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Multiuser Admission Control and Beamforming Optimization Algorithms for MISO Heterogeneous Networks

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ABSTRACT This paper investigates the problem of joint multiuser admission control and beamforming optimization for multiple input single-output heterogeneous networks (HetNets). Considered is a HetNet where multiple newly deployed femtocell base stations (FBSs) have the coverage overlapped with that of an existing macrocell base-station (MBS). The design objective is to serve as many femto users (FUEs) as possible at their quality-of-service (QoS) requirements while maintaining the QoS requirements at the macro user (MUE). This paper then proposes three algorithmic schemes to perform multiuser admission control and beamforming optimization based on the levels of coordination between the MBS and FBSs. In Scheme I with full MBS-FBS coordination, a joint optimization framework is presented, and two solution approaches are proposed to determine the admission control and beamforming design for the FUEs in a centralized manner. In Scheme II with limited MBS-FBS coordination, a distributed algorithm that allows each FBS to unilaterally determine its admission control and beamforming strategy is proposed. This algorithm requires a certain coordination from the MBS by setting a limit on the amount of cross-tier intercell interference (ICI) that can be generated by each FBS. The convergence of the proposed distributed algorithm to a fixed point, where the QoS at the MUEs and the admitted FUEs is guaranteed, is then proved. Finally, in Scheme III without any MBS-FBS coordination, a joint multiuser admission control and zero-forcing beamforming design is then proposed. In particular, each FBS distributively admits its own FUEs while suppressing its cross-tier ICI to the MUEs, which effectively maintains the QoS at these MUEs. The simulation results show comparable performances between the distributed algorithms and the centralized ones in terms of the number of FUEs served and the network power usage.

INDEX TERMS Admission control, heterogeneous network, MISO, multiuser beamforming, optimization.

I. INTRODUCTION

As the use of wireless-enabled devices becomes ubiquitous, more capacity is needed to support the rapid growth of mobile traffic. It is unavoidable that traditional cellular network cannot keep pace with this data explosion due to the limited spectrum resource. An interesting revolution in wireless technologies emerged in the past few years is the integration of small cells into the traditional network's macrocells to improve the spectrum utilization [2]. Small cells, such as femtocells which utilize short-range low-cost femtocell base-stations (FBS), provide a cost-effective means of offloading data traffic and enhancing coverage [3], [4]. To facilitate small cell deployments, various enhancements have been proposed in the LTE-Advanced Release 12, aiming to reduce mobility signaling in high density cells and improving user data rates by using macrocells and femtocells together [5]. One of the main advantages of femtocell deployment is the improvement in indoor coverage where macrocell base-station (MBS) signaling is weak. However, the overlapped coverage between femtocells and macrocells will induce certain level of *cross-tier* intercell interference (ICI) between different tiers in the multi-tier *heterogeneous* networks (HetNets). In the downlink, femtocell transmission may create *dead zone* to nearby macro-users (MUE) and impair the macrocell coverage [3], [6]. Thus, efficient radio resource management in femtocell deployment is imperative in mitigating the cross-tier ICI and thus maintaining the operation at the MUEs. At the same time, the femtocell has to adapt to its surrounding environment and allocate its radio resource wisely in the presence of ICI from the macrocell [3].

Maintaining a harmonized coexistence between neighboring femtocells and especially between the femtocells and the macrocell is considered to be one of the main challenges in femtocell networks. Enhanced intercell interference coordination (eICIC) has been proposed since LTE-Advanced Release 10 to standardize the interference control in HetNets [5], [7]. eICIC can effectively enhance the performance of small-cell networks (picocells, femtocells) by using macrocell-picocell cooperative scheduling scheme to mitigate the interference caused by macrocells to small-cell users [8]. Cognitive radio access techniques, such as interference coordination or interference cancellation, can facilitate interference mitigation in the multi-tier HetNets [9]–[11]. In [12], a distributed utility-based power control technique at femtocells has been proposed to alleviate cross-tier ICI from femtocells. In code division multi-access (CDMA) femtocell networks, joint power and admission control for distributed interference management has been examined in [13]. In multiple-input multiple-output (MIMO) networks, interference alignment [14]–[16] and interference draining [17] techniques have been proposed to mutually align the interfering signals from femtocells to the macrocells. However, these MIMO techniques might be limited to certain dimensions with given sizes of antenna sets and interfering signals.

In this work, we investigate the problem of joint multiuser admission control and beamforming optimization in a multiple-input single-output (MISO) HetNet where multiple femtocells are deployed within the coverage by a macrocell base-station (MBS). Since femtocells exploit the licensed spectrum owned by the macrocell network, the operation at the latter should not be affected by the former [3], [13], [18]. In fact, the quality-of-service (QoS) of the prioritized MUEs should be maintained at all time, whereas the FUEs attempt to utilize the remaining available system resource. With QoS protection at MUEs, sum-utility maximization for FUEs has been studied in [18]. While also attempting to protect the MUEs, the main objective of this work is to provide a fair resource allocation at the femtocells by scheduling/serving as many FUEs as possible.

User scheduling/admission control in wireless systems has been a research topic of many works in literature. Joint admission and power control have been studied in [19]–[23] for single-input single-output (SISO) systems. In another work [24], admission control for ad-hoc cognitive networks has been examined with consideration of QoS protection to a primary user. In MIMO single-cell system, the works in [25]–[27] have studied the problem of joint transmit beamforming, power allocation, and admission control in a multiuser scenario. In particular, an inflation-based admission control scheme was proposed in [26] where each user is sequentially admitted until the system becomes infeasible. In contrast, the deflation-based approach proposed in [27] initially assumes the admission of all users and sequentially drops each user until a feasible solution is found. In a more general multi-cell system, the problem of congestion control, downlink beamforming, power control, and access point allocation has been considered in [28]. However, to the best of our knowledge, no work in the literature has considered the problem of joint multiuser admission control and beamforming optimization to FUEs with QoS protection to MUEs in HetNets, which is the main focus of this study. More importantly, our study takes into account key considerations pertaining to the deployment of femtocell networks, including ICI mitigation, QoS at the users, protection of MUEs, and signaling reduction between the macrocell and the femtocells. This presented study can be divided into three main schemes based on the levels of coordination between the MBS and the FBSs: i.) Scheme I - Full coordination, ii.) Scheme II - Limited coordination, and iii.) Scheme III - No coordination.

