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# Statistical Resource Allocation Based on Cognitive Interference Estimation in Ultra-Dense HetNets

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**ABSTRACT** In this paper, we develop a statistical resource allocation scheme to mitigate the aggregated co-tier, cross-tier, and cross-link interference in ultra-dense *heterogenous networks* (HetNets). By statistically and cognitively characterizing the aggregated interference instead of instantaneous interference information exchange, our scheme allocates resources of power and channels to each femtocell distributively taking the impact on the macrocells into consideration. Simulation results show that the femtocell throughput is improved while reducing the macrocell throughput reduction simultaneously.

**INDEX TERMS** Ultra-dense HetNets, statistical resource allocation, cognitive, interference mitigation.

## I. INTRODUCTION

With the rapid development of smart devices and new applications, an exponential mobile traffic volume growth is foreseen in the future wireless communication networks. Through network densification, the ultra-dense *heterogeneous networks* (HetNets) have been widely considered as a promising approach to accommodate the explosive wireless data growth and ensure user experience for the 5G wireless evolution [1]–[4]. In such networks, the shortened transmissions within the crowded small cells are enabled and overlaid in the macrocells. Hence, benefiting from the spatially enhanced frequency reuse, the ultra-dense HetNets can enhance the capacity and the spectral efficiency significantly with low transmitting power.

The densely deployed small cells may suffer from severe mutual co-tier interference, cross-tier interference with macrocells, and even cross-link interference between uplink and downlink introduced by the flexible *time division duplex* (TDD) technology [5]. All these interferences will seriously degrade network performance apparently. Interference management to address these kinds of interferences is the key challenge to the ultra-dense HetNets deployment [4]–[6]. Therefore, resource allocation schemes are considered essentially for interference mitigation in ultra-dense HetNets, which can be classified into two categories of centralized approaches and distributed approaches.

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Among the centralized resource allocation schemes, the interference information from each small cell is reported to and gathered by a central entity like the *macrocell base station* (MBS) for example. Then MBS controls the resource allocation process to each small cell for interference mitigation through the separated or mix of frequency, time, space, power, and emerging polarization domains [7]–[9]. Interference management can be implemented through the assignment of orthogonal frequency channels among small cells. Almost blank sub-frame technologies are considered to allocate different kinds of sub-frames in each small cell dynamically [7]. Spatial interference management can be achieved by taking advantage of massive MIMO systems [8]. Besides, polarization is also utilized in resource allocation as an important property of wireless signals [9]. Generally, the centralized resource allocation schemes in the ultra-dense HetNets require significantly increased signalling overhead due to the interference related information exchange among the large number of deployed small cells, and the implementations are of great complexity.

Thus, the distributed resource allocation schemes are preferred to mitigate interference in the ultra-dense HetNets with more flexibility and less overhead [2]–[4]. Hypergraph theory based distributed resource allocation schemes are proposed to mitigate the inter-cell interference for ultra-dense HetNets with both the device-to-device communications and proactive caching [10]. Yoon *et al.* proposed an interference weight calculation scheme to reduce the computational complexity in [11]. An interference-aware distributed cooperation scheme

is proposed in [12] to explore the diversity gains and mitigate interference based on game theory. These existing resource allocation schemes generally need to share some deterministic interference related information such as channel state information or neighbor list in the cluster. Although the information is shared within local neighbor nodes, it is still a big challenge to exchange within the dynamically changed dense neighbors. Alternatively, statistical interference related information is more attractive to enable distributed resource allocation with several probabilistic parameters instead of deterministic parameters for each specific node, which can further reduce the exchange overhead significantly [4], [13].

In this paper, we propose a distributed statistical resource allocation scheme for the ultra-dense HetNets without deterministic interference related information exchange instantaneously or periodically. Here we use femtocell to stand for the various small cells of microcell, picocell, and femtocell. We extend our previous work of resource allocation for traditional HetNets in [14] to the ultra-dense HetNets. In this work, both the interference and network environments are different and much more severe and complex than in [14]. First, here we consider the intra macrocell cross-link interference besides the co- and cross-tier interference in [14], and pay more attention on the resource allocation performance of the cell edge users in the ultra-dense HetNets. Second and furthermore, the inter macrocell interference in the scenario of multiple macrocells is additionally involved to evaluate the performances of the proposed scheme in this work. Third and the most important, here the proposed scheme not only consider the data rate gain and data rate reduction of neighbors for each femtocell link as in [14], but also investigate the tradeoff between the gains and reductions through a priority factor. In this way, the proposed scheme here can benefit better statistics from the larger number of interferers in the ultra-dense HetNets, and improve the overall throughput when facing increased number of dense neighboring macrocell and femtocell links.

The main contribution of our paper is as following.

- 1) We exploit statistical model of the aggregated co-tier, cross-tier, and cross-link interference rather than instantaneous interference information exchange to enable distributed resource allocation among femtocells. By utilizing local cognitive interference estimation and the channel reciprocity in TDD pattern, the proposed scheme generates the statistical information of the co-tier, cross-tier, and cross-link interference. It is very effective and practical for resource allocation in ultra-dense HetNets, since it saves the enormous overhead caused by instantaneous interference information exchange.
- 2) In the proposed scheme, the femtocell links allocate channel and power resources individually with the statistical interference information. Each femtocell link not only maximizes its throughput but also mitigates the potential interference to the neighboring ultra-dense

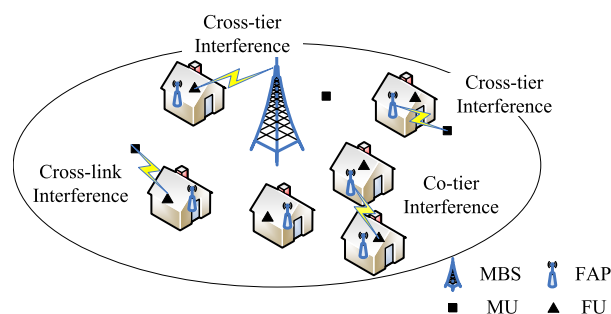


FIGURE 1. System model.

HetNets links. By estimating the aggregated interference, our scheme can control interference to macrocell thereby preserving macrocell throughput, which is extremely important for cellular system design.

- 3) Furthermore, we also set two parameters to evaluate the protection of macrocell throughput. One is a femto-free zone where the channels are exclusively used by macrocells, and the other is the priority of macrocell when it shares the channels with femtocells.

The rest of the paper is organized as following. We describe the system model considering the co-tier, cross-tier, and cross-link interference in Section II. The statistical resource allocation scheme of ultra-dense HetNets with cognitive interference estimation is investigated in Section III. Simulation results are presented in Section IV. Finally, conclusions are in Section V.

## II. SYSTEM MODEL

Assume that ultra-dense HetNets consist an MBS and multiple *macrocell users* (MUs), multiple femtocells, in which one link per femtocell is assumed between a *femtocell access point* (FAP) and a *femtocell user* (FU). The system model is shown in Fig. 1. They are assumed to be operated in the flexible TDD configuration [5], where the uplinks and downlinks can be transmitted simultaneously within the same frequency to meet the requirements of various services. Hence, the cross-tier interference takes place from a femtocell transmitter to macrocell receivers or from a macrocell transmitter to femtocell receivers. The co-tier interference is from a femtocell transmitter to the neighboring femtocell receivers. The cross-link interference can be explained as the interference from one uplink FU to another downlink FUs or MUs, from one downlink FAP to another uplink FAPs or the MBS, from one uplink MU to downlink FUs, or from the downlink MBS to uplink FAPs. We assume that there is no cross-link or co-tier interference among the macrocell links for simplicity since the MBS centrally controls the MUs.

