_{H_i U_h}, U_h \in \boldsymbol{S_i}$. As Table I shows, each QCI is associated with a specific resource type, priority and packet delay budget. Denote QCI_x as the QCI with index x. Let $\boldsymbol{QCI_{GBR}}$ denote the set of GBR-type QCIs and $\boldsymbol{QCI_{Non\text{-}GBR}}$ denote the set of Non-GBR-type QCIs. It is shown in Table I that $\boldsymbol{QCI_{GBR}}$ consists of $\text{QCI}_1, \text{QCI}_2, \text{QCI}_3$, and QCI_4, while $\boldsymbol{QCI_{Non\text{-}GBR}}$ consists of $\text{QCI}_5, \text{QCI}_6, \text{QCI}_7, \text{QCI}_8$, and QCI_9.

To reflect the service degree according to the priority of QCI, we define the weight of QCI_x, w_{QCI_x} as 10 - p_{QCI_x}, where p_{QCI_x} is the priority of QCI_x. Thus, we have $w_{\text{QCI}_1} = 8$, $w_{\text{QCI}_2} = 6$, $w_{\text{QCI}_3} = 7$, $w_{\text{QCI}_4} = 5$, $w_{\text{QCI}_5} = 9$, $w_{\text{QCI}_6} = 4$, $w_{\text{QCI}_7} = 3$, $w_{\text{QCI}_8} = 2$, $w_{\text{QCI}_9} = 1$, respectively. Assume the service type of $U_h, U_h \in \boldsymbol{S_i}$ is with QCI_x, then $SE_{H_i U_h}$ can be expressed as

$$SE_{H_i U_h} = w_{\text{QCI}_x}, U_h \in \boldsymbol{S_i}. \tag{2}$$

TABLE I. QCI CHARACTERISTICS [2]

QCI	Resource Type	Priority	Packet Delay Budget	Example Services
1	GBR	2	100 ms	Conversational Voice
2		4	150 ms	Conversational Video (Live Streaming)
3		3	50 ms	Real Time Gaming
4		5	300 ms	Non-Conversational Video (Buffered Streaming)
5	Non-GBR	1	100 ms	IMS Signalling
6		6	300 ms	Video (Buffered Streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		7	100 ms	Voice, Video (Live Streaming), Interactive Gaming
8		8	300 ms	Video (Buffered Streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file, sharing, progressive video, etc.)
9		9		

Based on the LTE standards [2], Resource Block (RB) is the smallest transmission unit in the LTE system, which consists of 2 time slots (1 ms) in time domain and 12 sub-carriers (180 KHz) in frequency domain. Consider an interference femtocell network consisting of K HeNBs, which share F RBs in downlink transmissions. For femtocell i, let σ_i^f, f = 1, 2, …. F, denote a binary variable which is 1 if RB f is allocated to femtocell i, and 0 otherwise. For RB f, the PHY data rate r_f can be expressed as [11],

$$r_f = \frac{R_f^{(c)} \log_2(M_f)}{T_s N_{RB}} DSC_{RB}, \tag{3}$$

where $R_f^{(c)}$ is the code rate associated with the Modulation and Coding Scheme (MCS) used by RB f; M_f is the constellation size of the MCS used by RB f; T_s is the OFDM symbol duration; N_{RB} is the number OFDM symbols in a RB, which can be 14 or 12 depending on whether a normal or extended cyclic prefix is used; DSC_{RB} is the number of data-carrying subcarriers for a RB.

Define the RB allocation problem as a constrained optimization problem which aims to maximize the overall spectrum efficiency of femtocell networks. The optimization problem can be formulated as follows:

$$\max \sum_{1 \le i \le K} \sum_{1 \le f \le F} \sigma_i^f \cdot r_f \tag{4}$$

subject to

$$P^{\min} \le P_i \le P^{\max}, \forall i \tag{5}$$

$$\sigma_i^f \sigma_j^f = 0, \forall H_j \in \boldsymbol{I_i}, \forall i \tag{6}$$