In Scheme I with full MBS-FBS coordination, the problem of multiuser admission control and beamforming optimization can be considered as a joint optimization. Since this problem is NP-hard [27], it might require a brute-force search to find the optimal solution. Inspired by the works in admission control for single-cell networks [26], [27], we adapt the aforementioned inflation-based and deflation-based approaches to tackle the problem of admission control for HetNets. Although the two approaches are capable of generating high quality suboptimal solutions, their implementation requires a centralized solver unit with full coordination between the MBS and the FBSs. Thus, centralized implementation for admission control and beamforming optimization are difficult to realize in practice.

To overcome the drawbacks of the centralized approaches, we investigate Scheme II where only limited MBS-FBS coordination is required. We then propose a distributed algorithm for implementing multiuser admission control and beamforming optimization at the femtocells with limited MBS-FBS signaling. The main idea of the proposed algorithm is based on the allocation of the cross-tier ICI that can be generated by each FBS. It is noted that the concept of ICI allocation was introduced in [29]–[31] as an immediate step to solve distributed resource allocation problems (sum-rate maximization or power minimization) for single-tier multicell networks. In our proposed algorithm for the multi-tier networks, the amount of allocated ICI is served as the threshold for admitting the FUEs. Specifically, the total amount of ICI, which can be tolerated by the macrocell, is first calculated by the MBS and informed to the FBSs. After acquiring these design parameters, each FBS optimizes its admission control and beamforming strategy while coordinating its inducing ICI under the informed limit. The MBS and the FBSs then iteratively update their allocation strategy in a fully distributed manner. It is then proved that the distributed algorithm will converge to a fixed-point where the desired QoS at the MUEs and the admitted FUEs is guaranteed. In addition, we also propose an adaptive scheme in allocating the cross-tier ICI limits among the FBSs. Based on the requests of the FBSs, the MBS then re-allocates the cross-tier ICI limits to enhance the efficiency in admission control decisions across the FBSs.

In Scheme III, we propose a simplified admission control and beamforming strategy which does not require any MBS-FBS coordination. Our proposed scheme stems from the concept of self-organizing network (SON) in the LTE standards, where the newly deployed femtocells are capable of self-configuring and self-optimizing without any coordination from the macrocell [5]. Based on zero-forcing (ZF) precoding, each FBS attempts to suppress its cross-tier ICI to MUEs within its expanded coverage region. On the contrary, if the channel state information (CSI) to the MUEs is not available, the FBS then relies its power control to manage its cross-tier ICI. The ZF beamforming design and admission control decision are then performed autonomously at each FBS. With no MBS-FBS coordination, the MBS and the FBSs then iteratively adapt their power allocation strategies until convergence.

It is observed in the simulation part that a higher level of MBS-FBS coordination does increase the number of FUEs served and reduce the sum power consumption at the MBS and the FBSs. However, the performance difference between Scheme II (limited coordination) and Scheme I (full coordination) is negligible. In addition, Scheme III (no coordination) also performs well when a number of femtocells deployed is low.

Notations: $(\mathbf{X})^*$, $(\mathbf{X})^T$, and $(\mathbf{X})^H$ denote the conjugate, the transpose, and conjugate transpose (Hermitian operator) of the matrix $\mathbf{X}$, respectively; $[\mathbf{X}]_{m,n}$ stands for the (m, n)th entry of the matrix $\mathbf{X}$; $\|\mathbf{x}\|$ denotes the norm-L_2 of the vector $\mathbf{x}$; $|x|$ stands for the absolute value of the scalar x whereas $|\mathcal{S}|$ stands the cardinality of the set $\mathcal{S}$; $\emptyset$ denotes a empty set; $x^\star$ denotes the optimal value of the variable x; FUE-(q, i) denotes FUE-i at femtocell-q.

II. SYSTEM MODEL AND PROBLEM STATEMENT

A. SYSTEM MODEL

Consider the downlink transmission in a two-tier HetNet, in which Q newly deployed femtocells share the same radio spectrum with one existing macrocell, as illustrated in Figure 1. We assume that the MBS is currently serving multiple MUEs at their QoS requirement, *i.e.*, the SINR at each MUE must exceed its desired threshold. At the same radio channel, Q FBSs are deployed to serve multiple FUEs under the condition that the QoS at the MUEs is not affected by the FBS deployment. Denote $\mathcal{F}_0$ as the set of MUEs and $\mathcal{F}_q$ as the set of FUEs served by FBS-q with $q = 1, \ldots, Q$, where $\mathcal{F}_q \bigcap \mathcal{F}_r = \emptyset$ if $q \neq r$. Denote $K_q = |\mathcal{F}_q|$ as the number of UEs in cell-q with $q = 0, \ldots, Q$. It is assumed that the MBS and the FBS-q are equipped with M_0 and M_q transmit antennas, respectively, while each MUE or FUE is equipped with one receive antenna.

Let $\mathbf{h}^*_{qr,i} \in \mathbb{C}^{M_q \times 1}$ denote the channel from the BS of cell-q to the UE-i of cell-r. Herein, $q = 0$ indicates the macrocell, whereas $q > 0$ indicates femtocell-q. Denote $\mathbf{V} = [\mathbf{v}_1, \ldots, \mathbf{v}_{K_0}] \in \mathbb{C}^{M_0 \times K_0}$ as the beamforming matrix for the K_0 MUEs and $\mathbf{W}_q = [\mathbf{w}_{q,1}, \ldots, \mathbf{w}_{q,K_q}] \in \mathbb{C}^{M_q \times K_q}$ as the beamforming matrix for the K_q FUEs at femtocell-q.

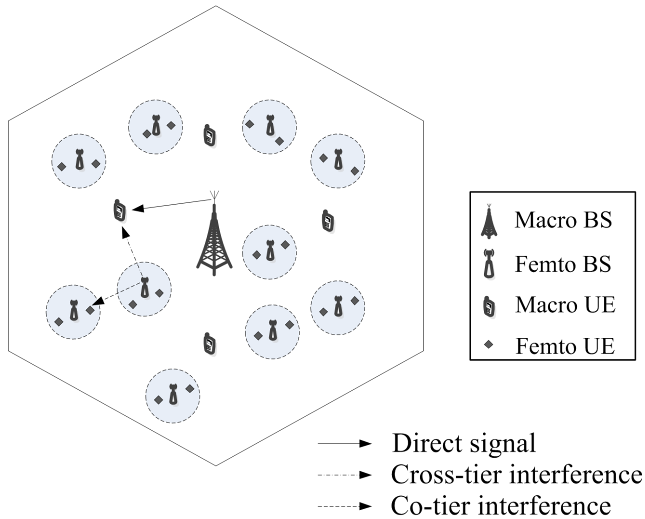

FIGURE 1. A heterogeneous network with 10 femtocells randomly deployed inside the coverage of an MBS.