To avoid the confusion of uplink and downlink, we focus on the aggressors and victims of interference by transmitters and receivers, instead of uplink and downlink. Hence, the macrocell and femtocell transmitters and receivers are illustrated as  $MTX_m$  and  $MRX_m$ ,  $1 \leq m \leq M$ ,  $FTX_n$  and

$FRX_n, 1 \leq n \leq N$ , respectively. Here the MBS is virtually considered as multiple transmitters in downlink or multiple receivers in uplink. Assume that there are  $K$  channels, within which a femto-free zone of  $K_m$  channels is exclusively used by the macrocell links. Apparently, it means these two tiers share all the channels when  $K_m = 0$ .

The aggregated interference for the  $n$ th femtocell link on channel  $k, I_{n,k}^{(F)}$ , can be expressed as

$$I_{n,k}^{(F)} = \sum_{m=1}^M I_{n,m,k}^{(FM)} + \sum_{n'=1, n' \neq n}^N I_{n,n',k}^{(FF)} \quad (1)$$

where  $I_{n,m,k}^{(FM)}$  is the cross-tier or cross-link interference from  $MTX_m$  on channel  $k$ , and  $I_{n,n',k}^{(FF)}$  is the co-tier or cross-link interference from  $FTX_{n'}$ . Each of them will be 0 if the corresponding link is not using channel  $k$ .

Then the data rate of the  $n$ th femtocell link on channel  $k$  is

$$R_{n,k}^{(F)} = a_{n,k}^{(F)} B \log \left( 1 + \frac{p_{n,k}^{(F)} h_{n,k}^{(FF)}}{I_{n,k}^{(F)} + \sigma^2} \right), \quad (2)$$

where  $a_{n,k}^{(F)}$  equals 1 if the  $n$ th femtocell link uses channel  $k$  and 0 otherwise,  $B$  is the bandwidth of each channel,  $p_{n,k}^{(F)}$  is the transmit power of  $FTX_n, h_{n,n,k}^{(FF)}$  is the channel gain between  $FTX_n$  and  $FRX_n$  on channel  $k$ , and  $\sigma^2$  is the power of additive Gaussian noise.

From (2), it indicates that the data rate  $R_{n,k}^{(F)}$  is influenced by the aggregated interference  $I_{n,k}^{(F)}$ . Similarly, we can also express the data rate of each macrocell link as  $R_{m,k}^{(M)}$  and the aggregated interference  $I_{m,k}^{(M)}$  suffered by the  $m$ th macrocell receiver on channel  $k$ . Denote  $I_{m,k}^{(M)}$  as the aggregated interference suffered by the  $m$ th macrocell receiver from the neighbor links except the  $n$ th femtocell link as

$$I_{m,k}^{(M)} = \sum_{m'=1, m' \neq m}^M I_{m,m',k}^{(MM)} + \sum_{n'=1, n' \neq n}^N I_{m,n',k}^{(MF)} \quad (3)$$

where  $I_{m,m',k}^{(MM)}$  is the co-tier interference from  $MTX_{m'}$  on channel  $k$ , and  $I_{m,n',k}^{(MF)}$  is the cross-tier or cross-link interference from  $FTX_{n'}$ . Let  $R_{m,k}^{(M)}$  be the original data rate without interference from  $FTX_n$ , which is expressed as

$$R_{m,k}^{(M)} = a_{m,k}^{(M)} B \log \left( 1 + \frac{p_{m,k}^{(M)} h_{m,k}^{(MM)}}{I_{m,k}^{(M)} + \sigma^2} \right), \quad (4)$$

where  $a_{m,k}^{(M)}$  denotes the channel usage of this macrocell link on  $k, p_{m,k}^{(M)}$  is the transmit power of  $MTX_m, h_{m,k}^{(MM)}$  denotes the channel gain.

Traditionally, the  $n$ th femtocell link can communicate with the MBS to obtain the deterministic aggregated interference information of all the other links as well as report its own interference suffering information. This information exchange needs backhaul support and consumes lots of resources in the control channel especially. Instead, we

will investigate the aggregated interference  $I_{n,k}^{(F)}$  and  $I_{m,k}^{(M)}$  statistically based on the cognitive radio techniques. In the following, we exploit cognitive spectrum sensing method to estimate the statistical parameters of the aggregated interference to relieve the traditional information exchange. Hence the distributed and statistical resource allocation will be enabled in the ultra-dense HetNets.

### III. STATISTICAL RESOURCE ALLOCATION WITH COGNITIVE INTERFERENCE ESTIMATION

In this section, the statistic resource allocation for each femtocell link is implemented distributively on the basis of the cognitive interference estimation, where the required interference information is derived through local cognitive spectrum sensing at each femtocell link as well as through the TDD reciprocity assumption.

#### A. PROBLEM FORMULATION

The key idea of our problem formulation is that the resource of both transmit power and channel will be adjusted by each femtocell link to minimize the aggregated co-tier, cross-tier, and cross-link interference and maintain reasonable data rates, simultaneously.

For the  $n$ th femtocell link, the receiver  $FRX_n$  can be the  $n$ th uplink FAP or downlink FU, then the aggregated interference comes from the uplink or downlink transmitters  $MTX_m$  and  $FTX_{n'}$ . In this way, each femtocell link not only considers to maximize its own data rate  $R_{n,k}^{(F)}$ , but also at the same time to minimize the data rate reduction caused by its transmission to all other links in the ultra-dense HetNets with denotation of  $\Delta R_k$  here. Meanwhile, in order to protect the macrocell links especially the cell edge users, we set  $K_m$  and  $\beta$  respectively to deploy weighted channel sharing and interference mitigation priority between the two tiers. Thus the statistical resource allocation problem for each femtocell link can be formulated as

$$\max_{a_n^{(F)}, p_n^{(F)}} \sum_{k=1}^{K-K_m} \left( R_{n,k}^{(F)} - \Delta R_k \right), \quad (5)$$

with

$$\Delta R_k = \beta \sum_{m=1}^M \Delta R_{m,k}^{(MF)} + (1 - \beta) \sum_{n'=1, n' \neq n}^N \Delta R_{n',k}^{(FF)}, \quad (6)$$

such that

$$0 \leq \beta \leq 1, \quad \sum_{k=1}^{K-K_m} p_{n,k}^{(F)} \leq p_n^{(F) \max}, p_{n,k}^{(F)} \geq 0, \\ a_{n,k}^{(F)} \in \{0, 1\}, \quad 1 \leq k \leq K - K_m,$$

where  $\mathbf{p}_n^{(F)} = [p_{n,1}^{(F)}, p_{n,2}^{(F)}, \dots, p_{n,K-K_m}^{(F)}]^T$  and  $\mathbf{a}_n^{(F)} = [a_{n,1}^{(F)}, a_{n,2}^{(F)}, \dots, a_{n,K-K_m}^{(F)}]^T$  denote transmit power and channel usage of  $FTX_n$ , respectively. Data rate reduction  $\Delta R_k$  includes  $\Delta R_{m,k}^{(MF)}$  and  $\Delta R_{n',k}^{(FF)}$ , denoting the data rate reduction

of the macrocell link  $m$  and the femtocell link  $n'$  caused by  $FTX_n$  on the  $k$ th channel, respectively.  $p_n^{(F)\max}$  is the maximum transmit power of  $FTX_n$ , and  $\beta \in [0, 1]$  regulates the priority to the macrocell tier relative to the femtocell tier. When  $\beta = 0.5$ , the data rate reduction is identically considered for the macrocell links and neighbor femtocell links. For  $\beta = 0$ , only the data rate reduction of neighbor femtocells is considered to manage the co-tier or cross-link interference. If  $\beta = 1$ , the  $n$ th femtocell link will focus on the macrocell links to mitigate the cross-tier interference. It is obvious that larger  $\beta$  can protect the macrocell link better, while affect the femtocell links each other worse. We also show this observation in the simulations of Section IV.