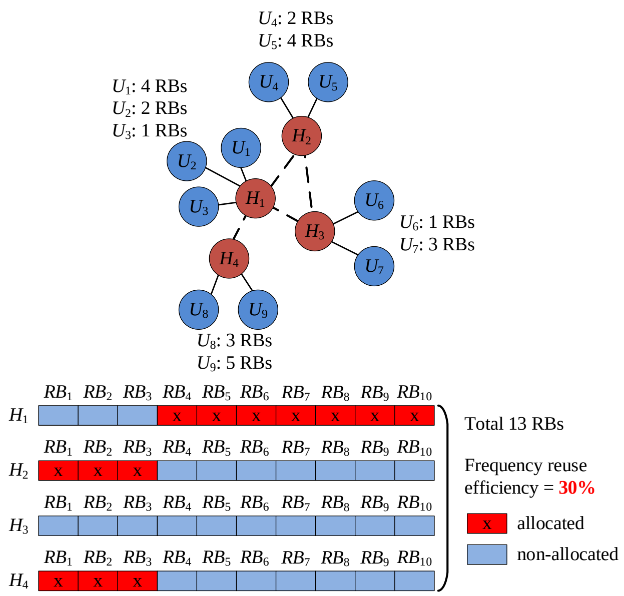

Figure 2. Example of RB allocation in a co-tier interference scenario

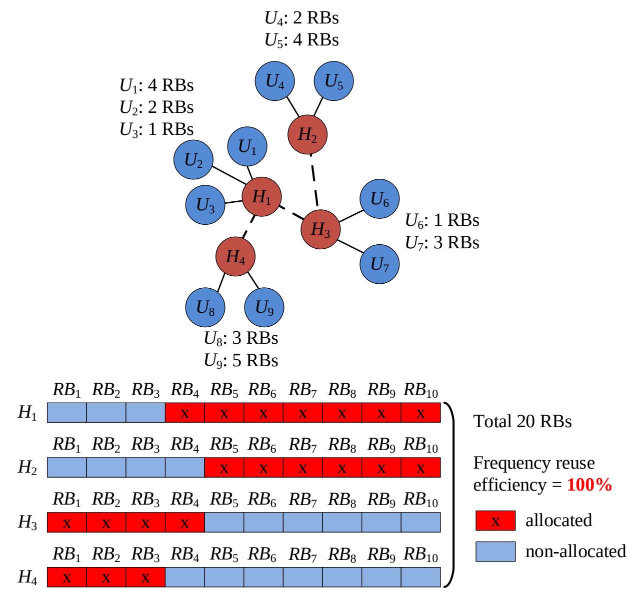

Figure 3. Example of RB allocation with the proposed power adjusting scheme

$$a_{U_h} = \gamma_{U_h}, \text{ for } \mathrm{QCI}(U_h) \in \boldsymbol{QCI}_{\boldsymbol{GBR}}, \forall U_h \quad (7)$$

$$1 \le a_{U_h} \le \gamma_{U_h}, \text{ for } \mathrm{QCI}(U_h) \in \boldsymbol{QCI}_{\boldsymbol{Non\text{-}GBR}}, \forall U_h \quad (8)$$

$$\sum_{1 \le f \le F} \sigma_i^f = \sum_{U_h \in \boldsymbol{S_i}} a_{U_h}, \forall i \quad (9)$$

where P_i is the transmission power of HeNB i; $P^{\min}$ and $P^{\max}$ are the specific minimum and maximum transmission power of LTE femtocell, respectively. γ_{U_h} is the amount of RBs requested by U_h, and a_{U_h} is the amount of allocated RBs. Equation (5) shows the constraints of transmission power for femtocells, and (6) states that the neighboring femtocells which are in the interference domain cannot use the same bands for data transmissions. Equation (7) expresses that the amount of allocated RBs is guaranteed for GBR-type users, whereas (8) expresses that there is no guarantee for Non-GBR-type users [5]. Equation (9) indicates that the RBs allocated to a femtocell are shared by its served users for data transmission.