Denote $u_{q,i}$ as a complex scalar symbol intended for UE-i in cell-q and denote $\mathbf{u}_q = [u_{q,1}, \ldots, u_{q,K_q}]^T$. Without loss of generality, let $\mathbb{E}[|u_{q,i}|] = 1$. By means of linear beamforming, the transmitted signals at the MBS and FBS-q are formed as $\mathbf{x}_0 = \sum_{i=1}^{K_0} \mathbf{v}_i u_{0,i} = \mathbf{V}\mathbf{u}_0$ and $\mathbf{x}_q = \sum_{i=1}^{K_q} \mathbf{w}_{q,i} u_{q,i} = \mathbf{W}_q \mathbf{u}_q$, respectively. At the macrocell, the received signal $y_{0,i}$ at MUE-i can be modeled as

$$\begin{aligned} y_{0,i} &= \mathbf{h}^H_{00,i}\mathbf{x}_0 + \sum_{q=1}^{Q} \mathbf{h}^H_{q0,i}\mathbf{x}_q + z_{0,i} \\ &= \underbrace{\mathbf{h}^H_{00,i}\mathbf{v}_i u_{0,i}}_{\text{desired signal}} + \underbrace{\sum_{j\neq i}^{K_0} \mathbf{h}^H_{00,i}\mathbf{v}_j u_{0,j}}_{\text{intracell interference}} + \underbrace{\sum_{q=1}^{Q} \mathbf{h}^H_{q0,i}\mathbf{W}_q\mathbf{u}_q}_{\text{cross-tier interference}} + z_{0,i}, \end{aligned} \tag{1}$$

where $z_{0,i}$ is the AWGN with power σ^2. The received SINR at MUE-i, denoted as $\text{SINR}_{0,i}$, can be obtained by

$$\text{SINR}_{0,i} = \frac{\left|\mathbf{h}^H_{00,i}\mathbf{v}_i\right|^2}{\sum_{j\neq i}^{K_0}\left|\mathbf{h}^H_{00,i}\mathbf{v}_j\right|^2 + \sum_{q=1}^{Q}\left\|\mathbf{W}^H_q\mathbf{h}_{q0,i}\right\|^2 + \sigma^2}. \tag{2}$$

Similarly, the received signal $y_{q,i}$ at FUE-(q, i) can be modeled as

$$\begin{aligned} y_{q,i} &= \mathbf{h}^H_{qq,i}\mathbf{x}_q + \sum_{r\neq q}^{Q} \mathbf{h}^H_{rq,i}\mathbf{x}_r + \mathbf{h}^H_{0q,i}\mathbf{x}_0 + z_{q,i} \\ &= \underbrace{\mathbf{h}^H_{qq,i}\mathbf{w}_{q,i}u_{q,i}}_{\text{desired signal}} + \underbrace{\sum_{j\neq i}^{K_q} \mathbf{h}^H_{qq,i}\mathbf{w}_{q,j}u_{q,j}}_{\text{intracell interference}} \\ &\quad + \underbrace{\sum_{r\neq q}^{Q} \mathbf{h}^H_{rq,i}\mathbf{W}_r\mathbf{u}_r}_{\text{co-tier interference}} + \underbrace{\mathbf{h}^H_{0q,i}\mathbf{V}\mathbf{u}_0}_{\text{cross-tier interference}} + z_{q,i}, \end{aligned} \tag{3}$$

where $z_{q,i}$ is the AWGN with power σ^2. Thus, the received SINR at FUE-(q, i) is given by

$$\mathrm{SINR}_{q,i} = \frac{\left|\mathbf{h}_{qq,i}^H \mathbf{w}_{q,i}\right|^2}{\sum_{j\neq i}^{K_q} \left|\mathbf{h}_{qq,i}^H \mathbf{w}_{q,j}\right|^2 + \sum_{r\neq q}^{Q} \left\|\mathbf{W}_r^H \mathbf{h}_{rq,i}\right\|^2 + \left\|\mathbf{V}^H \mathbf{h}_{0q,i}\right\|^2 + \sigma^2}. \quad (4)$$

Given the target SINRs $\gamma_{0,i}$ at MUE-i and $\gamma_{q,i}$ at FUE-(q, i), $\forall i, \forall q$ as the QoS constraints, one may attempt to jointly optimize the beamformers across the BSs by the following power minimization problem

$$\begin{aligned} \underset{\mathbf{V},\mathbf{W}_1,\ldots,\mathbf{W}_Q}{\text{minimize}} \quad & \sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 + \sum_{q=1}^{Q}\sum_{i=1}^{K_q} \|\mathbf{w}_{q,i}\|^2 \\ \text{subject to} \quad & \mathrm{SINR}_{0,i} \geq \gamma_{0,i}, \quad \forall i \in \mathcal{F}_0 \\ & \mathrm{SINR}_{q,i} \geq \gamma_{q,i}, \quad \forall i \in \mathcal{F}_q, q=1,\ldots,Q. \end{aligned} \quad (5)$$

It is noted that problem (5) is a convex second-order conic program (SOCP), where the SINR constraints can be recast into SOC constraints. Thus, the problem can be efficiently solved by standard convex optimization techniques or specialized iterative algorithms [32].

Remark 1: There are situations in which problem (5) becomes infeasible. One example is the congested system where too many users want to communicate at the same time or where the number of users at a particular cell exceeds the number of transmit antennas at its BS (*e.g.*, $K_q > M_q$). In addition, imposing power constraints $\sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 \leq P_0$ and $\sum_{i=1}^{K_q} \|\mathbf{w}_{q,i}\|^2 \leq P_q, \forall q$ at the BSs also make problem (5) infeasible under high SINR targets. In any case of infeasibility, some of the users should be temporarily refused access to the system to support a feasible solution at which the desired QoS at admitted users is attainable [28]. It also makes sense to maximize the number of admitted users [27]. The dropped users may be admitted later when their channel conditions become more favorable. This admission/refusal procedure was termed as "congestion control" in [28] or "admission control" in [27]. In this work, we use the term "admission control" to describe the admission of FUEs to the considered HetNet. It should be emphasized that the proposed admission control schemes are performed at the physical layer based on instantaneous CSI conditions. This procedure is different from the "call admission control" which makes accept/reject decisions when new/handoff calls arrive [33].