We use two widely used resource allocation schemes, centralized and greedy resource allocation scheme, applicable to the system described above for comparison with our proposed scheme. For the centralized resource allocation scheme, the MBS maximizes the weighted data rate centrally

$$\begin{aligned} & \max_{a_n^{(F)}, p_n^{(F)}} \sum_{k=1}^K \sum_{m=1}^M (R_{m,k}^{(M)} + R_{n,k}^{(F)}), \\ & \text{subject to } \sum_{k=1}^K p_{n,k}^{(F)} \leq p_n^{(F)\max}, \quad p_{n,k}^{(F)} \geq 0, \\ & \sum_{k=1}^K p_{m,k}^{(M)} \leq p_m^{(M)\max}, \quad p_{m,k}^{(M)} \geq 0, \forall k, \end{aligned} \quad (7)$$

where  $R_{m,k}^{(M)}$  is the data rate of macrocell link  $m$ ,  $p_m^{(M)\max}$  and  $p_n^{(F)\max}$  are the maximum transmit power of  $MTX_m$  and  $FTX_n$ , respectively, and  $p_{m,k}^{(M)}$  is the transmit power of  $MTX_m$  on channel  $k$ .

For the greedy resource allocation scheme, the  $n$ th femtocell link only optimizes its own data rate as

$$\max_{a_n^{(F)}, p_n^{(F)}} \sum_{k=1}^{K-K_m} R_{n,k}^{(F)}, \quad (8)$$

subject to

$$\sum_{k=1}^{K-K_m} p_{n,k}^{(F)} \leq p_n^{(F)\max}, \quad p_{n,k}^{(F)} \geq 0, 1 \leq k \leq K - K_m.$$

Utilizing mutual interference information exchange among the ultra-dense links, either the centralized or the greedy resource allocation scheme can grasp instantaneous interference information at all receivers as well as the channel state information. However, information exchange is somehow a waste of limited resource due that it introduces tremendous overhead in the intensive networks. Moreover, in the greedy one, the aggressive usage of resources may incur severe co-tier, cross-tier, and cross-link interference to the neighboring links.

## B. COGNITIVE INTERFERENCE ESTIMATION

It is crucial for the proposed statistical resource allocation to obtain the data rates in (5) with parameters such as the

interference and channel information, especially the data rate reductions of  $\Delta R_{m,k}^{(MF)}$  and  $\Delta R_{n',k}^{(FF)}$ . In this section, we will deal with how to estimate the data rate reductions using cognitive spectrum sensing, since the corresponding instantaneous parameters are unknown.

We will introduce interference statistics to estimate the data rate reductions of neighboring links by each femtocell link itself. Co-channel interference statistics have been widely studied with various empirical and statistical-physical methods [13]. We choose the interference model developed in [13], which is appropriate to the two-tier networks with the Poisson interferer distribution over finite-area and infinite-area annular region. In the following, average aggregated interference suffered by the  $MRX_M$  is analyzed statistically to obtain the data rate reduction, which enables distributed resource allocation in the  $n$ th femtocell link.

### 1) DATA RATE REDUCTION OF MACROCELLS

Consider  $\Delta R_{m,k}^{(MF)}$ , which is the difference between the data rates of  $MRX_m$  before and after  $FTX_n$  transmitting on channel  $k$ . The data rate reduction influenced by the access of  $FTX_n$  on channel  $k$  is accordingly

$$\Delta R_{m,k}^{(MF)} = R_{m,k}^{(M)} - a_{m,k}^{(M)} B \log \left( 1 + \frac{p_{m,k}^{(M)} h_{m,k}^{(MM)}}{I_{m,n,k}^{(MF)} + I_{m,k}^{(M)} + \sigma^2} \right), \quad (9)$$

where  $I_{m,n,k}^{(MF)}$  is the cross-tier or cross-link interference to  $MRX_m$  caused by  $FTX_n$ .

Next we will investigate how to estimate the data rate reduction in (9) cognitively by taking advantage of the statistics of the aggregated interference. Hence, information exchange consuming additional operations and resources can be avoided effectively.

We first clarify some key assumptions to use the inference model particularly for Case II in a Poisson field of interferers in [13]. With the assumption of perfect interference mitigation inside the macrocell, interference suffered by  $MRX_m$  is the sum of that from all the femtocell transmitters. That is, all the interferers around  $MRX_m$  are either FAPs in downlink or FUs in uplink. They have the same maximum transmit power and are distributed according to a homogeneous spatial Poisson point process [15]. Furthermore, to simplify the analysis, it is assumed that all the femtocell transmitters have equal transmit power. Although it may not be true in real networks, the interference statistics are related to the average transmit power among all the interferers rather than the individual. Moreover, the estimation error due to this ideal assumption can be revised using intelligent algorithms with cognitive radio techniques [16].

From the above, the interferers of femtocell transmitters, with the *independent and identically distributed (i.i.d.)* emissions, are scattered over a finite-area annular region within the MBS. The overall interference,  $I_{m,k}^{(M)}$ , accordingly follows the log-characteristic function of a Middleton Class A

distribution [17] as

$$\psi_{I_{m,k}^{(M)}}(\omega) = N_I \left( e^{-\frac{\omega^2 \Omega_{2N_I}}{2N_I}} - 1 \right), \quad (10)$$

and the distribution function is

$$F_{I_{m,k}^{(M)}}(\omega) = 1 - e^{-N_I} \sum_{x=1}^{\infty} \frac{N_I^x}{x!} e^{-\frac{N_I \omega^2}{2x \Omega_{2N_I}}}, \quad \omega \geq 0, \quad (11)$$

where  $N_I$  denotes the number of interfering femtocell links on channel  $k$  and  $\Omega_{2N_I}$  is the average intensity of interference.