IV. PROPOSED POWER CONTROL ALGORITHM

To illustrate the key idea of our power control and resource allocation scheme, consider the example shown in Figure 2. H_1 has three users which request 7 RBs totally; H_2 has two users which request 6 RBs; H_3 has two users which request 4 RBs; H_4 has two users which request 8 RBs. The number of the total required RBs for the four HeNBs is 25. H_1 is regarded as a "troubling node" for its largest amount of interferences over the considered femtocell network (the number of the interference edges of H_1, H_2, H_3 and H_4 is 3, 2, 2, and 1, respectively). If we allocate all the required RBs for H_1 without adjusting its power, the number of the total allocated RBs in the femtocell network is 13, and there are 12 RBs unable to be allocated for H_2, H_3 and H_4 (3 RBs with H_2, 4 RBs with H_3 and 5 RBs with H_4). The frequency reuse efficiency is only 30%. In this example, if the transmission power of H_1 is decreased to a certain level, the overall transmission efficiency can therefore be improved. For instance, consider another situation when the transmission power of H_1 is lessened such that H_1 has only 2 interference edges, as shown in Figure 3. Hence, the number of the total allocated RBs increases as 20 (7 RBs for H_1, 6 RBs for H_2, 4 RBs for H_3 and 3 RBs for H_4) and the frequency reuse efficiency becomes as large as 100%. The example illustrates that a power restriction on the "troubling node" can provide improvements of the overall transmission efficiency in the femtocell network.

Consider K HeNBs in a femtocell network. For HeNB i, let δ_i denote the amount of RBs requested by its served users. δ_i can be expressed as:

$$\delta_i = \sum_{U_h \in \boldsymbol{S_i}} \gamma_{U_h}, \quad (10)$$

1: **for** each cycle of resource allocation
2: Input:
(1) the transmission power of HeNB $i, P_i, (1 \le i \le K), (P_1, P_2, \ldots. P_K)$
(2) the amount of RBs requested by HeNB i, δ_i $(1 \le i \le K)$, $\delta_i = \sum_{U_h \in \boldsymbol{S_i}} \gamma_{U_h}$, γ_{U_h} is obtained with constraints in Eq. (7) and (8)
3: First-step co-channel RB assignment with constraints in Equation (6) and obtain $(\boldsymbol{\theta}_1, \boldsymbol{\theta}_2, \ldots. \boldsymbol{\theta}_K)$, $\boldsymbol{\theta}_K$ is the set of RBs assigned for HeNB i
4: **while** $\sum_{i=1}^{K} |\boldsymbol{\theta}_i| > B$ && $\forall P_i \le P^{\min}$ // check whether the required amount of RBs by co-channel assignment exceeds the amount of allocated RBs, B, and the transmission power of HeNB is smaller than the specific minimum value $P^{\min}$.
5: Sort the K HeNBs in descending order of their power tuning parameter, μ_i, Assume that the order is $\mu_1, \mu_2, \ldots\ldots \mu_K$, i.e., $\mu_1 \ge \mu_2 \ge \cdots \mu_K$
6: $P_1' = \max(P_1 * b, P^{\min}), 0 < b < 1$ // power back off without being lower than the specific smallest power in LTE standards, $P^{\min}$
7: Output:
(1) the adjusted transmission power $(P_1', P_2, \ldots. P_K)$
(2) the new assignment of RBs $(\boldsymbol{\theta}_1', \boldsymbol{\theta}_2', \ldots. \boldsymbol{\theta}_K')$
8: Replace $\boldsymbol{\theta}_i'$ as $\boldsymbol{\theta}_i$ and P_1' as P_1
9: **end while**
10: **end for**

Figure 4. The proposed QoS-aware power control algorithm (QAPC)

where γ_{U_h} is the amount of RBs requested by U_h. We assume that the co-channel aware scheme is used for RB allocation, i.e., the HeNBs in the interference domain will select different RBs as possible. Assume $\boldsymbol{\theta}_i$ is the set of RBs assigned for HeNB i by the co-channel aware assignment, and $|\boldsymbol{\theta}_i|$ is the number of RBs assigned for HeNB i. $|\boldsymbol{\theta}_i|$ can be expressed as:

$$|\boldsymbol{\theta}_i| = \sum_{U_h \in \boldsymbol{S}_i} a_{U_h}, \tag{11}$$

where a_{U_h} is the amount of RBs allocated to user U_h stated in (7) and (8) for GBR and Non-GBR users, respectively. According to the constraints stated in (7) and (8), we have

$$|\boldsymbol{\theta}_i|^{\max} = \sum_{U_h \in \boldsymbol{S}_i} \gamma_{U_h} = \delta_i, \tag{12}$$

$$|\boldsymbol{\theta}_i|^{\min} = \sum_{\text{all } U_h \in \boldsymbol{S}_i \text{ with QCI} \in \boldsymbol{QCI}_{GBR}} \gamma_{U_h} + \sum_{\text{all } U_h \in \boldsymbol{S}_i \text{ with QCI} \in \boldsymbol{QCI}_{Non\text{-}GBR}} 1, \tag{13}$$

$$|\boldsymbol{\theta}_i|^{\min} \le |\boldsymbol{\theta}_i| \le |\boldsymbol{\theta}_i|^{\max}. \tag{14}$$