B. PROBLEM STATEMENT

In the considered HetNet, the MUEs are prioritized in terms of QoS than the FUEs. Specifically, the SINR at MUE-i must always exceed a given target $\gamma_{0,i}$. This target SINR is assumed to be achievable when no femtocell is deployed. Our study is to schedule as many FUEs as possible without affecting the QoS of the MUEs via the optimization of the beamforming strategy $\mathbf{V}$ and $\{\mathbf{W}_1, \ldots, \mathbf{W}_Q\}$.

Mathematically, the problem can be described in two stages. In the first stage, one may attempt to select subsets of the FUEs with largest number of elements as

$$\begin{aligned} \mathcal{S}_1^o, \ldots, \mathcal{S}_Q^o = \underset{\mathbf{V},\mathbf{W}_q,\mathcal{S}_q\subset\mathcal{F}_q}{\arg\max} \quad & \sum_{q=1}^{Q} |\mathcal{S}_q| \\ \text{subject to} \quad & \mathrm{SINR}_{0,i} \geq \gamma_{0,i}, \quad \forall i \in \mathcal{F}_0 \\ & \mathrm{SINR}_{q,i} \geq \gamma_{q,i}, \quad \forall i \in \mathcal{S}_q, \forall q \\ & \sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 \leq P_0 \\ & \sum_{i\in\mathcal{S}_q} \left\|\mathbf{w}_{q,i}\right\|^2 \leq P_q, \forall q, \end{aligned} \quad (6)$$

where $\mathcal{S}_q \subset \mathcal{F}_q$ denotes the set of selected FUEs. In the second stage, the objective is to minimize the transmit power with a given set of FUEs from $\{\mathcal{S}_1^o, \ldots, \mathcal{S}_Q^o\}$ as

$$\begin{aligned} \underset{\mathbf{V},\{\mathbf{w}_{q,i}\}_{i\in\mathcal{S}_q^o}}{\text{minimize}} \quad & \sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 + \sum_{q=1}^{Q}\sum_{i\in\mathcal{S}_q^o} \|\mathbf{w}_{q,i}\|^2 \\ \text{subject to} \quad & \mathrm{SINR}_{0,i} \geq \gamma_{0,i}, \quad \forall i \in \mathcal{F}_0 \\ & \mathrm{SINR}_{q,i} \geq \gamma_{q,i}, \quad \forall i \in \mathcal{S}_q^o \\ & \sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 \leq P_0, \sum_{i\in\mathcal{S}_q^o} \left\|\mathbf{w}_{q,i}\right\|^2 \leq P_q, \quad \forall q. \end{aligned} \quad (7)$$

Note that the optimization at the second stage is a convex SOCP, like problem (5). Thus, problem (7) can be solved by standard convex optimization techniques or disciplined convex optimization solver, such as `cvx` [34]. However, a brute-force search might be required to find the optimal solution of the two-stage problem (6)–(7), where the SOCP (7) is solved each time for a subset of users. In fact, the joint downlink beamforming and admission control problem has been shown to be non-convex and NP-hard, even for a relatively simple single-cell setting [27]. Thus, it can be deduced from [27] that the overall two-stage problem (6)–(7) is also non-convex and NP-hard under the considered multi-tier multicell setting. In this work, our focus is on proposing algorithmic solution approaches that are capable of generating high quality suboptimal solutions. These approaches, classified into three schemes based on the levels of MBS-FBS coordination, are summarized in Table 1. The CSI requirement and implementation aspect of each scheme is also given in the table. Details of each scheme will be presented in subsequent sections.

III. SCHEME I: MULTIUSER ADMISSION CONTROL AND BEAMFORMING OPTIMIZATION WITH FULL COORDINATION

This section examines two solution approaches to the two-stage problem (6)–(7) that require full MBS-FBS coordination. In the first one, namely *Inflation-based approach*,

TABLE 1. Admission control and beamforming optimization strategies.

Scheme	Solution Approach	CSI requirement	Implementation
I - Full Coordination	Inflation-based Deflation-based	Full CSI of all channels at a centralized unit	**Centralized** - Admission control and beamforming decision passed to FBSs
II - Limited Coordination	Inflation-based Deflation-based	Local CSI at macrocell and femtocells, FBS-MUE CSI for ICI coordination	**Distributed** - Local admission control and beamforming decision at each FBS
III - No Coordination	ZF beamforming Power Control	Local CSI at macrocell and femtocells	**Distributed** - Local admission control and beamforming decision at each FBS

each FUE is admitted sequentially until no more feasible solution to problem (7) is found. In the second one, namely *Deflation-based approach*, all FUEs are admitted at first then the FUE with lowest SINR margin is sequentially dropped until a feasible solution to problem (7) is found.

A. INFLATION-BASED APPROACH

The principle of the inflation-based approach is quite straightforward: given already admitted FUEs, consider adding one more FUE (corresponding to the first stage) until the problem becomes infeasible [26]. When there is more than one option to admit a new FUE, it is natural to choose the new user which minimizes the sum transmit power at the MBS and FBSs. This greedy admission scheme is repeated until no more FUE can be admitted. We describe the inflation-based approach with joint optimization between the MBS and FBSs in the following algorithm.

Due to the M_q spatial degrees of freedom offered by FBS-q, at most a total of $M_{\text{total}} \triangleq \sum_{q=1}^{Q} M_q$ FUEs can be admitted across Q femtocells. At each instance in step 2) of Algorithm 1, one may need to generate up to $K_{\text{total}} \triangleq \sum_{q=1}^{Q} K_q$ candidate sets. Thus, the inflation approach may generate as many as $\sum_{i=0}^{M_{\text{total}}-1}(K_{\text{total}} - i) = M_{\text{total}}(2K_{\text{total}} + M_{\text{total}} - 1)/2$ candidate sets in order to admit the maximum M_{total} FUEs. Since problem (7) has to be solved for each candidate set, the inflation-based approach is prohibitively complex and becomes impractical for optimizing the HetNets with many co-located femtocells.