In this case, the two parameters in (11) can be obtained by cognitive spectrum sensing. The  $n$ th femtocell link can sense the number of interferers,  $N_I$ . It detects on the  $k$ th channel and decides whether a neighbor femtocell is present or not [18], i.e.,  $a_{n',k}^{(F)}$  equals 0 or 1. We can then obtain  $N_I = \sum a_{n',k}^{(F)}$ . As for the average intensity of interference,  $\Omega_{2N_I} = N_I \times E \left\{ h_{m,n,k}^{(MF)} p_{n,k}^{(F)} \right\}$ , the  $n$ th femtocell link can estimate the received pilot signal strength of the neighboring femtocell links, which depends on  $N_I$  and the average interference caused by each neighboring femtocell link  $E \left\{ h_{m,n,k}^{(MF)} p_{n,k}^{(F)} \right\}$ . Therefore, the cognitive interference estimation is based on the sensing methods like energy detection and the received pilot signals strength, which are feasible in the practical networks. Then put these two estimated parameters into (11), we can get the average aggregated interference at  $MRX_m$  through the integral of the distribution function as

$$\bar{I}_{m,k}^{(M)} = \int_0^{\infty} \omega dF_{I_{m,k}^{(M)}}(\omega). \quad (12)$$

Hence, we can obtain the aggregated interference with the aid of the statistics of the interference, by which can reduce the information exchange among the enormous links and save the resource consumptions on feedback. The sensing of the average aggregated interference estimation and the data transmission can be implemented alternately in each signal interval like the conventional cognitive sensing implemented. For example, sensing can be implemented during the traditional channel detection which is between the pilot signals reception and the channel state information feedback. The difference is that here the  $n$ th femtocell link senses the average aggregated interference from neighboring interfering transmitters rather than from its own transmitter. After that in the same signal interval, the  $n$ th femtocell link can transmit and receive its data with appropriate transmit power and channels allocated by the proposed statistical resource allocation scheme as we described in Section III C.

The data rate reduction of the  $m$ th macrocell link caused by the  $n$ th femtocell link,  $\Delta R_{m,k}^{(MF)}$ , can be estimated as

$$\Delta \hat{R}_{m,k}^{(MF)} = a_{m,k}^{(M)} B \left[ \log \left( 1 + \frac{P_{m,k}^{(M)} h_{m,k}^{(MM)}}{\bar{I}_{m,k}^{(M)} + \sigma^2} \right) - \log \left( 1 + \frac{P_{m,k}^{(M)} h_{m,k}^{(MM)}}{I_{m,n,k}^{(MF)} + \bar{I}_{m,k}^{(M)} + \sigma^2} \right) \right], \quad (13)$$

where channel gain and transmit power of  $MTX_m$  can be estimated by the  $n$ th femtocell link with the cognitive sensing method in [19].

For simplification, let  $R_{m,k}^{(M) \prime}$  denote the first derivative of data rate  $R_{m,k}^{(M)}$  related to the aggregated interference on channel  $k$ . Then  $R_{m,k}^{(M) \prime} \left( \bar{I}_{m,k}^{(M)} \right)$  is the rate of change of data rate  $R_{m,k}^{(M)}$  at the point where the aggregated interference equals  $\bar{I}_{m,k}^{(M)}$ . If the interference power is increased by  $I_{m,n,k}^{(MF)}$ , the data rate reduction can be approximated on the basis of Taylor expansion as

$$\Delta \hat{R}_{m,k}^{(MF)} \approx -R_{m,k}^{(M) \prime} \left( \bar{I}_{m,k}^{(M)} \right) I_{m,n,k}^{(MF)}, \quad (14)$$

where

$$R_{m,k}^{(M) \prime} \left( \bar{I}_{m,k}^{(M)} \right) = \frac{-a_{m,k}^{(M)} B p_{m,k}^{(M)} h_{m,k}^{(MM)}}{\left( P_{m,k}^{(M)} h_{m,k}^{(MM)} + \bar{I}_{m,k}^{(M)} + \sigma^2 \right) \left( \bar{I}_{m,k}^{(M)} + \sigma^2 \right) \ln 2}. \quad (15)$$

## 2) DATA RATE REDUCTION OF NEIGHBOR FEMTOCELLS

Consider the data rate reduction of neighbor femtocells,  $\Delta R_{n',k}^{(FF)}$ . The aggregated interference,  $I_{n',k}^{(F)}$ , at the  $n'$ th femtocell receiver can be expressed as

$$I_{n',k}^{(F)} = \sum_{m=1}^M I_{n',m,k}^{(FM)} + \sum_{n=1, n \neq n'}^N I_{n',n,k}^{(FF)}, \quad (16)$$

where  $I_{n',m,k}^{(FM)}$  is the total cross-tier and cross-link interference from  $MTX_m$  on channel  $k$ , and  $I_{n',n,k}^{(FF)}$  is the total co-tier and cross-link interference from  $FTX_n$  on channel  $k$ .

Obviously, the estimation in uplink case is similar to that of the macrocells since the uplink interferers of MUs and FUs can meet the key assumptions of the interference model. In downlink, the aggregated interference also meets the key assumptions. However, the transmit power of the MBS is generally different from that of MU, FU, and FAP. There are three reasons here the large transmit power of the MBS has little effect on the cognitive interference estimation. First, the total transmit power of the MBS is separately allocated to multiple MUs on each channel in the downlink, while the total transmit power of FAP is only allocated to one FU in the downlink and the total transmit power of MU is only allocated to the MBS and FU only to FAP in the uplink. Thus, the cross-link interference cause by the MBS to FAPs and the cross-tier interference to FUs would be separately reduced by multiple MUs. Second, the distance between the MBS and the interference victims of receivers is generally longer than that between the femtocell link itself. Then the cross-link or cross-tier interference cause by the MBS would be reduced further. Third, we will evaluate the cognitive interference estimation in Section IV. The results show that the cognitive interference estimation has robust performance with different total transmit power for the MBS and the other transmitters in the simulation.

The same approach can be used to estimate data rate reduction of other femtocell links in uplink and that caused by the aggregated interference in downlink. Average aggregated interference,  $\bar{I}_{n',k}^{(F)}$ , is obtained through the statistical interference analysis. Hence, the data rate reduction of the  $n'$ th femtocell link is

$$\Delta \hat{R}_{n',k}^{(FF)} \approx -R_{n',k}^{(F)'} \left( \bar{I}_{n',k}^{(F)} \right) I_{n',n,k}^{(FF)} \quad (17)$$

where  $I_{n',n,k}^{(FF)}$  denotes the interference caused by the  $n$ th femtocell, and  $R_{n',k}^{(F)'}$  is the first derivative of data rate of the  $n'$ th femtocell link as

$$R_{n',k}^{(F)'} \left( \bar{I}_{n',k}^{(F)} \right) = \frac{-a_{n',k}^{(F)} B p_{n',k}^{(F)} h_{n',k}^{(FF)}}{\left( p_{n',k}^{(F)} h_{n',k}^{(FF)} + \bar{I}_{n',k}^{(F)} + \sigma^2 \right) \left( \bar{I}_{n',k}^{(F)} + \sigma^2 \right) \ln 2}, \quad (18)$$

where  $p_{n',k}^{(F)}$  is the transmit power of the  $n'$ th femtocell link with channel gain  $h_{n',n',k}^{(FF)}$ .

Note that the cognitive interference estimation is easily to extend to other practical scenarios. For example, when there are multiple FUs in each femtocell, the interference models with Poisson-Poisson cluster distribution in a finite-area annular region can be used. For multiple macrocells, the interference region can be considered as an infinite plane, which is also be discussed in [13]. Meanwhile, the statistics of the aggregated interference can be also extended from a particular form of a Middleton Class A distribution to the Gaussian mixture distribution.

### C. STATISTICAL RESOURCE ALLOCATION

With the cognitive interference estimation we will solve the statistical resource allocation in (5) by Lagrange dual decomposition [20].