Consider B as the total amount of RBs in the femtocell network. If the condition stated in (15) happens,

$$\sum_{i=1}^{K} |\boldsymbol{\theta}_i| > B, \tag{15}$$

the network capacity is insufficient to support the total service requirements of users due to interferences between HeNBs. In this case, we argue that the power level of troubling nodes should be decreased to improve the RB reuse efficiency. However, a trouble node also acts as a service node with respect to its users. Thus, we propose an adaptive power control algorithm which dynamically adjusts the power of HeNB according to both the interference factors and service factors. The interference factor of HeNB i is expressed as $|\boldsymbol{I}_i|$ which is the number of interfered femtocells. The service factor of HeNB i, ψ_i can be expressed as

$$\psi_i = \sum_{U_h \in \boldsymbol{S}_i} SE_{H_i,U_h} \cdot \gamma_{U_h} \tag{16}$$

where SE_{H_i,U_h} denotes the degree of service for U_h by H_i in terms of the QCI weight, which is illustrated in (2). The feasible transmission power of HeNB should be determined by both the interference factor $|\boldsymbol{I}_i|$ and service factor ψ_i. For example, when $|\boldsymbol{I}_i|$ is large, we should decrease the power to lessen the interference to the neighboring HeNBs. On the other hand, when ψ_i is large, we should increase the power to provide service qualities for users. Thus, we define a power tuning parameter, μ_i, which is the ratio of $|\boldsymbol{I}_i|$ to ψ_i. That is,

$$\mu_i = \frac{|\boldsymbol{I}_i|}{\psi_i}. \tag{17}$$

When μ_i is large, we should decrease the power to lessen the interference to the neighboring HeNBs; on the other hand, when μ_i is small, we should increase the power to improve service qualities for users. In case that the network resource is insufficient to support the total service requirements of users due to severe interferences, the power level of HeNBs with the largest μ_i should be decreased by multiplication with a factor b ($0 < b < 1$), That is,

$$i^* = \arg \max_{1 \le i \le K} \mu_i \tag{18}$$

$$P_{i^*} = \max(b \cdot P_{i^*}, P^{\min}). \tag{19}$$

Equation (19) states that the adjusted power cannot be lower than the specific minimum value $P^{\min}$.

After the power of the trouble node is adjusted, the new assignment of RBs by the co-channel aware scheme, ($\boldsymbol{\theta}'_1$, $\boldsymbol{\theta}'_2$, …. $\boldsymbol{\theta}'_K$), can therefore be obtained. The pseudo code of the proposed QoS-aware Power Control (QAPC) is shown in Figure 4. The power control algorithm will be iteratively executed until the network resource is sufficient to support the total amount of RBs allocated for users, or the adjusted power is lower than the specific minimum value $P^{\min}$.

TABLE II. SIMULATION PARAMETERS

Parameter	Value
Map Size	100 m × 100 m
System Bandwidth	5 MHz
Number of cells	3 or 6
Cell distribution	uniform
Number of RBs	25
Frame Structure	FDD
One Subframe	1 ms
Femtocell Min/Max. Tx Power	10 dBm / 20 dBm
Femtocell Noise Figure	8 dB
Femtocell Min/Max. Radius	2 m / 20 m
Distance from Femtocell to User	2 m
Number of Users	5
Thermal Noise	−174 dBm / Hz
Path Loss	Dual-Stripe Model
Inner Wall	5 dB
Number of Penetrated Wall and Floor	1/0
$d_{\text{2D, indoor}}$	0