Algorithm 1 Inflation-Based Admission Control and Beamforming Design With Full Coordination

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1 Initialize $\mathcal{S}_q = \emptyset, \forall q$;

2 For a current set of admitted FUEs $\mathcal{S} = \mathcal{S}_1 \cup \ldots \cup \mathcal{S}_Q$, generate selected FUE set candidates as: $\mathcal{S}_q^i = \mathcal{S} \cup \{i\}$, where $i \in \mathcal{F}_q$;

3 For each candidate $\mathcal{S}_q^i$, solve the second-stage optimization problem (7);

4 **If** no feasible solution is found, **then** exit; **else** select the candidate $\mathcal{S}_{q^\star}^{i^\star}$ corresponding to FUE-$(q^\star, i^\star)$, which results in the lowest sum transmit power by

$$\mathcal{S}_{q^\star} = \mathcal{S}_{q^\star} \cup \{i^\star\}, \quad \mathcal{F}_{q^\star} = \mathcal{F}_{q^\star} \backslash \{i^\star\};$$

If $\mathcal{F}_q = \emptyset, \forall q$, **then** exit; **else** return to step 2;

B. DEFLATION-BASED APPROACH

In [27], the deflation approach was proposed as a simpler alternative to solve the problem of multiuser admission control and beamforming optimization in a single-cell system. The principle of the deflation approach is somewhat opposite to the inflation approach, where all users are admitted at first, and sequentially dropped until a feasible solution is found. In order to apply the deflation approach, the two-state optimization (6)–(7) is relaxed into a single-stage optimization problem as follows:

$$\begin{aligned}
\underset{\substack{\mathbf{v},\{\mathbf{w}_{q,i}\}_{i\in\mathcal{S}_q}\\ \{s_{q,i}\}_{i\in\mathcal{S}_q}}}{\text{minimize}} \quad & \sum_{i=1}^{K_0}\|\mathbf{v}_i\|^2 + \sum_{q=1}^{Q}\sum_{i\in\mathcal{S}_q}\|\mathbf{w}_{q_i}\|^2 + M\sum_{q=1}^{Q}\sum_{i\in\mathcal{S}_q} s_{q,i}^2\\
\text{subject to} \quad & \sqrt{1+\gamma_{0,i}}\,\mathbf{h}_{00,i}^H\mathbf{v}_i \\
& \geq \sqrt{\gamma_{0,i}}\left\|\begin{matrix}\mathbf{V}^H\mathbf{h}_{00,i}\\ \{\mathbf{h}_{q0,i}^H\mathbf{w}_{q,j}\}_{j\in\mathcal{S}_q}\\ \sigma\end{matrix}\right\|, \quad \forall i\in\mathcal{F}_0\\
& \sqrt{1+\gamma_{q,i}}\,\mathbf{h}_{qq,i}^H\mathbf{w}_{q,i} + s_{q,i}\\
& \geq \sqrt{\gamma_{q,i}}\left\|\begin{matrix}\mathbf{V}^H\mathbf{h}_{0q,i}\\ \{\mathbf{h}_{rq,i}^H\mathbf{w}_{r,j}\}_{j\in\mathcal{S}_r}\\ \sigma\end{matrix}\right\|, \quad \forall i\in\mathcal{S}_q, \forall q\\
& \sum_{i=1}^{K_0}\|\mathbf{v}_i\|^2 \leq P_0, \sum_{i\in\mathcal{S}_q}\left\|\mathbf{w}_{q,i}\right\|^2 \leq P_q, \quad \forall q, \qquad (8)
\end{aligned}$$

where M is a sufficiently large positive constant and $\mathcal{S}_q$ is the set of FUEs at femtocell-q under consideration for admission.[1] Herein, the SINR constraints are now recast into SOC sets, which are convex. Given that the objective functions and the power constraints are in convex quadratic form, problem (8) is a convex SOCP. Note that the auxiliary variable $s_{q,i}$ is added to the objective function and the SINR constraint of FUE-(q, i) as the penalty for dropping FUE-(q, i). In particular, due to the formulation of the objective function with large M, the optimization imposes s_{q_i}'s as close to 0 as possible. Whenever $s_{q_i} = 0$, the SINR constraint of FUE-(q, i) is feasible. On the contrary, a large s_{q_i} indicates infeasibility of the SINR constraint at FUE-(q, i). In this case, FUE-(q, i) should be dropped. This observation suggests that one FUE (with the largest s_{q_i}) is dropped one at a time until all the SINR constraints become feasible. We describe the deflation-based approach for the admission control of FUEs in Algorithm 2.

[1] In the simulation part, M set in the order of 10^3 is sufficient.

Algorithm 2 Deflation-Based Admission Control and Beamforming Design With Full Coordination

1 Initialize $\mathcal{S}_q = \mathcal{F}_q, \forall q$;
2 Solve the optimization problem (8) and let $\mathbf{v}_i^\star$ and $\mathbf{w}_{qi}^\star$ denote the resulting beamforming vectors;
3 For each $i \in \mathcal{S}_q, \forall q$, verify whether $\text{SINR}_{q,i} \geq \gamma_{q,i}$ holds;
4 **If** so, **then** exit; **else**, pick the FUE-$(q^\star, i^\star)$ with the lowest SINR margin, where $(q^\star, i^\star) = \arg\min_{q,i} \text{SINR}_{q,i}/\gamma_{q,i}$, and drop it from the corresponding set $\mathcal{S}_{q^\star}$. Return to step 2;
5 **If** $\mathcal{S}_q = \emptyset, \forall q$ (no feasible solution is found), **then** exit;

The choice for dropping FUE-$(q^\star, i^\star)$ in step 4 of Algorithm 2 is equivalent to dropping the FUE corresponding to the largest $s_{q,i}$. Intuitively, the deflation-based algorithm has lower complexity than the inflation-based algorithm because the former only needs to solve at most $\min(K_{\text{total}}, M_{\text{total}})$ instances of problem (8). Nevertheless, both solution approaches are highly complicated due to their centralized implementation. Essentially, a centralized unit with an optimization solver is required to execute the two algorithms. The centralized unit, likely the MBS, needs to possess the CSI knowledge of every channel in the network and then inform the admission control and beamforming decision back to each FBS. This implementation aspect demands *full coordination* among the MBS and FBSs. Thus, for randomly deployed and highly scalable HetNets, centralized implementation with a high level of coordination becomes impractical.

IV. SCHEME II: MULTIUSER ADMISSION CONTROL AND BEAMFORMING OPTIMIZATION WITH LIMITED COORDINATION

From the perspective of practical implementation, the MUEs are the primary occupants of the spectrum while the resource allocation for FUEs at the femtocell is only secondary. Thus, it is not necessary to have the MBS involved in admission control and beamforming optimization at the femtocells. Ideally, the operation of the macrocell remains unaffected by the transmissions from the femtocells. Instead, the MBS can offer limited coordination by minimizing its own transmit power and informing certain design parameters to the FBS. Each FBS then can determine its admission control and beamforming strategy for its FUEs in a distributed manner while protecting the QoS of the MUEs. In a nutshell, the proposed algorithm involves three steps:

A. The MBS calculates and informs the FBSs the maximum amount of cross-tier ICI that can be generated to the macrocell.
B. Each FBS independently composes a set of admissible FUEs which are potentially admitted later.
C. The MBS and the FBSs iteratively update their transmit powers until convergence. Certain FUEs from these admissible sets might be dropped by their connected FBS to maintain the power constraints at the MBS and FBSs as well as the QoS requirements of the MUEs and the admitted FUEs.