The Lagrangian function is given by

$$L = \sum_{k=1}^{K-K_m} \left( R_{n,k}^{(F)} - \beta \sum_{m=1}^M \Delta \hat{R}_{m,k}^{(MF)} - (1-\beta) \sum_{n'=1, n' \neq n}^N \Delta \hat{R}_{n',k}^{(FF)} \right) + \lambda_n \left( p_n^{(F) \max} - \sum_{k=1}^{K-K_m} a_{n,k}^{(F)} p_{n,k}^{(F)} \right), \quad (19)$$

where  $\lambda_n$  is the Lagrange multiplier updated by the subgradient approach [20] as

$$\lambda_n^{l+1} = \left[ \lambda_n^l - \delta^l \left( p_n^{(F) \max} - \sum_{k=1}^{K-K_m} a_{n,k}^{(F)l} p_{n,k}^{(F)l} \right) \right]^+, \quad (20)$$

where  $[\cdot]^+ = \max(\cdot, 0)$ , and  $\delta^l = \delta_0/l$  is the step size in the  $l$ th iteration tuned with initial step size,  $\delta_0$ . We will analyze

TABLE 1. The lagrange dual decomposition algorithm for statistical resource allocation.

1:	$l = 0;$
2:	initialize $\lambda_n;$
3:	<b>while</b> $\left  p_n^{(F) \max} - \sum_{k=1}^{K-K_m} a_{n,k}^{(F)} p_{n,k}^{(F)} \right  > \epsilon$ <b>do</b>
4:	update stepsize $\delta^l;$
5:	calculate $p_{n,k}^{(F)l}$ for all $k$ with (21);
6:	determine $a_{n,k}^{(F)l}$ for all $k$ with (22);
7:	update $\lambda_n^l$ using subgradient method with (20);
8:	$l = l + 1;$
9:	<b>end while</b>
10:	return $p_{n,k}^{(F)} = p_{n,k}^{(F)l}, a_{n,k}^{(F)} = a_{n,k}^{(F)l}, \forall k = [1, 2, \dots, K - K_m].$

the convergence performance of the proposed solution in the next section.

According to the Karush-Kuhn-Tucher (KKT) condition in [20], the transmit power  $p_{n,k}^{(F)}$  can be allocated in a water-filling fashion when  $\partial L / \partial p_{n,k}^{(F)} = 0$ , i.e., shown in (21), at the bottom of this page, where  $h_{m,n,k}^{(MF)}$  and  $h_{n',n,k}^{(FF)}$  are the channel gain from  $FTX_n$  to  $MRX_m$  and  $FRX_{n'}$ , respectively. Then the channels are allocated as

$$a_{n,k}^{(F)} = \begin{cases} 1, & \text{for } p_{n,k}^{(F)} > 0, \\ 0, & \text{otherwise.} \end{cases} \quad (22)$$

The iterative algorithm of the Lagrange dual decomposition approach for the statistical resource allocation is summarized in Table 1, where  $\epsilon$  should be set small enough to guarantee the convergence of the Lagrange multiplier.

Considering both its own data rate and the data rate reduction to neighboring links, the femtocell link statistically allocates the resources of power and channels. This allocation is implemented in a distributed manner avoiding centralized control and additional information exchange. In practice, the complexity of the proposed statistical resource allocation scheme is mainly related to two aspects of the statistics of the aggregated interference and the large number of neighboring femtocell links. On one hand, larger number of femtocell links, more complexity for the aggregated interference estimation and resource allocation. On the other hand, to take better advantage of the statistics of the aggregated interference with more sample of interferers, the proposed statistical resource allocation scheme is more applicable in the ultra-dense networks scenario rather than scattered. It is necessary for the proposed scheme to trade off between the data rate gain and reduction for each femtocell link, e.g. to set the priority factor  $\beta$  and the femto-free zone ratio  $K_m/K$  dynamically and reasonably.

$$p_{n,k}^{(F)} = \left[ \frac{B / \ln 2}{\lambda_n - \beta \sum_{m=1}^M R_{m,k}^{(M)'} (\bar{I}_{m,k}^{(M)}) h_{m,n,k}^{(MF)} - (1-\beta) \sum_{n'=1, n' \neq n}^N R_{n',k}^{(F)'} (\bar{I}_{n',k}^{(F)}) h_{n',n,k}^{(FF)}} - \frac{I_{n,k}^{(F)} + \sigma^2}{h_{n,k}^{(FF)}} \right]^+, \quad (21)$$

TABLE 2. Simulation parameters of channels.

	Path Loss (dB)	SDSF
MBS → MU	$PL=15.3 + 37.6 \log_{10} d$	10 dB
MBS → FU	$PL=15.3 + 37.6 \log_{10} d + PL_w$ , $PL_w = 10$ dB	12 dB
FAP → MU	$PL=15.3 + 37.6 \log_{10} d + PL_w$ , $PL_w = 10$ dB	7 dB
FAP → serving FU	$PL=38.46 + 20 \log_{10} d + 0.7d$	6 dB
FAP → neighbor FU	$PL=15.3 + 37.6 \log_{10} d + PL_w$ , $PL_w = 20$ dB	7 dB

IV. SIMULATION RESULTS

In this section, we will evaluate the proposed statistical resource allocation scheme under two different scenarios: single macrocell and multiple macrocells. Meanwhile, it is compared with the centralized and greedy resource allocation schemes. We assume that each MBS centrally allocates the resources to its own MUs. After that, these femtocell resource allocation schemes are implemented among the links using the round-robin scheduling.

In the simulation, the macrocell coverage range is set as 500 m while 10 m for femtocell. The maximum transmit power is 36 dBm for the MBSs and 20 dBm for FAPs, MUs, and FUs. The bandwidth of each channel is 10 kHz. We assume Rayleigh fading channels with path loss (PL), wall penetration loss, and standard deviation of shadow fading (SDSF) based on the ITU path loss model [21] as shown in Table 2, where  $d$  is the distance between transmitter and receiver and  $PL_w$  is the wall penetration loss.

A. SINGLE MACROCELL

In this scenario, only one macrocell is considered without co-channel interference caused by neighboring macrocells. Multiple FAPs overlay in the coverage area of the MBS.

The throughput and data rate reduction with different femto-free zone ratio for single macrocell, where the priority factor  $\beta = 0.5$ , have been illustrated in our previous work [14]. For the proposed statistical resource allocation scheme and the comparing centralized and greedy ones, the throughput of the femtocell links decreases while the macrocell grows as the femto-free zone ratio increases. The bigger femto-free zone can better protect the macrocell throughput, however the overall throughput will be reduced. In the following, we will further evaluate the cell edge links throughput, data rate distributions, different priority factors, and convergence of the proposed scheme for the single macrocell scenario.