V. PERFORMANCE EVALUATION AND DISCUSSION

In this section, we conduct simulation scenarios of the downlink transmissions in the LTE femtocell network to demonstrate the effectiveness of the proposed power control scheme. The simulation is constructed by the C++ programming and followed the LTE standard closely [2]. The LTE PHY parameters and their values are listed in Table II. The simulation setup assumes a 100 m ∗ 100 m square area where the HeNBs are randomly deployed. We assume that the occurrence of each QCI is uniform, while the resource request process is Poisson with a constant size of 1000 bytes. The total simulation period is 120 seconds while the results are provided with the average values over 20 times of simulations. We compare the performance of the proposed power control algorithm with that of fixed power and distributed power control algorithms presented by ElBatt and Ephremides [12]. For all these power control approaches, the co-channel assignment scheme is used for resource allocation (i.e., the assignment of RBs will prevent interference as well as possible) to clearly examine the achieved performances with

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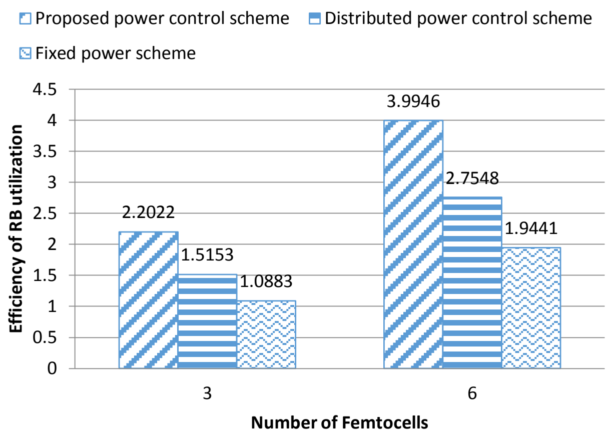

Figure 5. The efficiency of RB utilization with different power control schemes

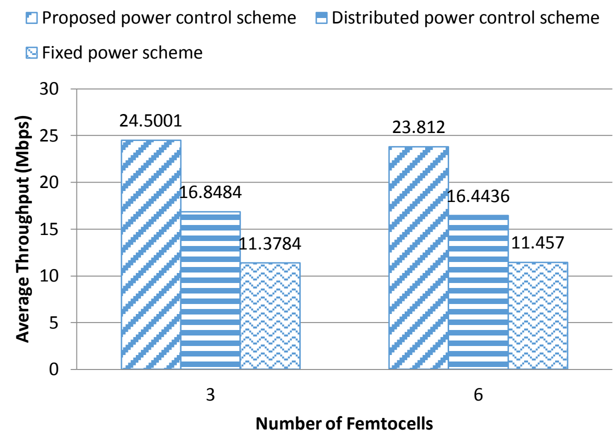

Figure 6. The average throughput with different power control schemes

different power control schemes. The performance metrics are indexed as the efficiency of RB utilization and average throughput.

First, we examine the efficiency of RB utilization with different power control schemes. It is shown in Figure 5 that the proposed CA scheme has the best performance in terms of RB efficiency in the two cases. In the 3-femtocell scenario, our proposed scheme can increase the RB efficiency by 45.33% and 102.35% in comparison with the distributed power control scheme and fixed power scheme, respectively. In the 6-femtocell scenario, our proposed scheme can even increase the RB efficiency by 45.01% and 105.47% with regard to the two schemes, respectively. Figure 6 shows the corresponding throughput performances with different power control schemes. As a result shown in Figure 6, our power control scheme averagely can increase the throughput by as large as 45.41% and 102.35% over the distributed power control and fixed power schemes, respectively, in the 3-femtocell scenario, and by 44.81% and 107.84%, respectively, in the 6-femtocell scenario. The simulation results demonstrate that our power control scheme which adjusts the transmitting power of troubling nodes to lessen interferences to neighboring femtocells can improve the RB utilization efficiency and overall system throughput in the LTE femtocell network.

VI. CONCLUSION AND FUTURE WORK

This study tackled the interference problems in femtocell and present an interference control scheme. The proposed scheme dynamically adjusts the transmission power of HeNB based on its “troubling” property and “servicing” property so as to balance the provisioning of QoS for users and the avoidance of interference to neighboring HeNBs. We conducted simulations to compare the performance of our proposed scheme with that of other approaches. The results illustrate that our approach can effectively improve the efficiency of resource utilization and system throughput of the LTE femtocell networks. Our future research will investigate the joint optimization problem with the proposed power control algorithm and Discontinuous Reception (DRX) mechanism for energy-efficiency and QoS performances field testing.

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