To this end, we address the details of the proposed algorithm.

A. CONSTRAINT ON THE CROSS-TIER ICI POWER INDUCED TO THE MACROCELL

Since the deployment of the femtocells will induce certain cross-tier ICI to the MUEs, it is important to constrain the level of cross-tier ICI under a limit that can be tolerated by the MUEs. Let $r_{0,i} = \sum_{q=1}^{Q} \left\| \mathbf{W}_q^H \mathbf{h}_{q0,i} \right\|^2$ denote the potential cross-tier ICI power induced by the FBSs to the MUE-i and $\mathbf{r}_0 \triangleq [r_{0,1}, \ldots, r_{0,K_0}]^T$. In order to establish the constraint on the cross-tier ICI power vector $\mathbf{r}_0$, we first present two following claims, which have been proved in [35].

Claim 1: Whenever the cross-tier ICI vector $\mathbf{r}_0$ *is changed, the MBS only needs to adjust the allocated power, but not the beam-patterns for its MUEs.*[2]

Per Claim 1, the MBS only needs to adapt its transmit power to compensate for the level of cross-tier ICI at its MUEs. By fixing the beam-patterns, the operation at macrocell can be significantly simplified in the presence of newly deployed femtocells. To first determine its beam-patterns, the MBS can consider the following optimization in the absence of the cross-tier ICI:

$$\begin{aligned} &\underset{\mathbf{v}_1,\ldots,\mathbf{v}_{K_0}}{\text{minimize}} \quad \sum_{i=1}^{K_0} \|\mathbf{v}_i\|^2 \\ &\text{subject to} \quad \frac{\left|\mathbf{h}_{00,i}^H \mathbf{v}_i\right|^2}{\sum_{j\neq i}^{K_0} \left|\mathbf{h}_{00,i}^H \mathbf{v}_j\right|^2 + \sigma^2} \geq \gamma_{0,i}, \quad \forall i \in \mathcal{F}_0, \end{aligned} \tag{9}$$

which can be optimally solved by various specialized iterative algorithms, such as [36] and [37]. Denote $\mathbf{v}_i^{(0)}$'s as the optimal solution to the above optimization problem. The beam-pattern for MUE-i then can be obtained as $\widetilde{\mathbf{v}}_i = \mathbf{v}_i^{(0)}/\|\mathbf{v}_i^{(0)}\|$, and the transmit power for MUE-i is given by $p_{0,i}^{(0)} = \|\mathbf{v}_i^{(0)}\|^2$. Due to the assumption that the QoS requirements at the MUEs are met at the first place, one has $\sum_{i=1}^{K_0} p_{0,i}^{(0)} \leq P_0$. In the presence of the cross-tier ICI, the MBS then adjusts its power allocation by solving the optimization

$$\begin{aligned} &\underset{p_{0,1},\ldots,p_{0,K_0}}{\text{minimize}} \quad \sum_{i=1}^{K_0} p_{0,i} \\ &\text{subject to} \quad \frac{p_{0,i}\left|\mathbf{h}_{00,i}^H \widetilde{\mathbf{v}}_i\right|^2}{\sum_{j\neq i}^{K_0} p_{0,j}\left|\mathbf{h}_{00,i}^H \widetilde{\mathbf{v}}_j\right|^2 + r_{0,i} + \sigma^2} \geq \gamma_{0,i}, \ \forall i \in \mathcal{F}_0, \end{aligned} \tag{10}$$

where $p_{0,i}$ is the allocated power for MUE-i. The optimal solution to problem (10) is given in the following claim [37].

Claim 2: Define a $K_0 \times K_0$ *matrix* $\mathbf{G}_0$ *where* $[\mathbf{G}_0]_{i,i} = (1/\gamma_{0,i})\left|\mathbf{h}_{00,i}^H \widetilde{\mathbf{v}}_i\right|^2$ *and* $[\mathbf{G}_0]_{i,j} = -\left|\mathbf{h}_{00,i}^H \widetilde{\mathbf{v}}_j\right|^2$ *if* $i \neq j$. *The optimal solution of (10),* $\mathbf{p}_0^\star = [p_{0,1}^\star, \ldots, p_{0,K_0}^\star]^T$,

[2] The beam-pattern for MUE-i is defined as the unit-norm vector $\mathbf{v}_i/\|\mathbf{v}_i\|$.

is given by

$$\mathbf{p}_0^\star = \mathbf{G}_0^{-1}\left(\mathbf{r}_0 + \mathbf{1}\sigma^2\right), \tag{11}$$

where $\mathbf{G}_0^{-1}$ *exists and is a positive component-wise matrix. Thus,* $\mathbf{p}_0^\star > 0, \forall \mathbf{r}_0 > 0$.

Clearly, with a change in the cross-tier ICI power vector $\mathbf{r}_0$, the MBS only needs to adjust its transmit power vector $\mathbf{p}_0$ as in (11). To ensure the feasibility of its power constraint $\sum_{i=1}^{K_0} p_{0,i} \le P_0$, one must have $\mathbf{1}^T\mathbf{G}_0^{-1}\left(\mathbf{r}_0 + \mathbf{1}\sigma^2\right) \le P_0$. Thus, the cross-tier ICI power vector $\mathbf{r}_0$ is constrained in the half-space defined by

$$\mathbf{1}^T\mathbf{G}_0^{-1}\mathbf{r}_0 \le P_0 - \mathbf{1}^T\mathbf{G}_0^{-1}\mathbf{1}\sigma^2 \Longleftrightarrow \mathbf{a}^T\mathbf{r}_0 \le P_0 - P_0^{(0)}, \tag{12}$$

where $\mathbf{a} = [a_1, \ldots, a_{K_0}]^T$ with $a_i = \sum_{j=1}^{K_0}\left[\mathbf{G}_0^{-1}\right]_{j,i}$, and $P_0^{(0)} = \mathbf{1}^T\mathbf{G}_0^{-1}\mathbf{1}\sigma^2 = \sum_{i=1}^{K_0} p_{0,i}^{(0)}$ is the sum transmit power at the MBS in the absence of the cross-tier ICI. Herein, a_i can be interpreted as the weight for the cross-tier ICI induced by the FBSs to MUE-i. From the above analysis, to concurrently satisfy the QoS requirements at the MUEs and the power constraint at the MBS, the weighted sum of the cross-tier ICI to the MUEs must not exceed $I_{\max} \triangleq P_0 - P_0^{(0)}$.