5% throughput of the macrocell links, as the cell-edge performance when deploying different sizes of femto-free zone for the different schemes, is evaluated in Fig. 2, where  $M = 10$ ,  $K = 50$ , and  $\beta = 0.5$ . The 5% throughput indicates the sum data rates of 5% links with the minimum data rates. The proposed scheme effectively guarantees the cell-edge performance of the macrocell as shown in Fig. 2. It gains 54.7% and 88.7% more than the centralized and greedy

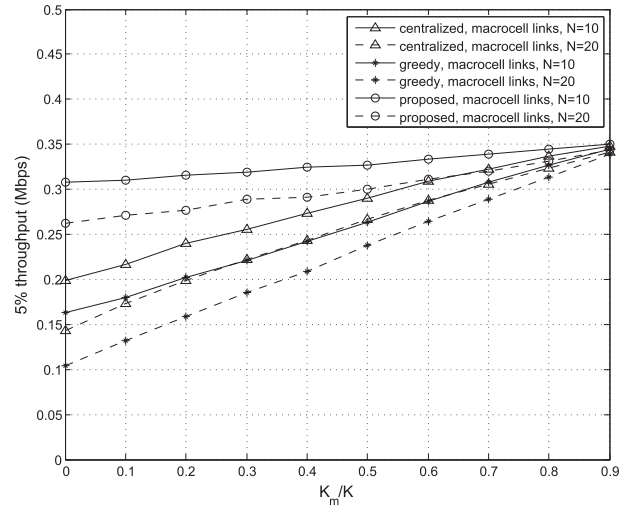


FIGURE 2. The 5% throughput of macrocell links with respect to different femto-free zone ratios.

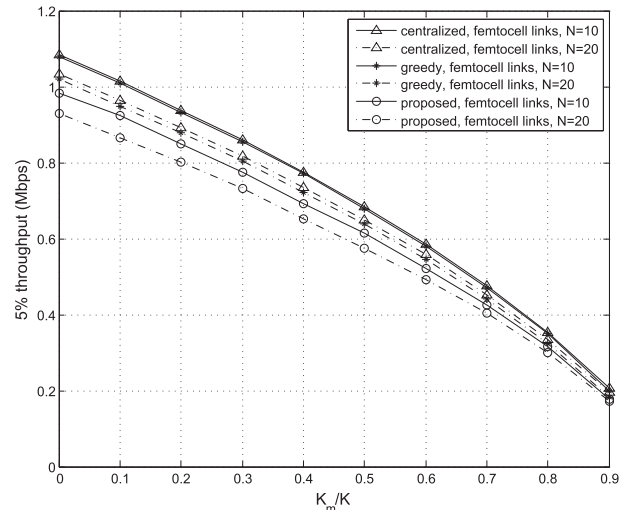
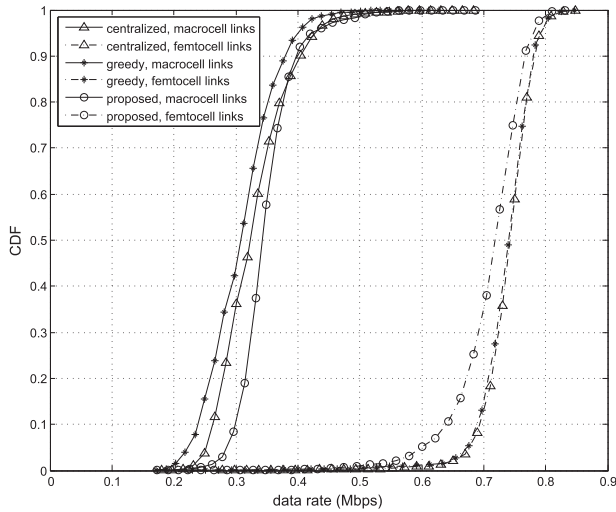


FIGURE 3. The 5% throughput of femtocell links with respect to different femto-free zone ratios.

schemes when  $N = 10$  and  $K_m/K = 0$ , respectively. Moreover, it maintains the 5% macrocell throughput around from 0.25 to 0.35 Mbps for both  $N = 10$  and  $N = 20$ . Therefore, the influence of the cross-tier or cross-link interference to the macrocell links is minimized by the proposed scheme. In other words, the smallest femto-free zone is needed by the proposed scheme to ensure acceptable macrocell coverage. Since more interference will be introduced when the number of the femtocell links increases, the 5% macrocell throughput decreases for  $N = 20$  comparing to  $N = 10$  in each scheme.

For the 5% throughput of the femtocell links in Fig. 3, the proposed scheme that conservatively uses the resources sacrifices more cell-edge performance of the femtocell links to mitigate the cross-tier or cross-link interference. Furthermore, a large size of femto-free zone significantly reduces the

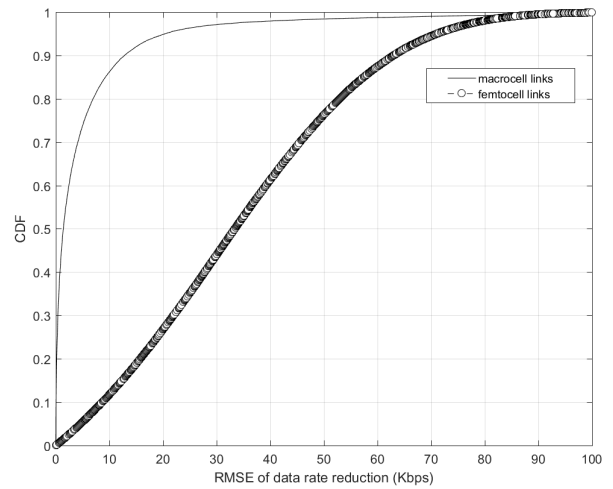


**FIGURE 4.** The CDF of the data rate for each macrocell and femtocell link when the femto-free zone ratio is  $K_m/K = 0.5$ .

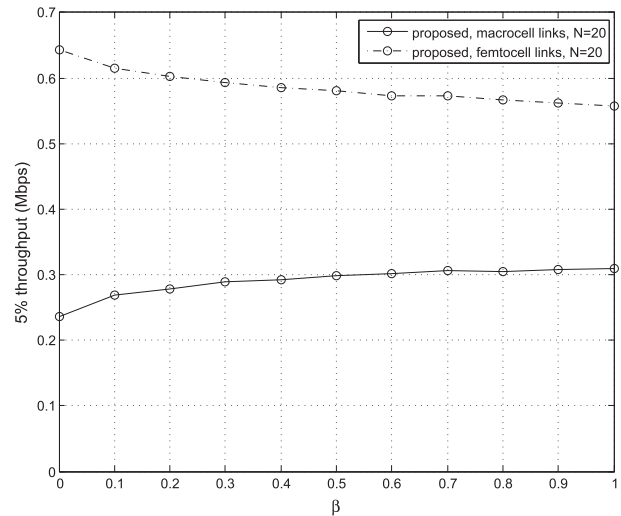
5% femtocell throughput while improves the 5% macrocell throughput. It is a tradeoff between to protect the macrocell throughput and to enhance the femtocell throughput.

Regarding the data rate of each link, the *cumulative distribution function* (CDF) curves for the macrocell and femtocell links are shown in Fig. 4, where  $N = 20$ ,  $M = 10$ ,  $K = 50$ ,  $K_m/K = 0.5$ , and  $\beta = 0.5$ . The minimum data rate of the macrocell links is improved significantly by our scheme. For example, when CDF equals 0.05, the proposed scheme can ensure the minimum data rate of the rest 95% macrocell links to be 0.29 Mbps while the centralized and greedy schemes get 0.25 Mbps and 0.22 Mbps, respectively. Note that there is a tradeoff in terms of loss in femtocell performance compared to macrocell throughput preservation. The proposed scheme offers the macrocell links the best protection with the cost of limited reduced femtocell data rate compared with other two schemes.

More specifically, the cognitive interference estimation described in Section III B is evaluated. We investigate the *root mean square error* (RMSE) of data rate reduction between the original value in (9) and the estimated in (13) for each macrocell link, and similarly for each femtocell link. The CDF curves of RMSE of data rate reduction for both the macrocell and femtocell links are shown in Fig. 5, where  $N = 20$ ,  $M = 10$ ,  $K = 50$ ,  $K_m/K = 0.5$ , and  $\beta = 0.5$ . It is illustrated that for the 80% macrocell links the RMSE of data rate reduction is below 6.95 Kbps and for 95% is below 20.32 Kbps, comparing with the data rates of the 80% and 95% macrocell links are above 0.32 Mbps and 0.29 Mbps as we show in Fig. 4, respectively. Meanwhile, for the 80% and 95% femtocell links the RMSE of data rate reduction are respectively lower than 52.89 Kbps and 70.03 Kbps when the data rates are larger than 0.67 Mbps and 0.62 Mbps. Moreover, the normalized RMSEs are respectively 0.02 and 0.08 for the 80% macrocell and femtocell links, and 0.07 and



**FIGURE 5.** The CDF of RMSE of data rate reduction for the macrocell and femtocell links with the cognitive interference estimation, where  $K_m/K = 0.5$ .



**FIGURE 6.** The 5% throughput of the macrocell and femtocell links with respect to different priority factors.

0.11 for the 95% macrocell and femtocell links. Therefore, the cognitive interference estimation has robust performance for most of the macrocell and femtocell links, and it can protect the macrocell links better with lower RMSE.

In Fig. 6, we evaluate the 5% throughput of the macrocell and femtocell links with different priority factors to the macrocell tier,  $\beta$ , where  $N = 20$ ,  $M = 10$ ,  $K = 50$ , and  $K_m/K = 0.5$ . As  $\beta$  changes, the femtocell link behaves differently on the macrocell links and the neighbor femtocell links. For  $\beta = 1$ , the highest 5% throughput of the macrocell links is achieved since the femtocell link focuses on mitigating cross-tier or cross-link interference to the macrocell links while the 5% femtocell throughput is the lowest. It indicates that a large priority factor can enhance the data rates of cell-edge macrocell links.



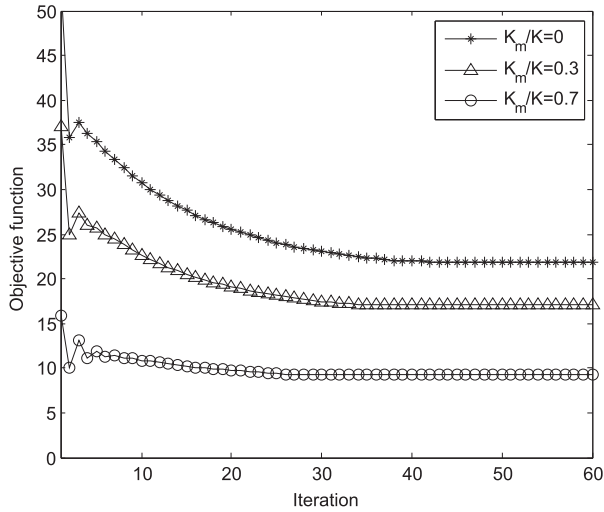


FIGURE 7. Evolution of the proposed scheme with respect to different  $K_m/K$ .

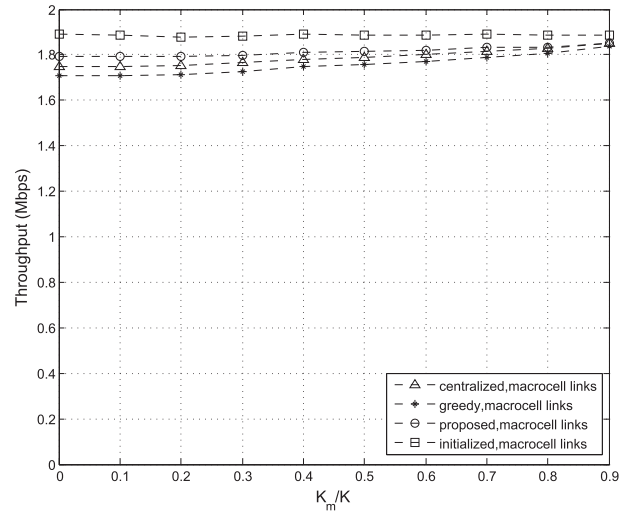


FIGURE 9. The throughput of macrocell links for multiple macrocells scenario.

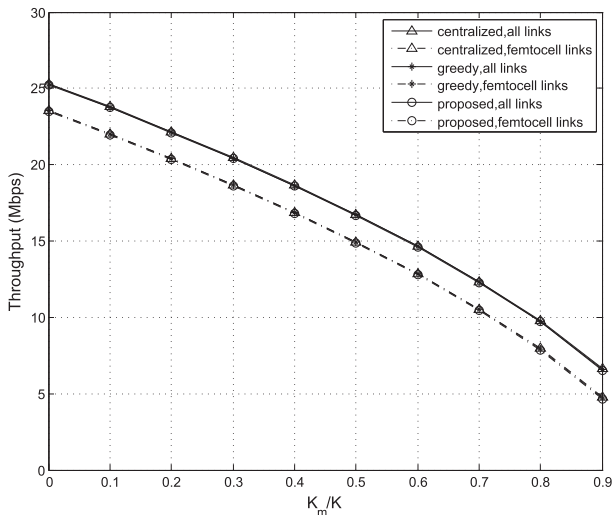


FIGURE 8. The throughput of all links and femtocell links for multiple macrocells scenario.

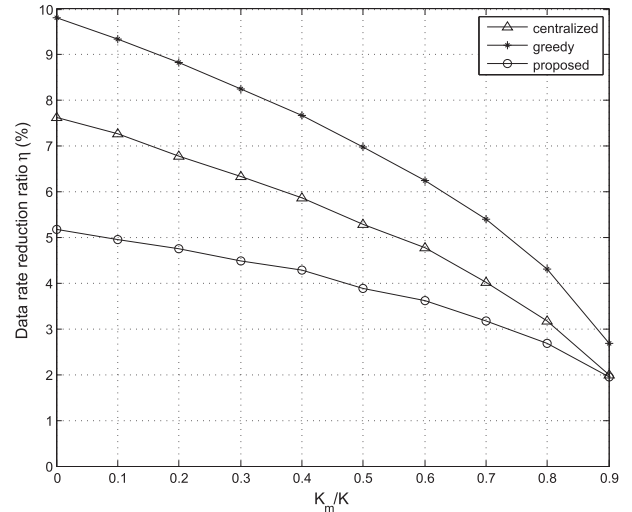


FIGURE 10. The data rate reduction ratios of macrocell links with respect to different femto-free zone ratios for multiple macrocells scenario.

Finally, the convergence of the proposed scheme is shown in Fig. 7, where  $N = 20$ ,  $M = 10$ ,  $K = 50$ , and  $\beta = 0.5$ . For each specific  $K_m/K$ , the proposed scheme can converge rapidly within tens of iterations. Meanwhile, the objective function is decreased as the growing iterations before convergence. That is because the femtocell links are initialized without data transmission and the proposed scheme is tend to allocate the channels with large transmit power aggressively at the beginning. As the iteration grows, the increased data rate reduction will lead to conservative resource allocation and the objective function is decreased relatively. Moreover, for  $K_m/K$  from 0 to 0.7, the channels that can be accessed by the femtocell links get fewer and fewer. Therefore, the proposed scheme needs fewer iterations to reach convergence.