Remark 2: In order to impose constraint (12), the MBS needs to inform each FBS certain design parameters including: the weight vector $\mathbf{a}$ and the maximum amount of cross-tier ICI can be generated by the FBS. Let us denote I_q as the limit on cross-tier ICI generated by FBS-q. Certainly, it is required that $\sum_{q=1}^{Q} I_q \le I_{\max}$. After acquiring $\mathbf{a}$ and I_q, FBS-q can proceed to perform its admission control and beamforming decision on its connected FUEs, as will be shown in Sections IV-B and IV-C. The problem of adaptive allocation of I_q's among the FBSs will be addressed in Section IV-D.

B. THE SET OF ADMISSIBLE FUEs AT EACH FBS

At the femtocells, it is required that each FBS possesses its corresponding channels to MUEs in order to manage its inducing cross-tier ICI. Then, given the obtained information from the MBS, an FBS, say FBS-q, can constrain its inducing cross-tier ICI. In addition, the FBS also needs to acquire the channels to its FUEs and the current total cross-tier ICI plus noise (IPN) level at its FUEs to facilitate its beamforming and admission control strategy. Under the condition that the FBSs are *yet* to transmit, there is no co-tier ICI and the total IPN at FUE-(q, i) is given by $\left\|\mathbf{V}^H\mathbf{h}_{0q,i}\right\|^2 + \sigma^2$. This IPN level can be measured at the FUE-(q, i) and fed back to FBS-q. Given $\mathbf{W}_q$ as the beamforming matrix at FBS-q, the expected SINR at FUE-(q, i) with no co-tier ICI is given by

$$\widehat{\mathrm{SINR}}_{q,i} = \frac{\left|\mathbf{h}_{qq,i}^H\mathbf{w}_{q,i}\right|^2}{\sum_{j\neq i}^{K_q}\left|\mathbf{h}_{qq,i}^H\mathbf{w}_{q,j}\right|^2 + \left\|\mathbf{V}^H\mathbf{h}_{0q,i}\right\|^2 + \sigma^2}. \tag{13}$$

Based on the expected SINR at the FUEs, FBS-q can compose a list of admissible FUEs. Intuitively, the transmissions to these admissible FUEs should induce low cross-tier ICI to the macrocell while obtaining high SINRs at the receiving ends. To compose the admissible FUEs set, both the inflation- and deflation-based approaches can be applied as follows.

1) INFLATION-BASED APPROACH

The principle of the inflation-based algorithm here is similar to that in Section III-A. The distinction in the proposed distributed algorithm is that FBS-q makes the admission decision on its own with a new design criterion. Instead of choosing the admission control and beamforming strategy to minimize its own transmit power, the FBS also attempts to limit its inducing cross-tier ICI to the MBS. Specifically, for a candidate set $\mathcal{S}_q$, we consider the following optimization at FBS-q

$$\begin{aligned}
\underset{\{\mathbf{w}_{q,i}\}_{i\in\mathcal{S}_q}}{\text{minimize}}\ & \alpha_q\sum_{i\in\mathcal{S}_q}\|\mathbf{w}_{q,i}\|^2 + (1-\alpha_q)\sum_{j=1}^{K_0} a_j\sum_{i\in\mathcal{S}_q}\left|\mathbf{h}_{q0,j}^H\mathbf{w}_{q_i}\right|^2\\
\text{subject to}\ & \widehat{\mathrm{SINR}}_{q,i} \ge \gamma_{q,i}, \quad \forall i \in \mathcal{S}_q\\
& \sum_{i\in\mathcal{S}_q}\left\|\mathbf{w}_{q,i}\right\|^2 \le P_q\\
& \sum_{j=1}^{K_0} a_j\sum_{i\in\mathcal{S}_q}\left|\mathbf{h}_{q0,j}^H\mathbf{w}_{q_i}\right|^2 \le I_q.
\end{aligned} \tag{14}$$

Herein, the last constraint is on the cross-tier ICI generated by the FBS-q. The objective function, which includes the cross-tier ICI terms, is to encourage FBS-q to adapt a more cooperative beamforming strategy by reducing its cross-tier ICI. The weight $0 \le \alpha_q \le 1$ indicates the trade-off between minimizing the transmit power and the cross-tier ICI power. The candidate set, which jointly minimizes this weighted sum power, is then chosen. In the simulation part, w_q is set at 0.5.

2) DEFLATION-BASED APPROACH

In this approach, FBS-q initially admits all the FUEs within its cell coverage and sequentially drops the FUEs until a feasible solution is found. The auxiliary variable $s_{q,i}$ is added to the objective function and the SINR constraint of FUE-(q, i) as the penalty for dropping FUE-(q, i). Initializing $\mathcal{S}_q = \mathcal{F}_q$, then for a current set of admissible FUEs $\mathcal{S}_q$, consider the following optimization

$$\begin{aligned}
\underset{\substack{\{\mathbf{w}_{q,i}\}_{i\in\mathcal{S}_q}\\ \{s_{q,i}\}_{i\in\mathcal{S}_q}}}{\text{minimize}}\ & \alpha_q\sum_{i\in\mathcal{S}_q}\|\mathbf{w}_{q,i}\|^2 + (1-\alpha_q)\sum_{j=1}^{K_0} a_j\sum_{i\in\mathcal{S}_q}\left|\mathbf{h}_{q0,j}^H\mathbf{w}_{q,i}\right|^2\\
& + M\sum_{i\in\mathcal{S}_q} s_{q,i}^2\\
\text{subject to}\ & \sqrt{1+\gamma_{q,i}}\,\mathbf{h}_{qq,i}^H\mathbf{w}_{q,i} + s_i\\
& \ge \sqrt{\gamma_{q,i}}\left\|\frac{\{\mathbf{h}_{qq,i}^H\mathbf{w}_{q,j}\}_{j\in\mathcal{S}_q}}{\sqrt{\left\|\mathbf{V}^H\mathbf{h}_{0q,i}\right\|^2 + \sigma^2}}\right\|, \quad \forall i \in \mathcal{S}_q\\
& \sum_{i\in\mathcal{S}_q}\left\|\mathbf{w}_{q,i}\right\|^2 \le P_q\\
& \sum_{j=1}^{K_0} a_j\sum_{i\in\mathcal{S}_q}\left|\mathbf{h}_{q0,j}^H\mathbf{w}_{q,i}\right|^2 \le I_q.
\end{aligned} \tag{15}$$