### B. MULTIPLE MACROCELLS

In this scenario, the simulation involves multiple MBSs and FAPs. There are 19 macrocells with uniformly dropped FAPs, and only the performance of the central macrocell is evaluated. Assume frequency reuse factor of 1 among all the MBSs and FAPs. The neighbor MBSs around the central MBS are assumed applying maximum transmit power on each channel.

The overall throughput of all links, macrocell links, and femtocell links versus femto-free zone ratio,  $K_m/K$ , using different resource allocation schemes is shown in Fig. 8 and Fig. 9, where  $N = 20$ ,  $M = 10$ ,  $K = 50$ , and  $\beta = 0.5$ . Comparing to the corresponding metrics in [14], the performance of all links is reduced significantly while the femtocell throughput is similar to that in the single macrocell scenario. Meanwhile, the macrocell throughput is much lower than that in the single macrocell scenario as shown. However, the data

rate reduction of macrocell links caused by the deployment of femtocells is the lowest with the proposed scheme in Fig. 10. we define the data rate reduction ratio  $\eta$  as

$$\eta = \frac{\sum_{m=1}^M \sum_{k=1}^K R_{m,k}^{(M)\text{initialized}} - \sum_{m=1}^M \sum_{k=1}^K R_{m,k}^{(M)}}{\sum_{m=1}^M \sum_{k=1}^K R_{m,k}^{(M)\text{initialized}}}, \quad (23)$$

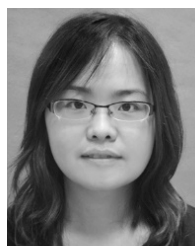
where  $R_{m,k}^{(M)\text{initialized}}$  is the initialized data rate of the  $m$ th macrocell link on channel  $k$ , and  $R_{m,k}^{(M)}$  denotes the data rate updated after the femtocell resource allocation. These results imply that the macrocell links are more sensitive to interference from the neighbor MBSs than the femtocell links since the channel conditions between the macrocell links are generally worse than those of the femtocell links. Therefore, the macrocell throughput can be enhanced by the proposed scheme and further by using advanced macrocell interference mitigation techniques such as multiple-input and multiple-output and fractional frequency reuse.

## V. CONCLUSION

In this paper, we have investigated the distributed statistical resource allocation for interference mitigation in the ultra-dense HetNets. The proposed scheme independently operates resource allocation at each femtocell link distributively and statistically. Each femtocell link first estimates the aggregated co-tier, cross-tier, and cross-link interference and the data rate reduction caused to its neighboring links, and then determines the channel usage and relative transmit power. The femtocells are enabled to maximize their own throughput while considering the impact on macrocell throughput and outage. The proposed scheme considerably reduces the system overhead with the cognitive interference estimation.

## REFERENCES

- [1] T. O. Olwal, K. Djouani, and A. M. Kurien, "A survey of resource management toward 5G radio access networks," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1656–1686, 3rd Quart., 2016.
- [2] M. Kamel, W. Hamouda, and A. Youssef, "Ultra-dense networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2522–2545, 4th Quart., 2016.
- [3] S. Chen, F. Qin, B. Hu, X. Li, and Z. Chen, "User-centric ultra-dense networks for 5G: Challenges, methodologies, and directions," *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 78–85, Apr. 2016.
- [4] Y. Teng, M. Liu, F. R. Yu, V. C. M. Leung, M. Song, and Y. Zhang, "Resource allocation for ultra-dense networks: A survey, some research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2134–2168, 3rd Quart., 2019.
- [5] A. Lukowa and V. Venkatasubramanian, "Centralized UL/DL resource allocation for flexible TDD systems with interference cancellation," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 2443–2458, Mar. 2019.
- [6] P.-H. Huang, H. Kao, and W. Liao, "Cross-tier cooperation for optimal resource utilization in ultra-dense heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 12, pp. 11193–11207, Dec. 2017.
- [7] A. R. Elsherif, W.-P. Chen, A. Ito, and Z. Ding, "Adaptive resource allocation for interference management in small cell networks," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2107–2125, Jun. 2015.
- [8] E. Castaneda, A. Silva, A. Gameiro, and M. Kountouris, "An overview on resource allocation techniques for multi-user MIMO systems," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 1, pp. 239–284, 1st Quart., 2017.
- [9] S. Chen, Z. Zeng, and C. Guo, "Exploiting polarization for system capacity maximization in ultra-dense small cell networks," *IEEE Access*, vol. 5, pp. 17059–17069, 2017.
- [10] H. Zhang, L. Song, Y. Li, and G. Y. Li, "Hypergraph theory: Applications in 5G heterogeneous ultra-dense networks," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 70–76, Dec. 2017.
- [11] M. Yoon, M.-S. Kim, and C. Lee, "A dynamic cell clustering algorithm for maximization of coordination gain in uplink coordinated system," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1752–1760, Mar. 2016.
- [12] C. Yang, J. Xiao, J. Li, X. Shao, A. Anpalagan, Q. Ni, and M. Guizani, "DISCO: Interference-aware distributed cooperation with incentive mechanism for 5G heterogeneous ultra-dense networks," *IEEE Commun. Mag.*, vol. 56, no. 7, pp. 198–204, Jul. 2018.
- [13] K. Gulati, B. L. Evans, J. G. Andrews, and K. R. Tinsley, "Statistics of co-channel interference in a field of Poisson and Poisson-Poisson clustered interferers," *IEEE Trans. Signal Process.*, vol. 58, no. 12, pp. 6207–6222, Dec. 2010.
- [14] F. Liu, X. Zhou, N. Himayat, S.-P. Yeh, S. Srikanteswara, S. Talwar, C. Feng, and G. Y. Li, "Exploiting statistical interference models for distributed resource allocation in cognitive femtocells," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Ottawa, ON, Jun. 2012, pp. 1816–1820.
- [15] V. Chandrasekhar and J. Andrews, "Spectrum allocation in tiered cellular networks," *IEEE Trans. Commun.*, vol. 57, no. 10, pp. 3059–3068, Oct. 2009.
- [16] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Apr. 1999.
- [17] D. Middleton, "Statistical-physical models of electromagnetic interference," *IEEE Trans. Electromagn. Compat.*, vol. EMC-19, no. 3, pp. 106–127, Aug. 1977.
- [18] D. Cabric, A. Tkachenko, and R. Brodersen, "Spectrum sensing measurements of pilot, energy, and collaborative detection," in *Proc. MILCOM*, Berkeley, CA, USA, Oct. 2006, pp. 1–7.
- [19] Q. Su, A. Huang, Z. Zhang, K. Xu, and J. Yang, "A non-cooperative method for path loss estimation in femtocell networks," in *Proc. IEEE Globecom Workshops*, Miami, FL, USA, Dec. 2010, pp. 684–689.
- [20] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. Commun.*, vol. 54, no. 7, pp. 1310–1322, Jul. 2006.
- [21] *Guidelines for Evaluation of Radio Transmission Technologies for IMT-2000*, document ITU-R Rec M.1225, Feb. 1997.



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