For each $i \in \mathcal{S}_q$, it can be verified whether $\widehat{\text{SINR}}_{q,i} \geq \gamma_{q,i}$ holds. If so, exit; else, pick the user with the lowest SINR margin, defined as $\widehat{\text{SINR}}_{q,i}/\gamma_{q,i}$, and drop it from $\mathcal{S}_q$, then solve problem (15) with the current set of admissible FUEs $\mathcal{S}_q$. It is noted that one can apply the above inflation and deflation-based approaches to generate the set of admissible FUE set $\mathcal{S}_q$ as well as the beam-pattern for each FUE in the set, *i.e.*, $\widetilde{\mathbf{w}}_{q,i} = \mathbf{w}_{q,i}/\|\mathbf{w}_{q,i}\|, i \in \mathcal{S}_q$.

Remark 3: It is noted that both problems (14) and (15) can be recast into convex SOCP. Thus, both problems can be solved in polynomial time by the interior-point method [38]. Compared to the original joint optimization problems (7) and (8), both problems (14) and (15) are much simpler to solve due to their smaller dimensions. In addition, to independently compose the set $\mathcal{S}_q$, FBS-q only needs to solve at most $M_q(2K_q - M_q + 1)/2$ instances of problem (14) in the inflation-based approach or $\min(K_q, M_q)$ instances of problem (15) in the deflation-based approach.

C. ITERATIVE POWER UPDATE BETWEEN THE MBS AND THE FBS

Once the FBSs start transmitting to potentially admitted FUEs, the MBS needs to boost its transmit power as given in (11), which consequently increases the cross-tier ICI at the FUEs. To counter with the increasing cross-tier ICI from the MBS as well as the co-tier ICI from other FBSs, each FBS may need to re-optimize its beamforming design and power allocation strategy. Interestingly, Claims 1 and 2 are also applicable to the optimization at each FBS. Specifically,

- Per Claim 1, FBS-q only needs to adjust its allocated power for the FUEs in $\mathcal{S}_q$, but not the beam-patterns $\widetilde{\mathbf{w}}_{q,i}$'s.
- Per Claim 2, define $r_{q,i} = \left\|\mathbf{V}^H\mathbf{h}_{0q,i}\right\|^2 + \sum_{r\neq q}^{Q}\left\|\mathbf{W}_r^H\mathbf{h}_{rq,i}\right\|^2$ as the total cross-tier and co-tier ICI at FUE-(q,i) and define $\mathbf{r}_q = [\{r_{q,i}\}_{i\in\mathcal{S}_q}]^T$, the optimal power allocation strategy $\mathbf{p}_q^\star = [\{p_{q,i}\}_{i\in\mathcal{S}_q}]^T$ at FBS-q is given by

$$\mathbf{p}_q^\star = \mathbf{G}_q^{-1}\left(\mathbf{r}_q + \mathbf{1}\sigma^2\right), \tag{16}$$

where $\mathbf{G}_q \in \mathbb{R}^{|\mathcal{S}_q|\times|\mathcal{S}_q|}$, defined as $[\mathbf{G}_q]_{i,i} = (1/\gamma_{q,i})\left|\mathbf{h}_{qq,i}^H\widetilde{\mathbf{w}}_i\right|^2$, and $[\mathbf{G}_q]_{i,j} = -\left|\mathbf{h}_{qq,i}^H\widetilde{\mathbf{v}}_j\right|^2$ if $i \neq j$, is invertible and its inverse is component-wise positive.

Note that the power update (16) is to meet the QoS requirement at FUE-(q,i), $\forall i \in \mathcal{S}_q$. Initially, all FUEs in the set $\mathcal{S}_q$ are potentially admitted (at time-0). However, when the ICI vector $\mathbf{r}_q$ increases, it may be possible that the power constraint $\sum_{i\in\mathcal{S}_q}p_{q,i}^\star \leq P_q$ or the sum cross-tier ICI constraint $\sum_{j=1}^{K_0}a_j\sum_{i\in\mathcal{S}_q}p_{q,i}^\star\left|\mathbf{h}_{q0,j}^H\widetilde{\mathbf{w}}_{q,i}\right|^2 \leq I_q$ is violated. In order to enforce these constraints, one or more FUEs in $\mathcal{S}_q$ might be dropped by FBS-q.

Suppose $\mathbf{r}_q^{(t)}$ being the ICI vector at time-t, we propose a simple algorithm for admitting/dropping the FUEs at femtocell-q by slightly modifying the power update (16) at time-$(t+1)$ as follows:

$$\mathbf{p}_q^{(t+1)} = \Sigma_q^{(t+1)}\mathbf{G}_q^{-1}\left(\mathbf{r}_q^{(t)} + \mathbf{1}\sigma^2\right). \tag{17}$$

Herein, $\Sigma_q^{(t+1)}$ is a diagonal matrix where $[\Sigma_q^{(t+1)}]_{i,i} = 1$ indicates the admission of FUE-(q,i) and $[\Sigma_q^{(t+1)}]_{i,i} = 0$ indicates the removal of FUE-(q,i), where $p_{q,i}^{(t+1)}$ is set to 0. To determine $\Sigma_q^{(t+1)}$, a simple iterative procedure can be applied by the following criteria:

1) Initialize with $\Sigma_q^{(0)} = \mathbf{I}$ (admit all FUEs in $\mathcal{S}_q$). At time-$(t+1)$, initialize with $\Sigma_q^{(t+1)} = \Sigma_q^{(t)}$.
2) Update the allocated power as in (17). Validate the two constraints, **if** valid, **then** exit; **else**
   - **If** both constraints are violated, **then** find $i^\star = \arg\max_{i\in\mathcal{S}_q}p_{q,i}^{(t+1)}\left(1 + \sum_{j=1}^{K_0}a_j\left|\mathbf{h}_{q0,j}^H\widetilde{\mathbf{w}}_{q,i}\right|^2\right)$.
   - **If** only the power constraint is violated, **then** find $i^\star = \arg\max_{i\in\mathcal{S}_q}p_{q,i}^{(t+1)}$.
   - **If** only the ICI constraint is violated, **then** find $i^\star = \arg\max_{i\in\mathcal{S}q}p_{q,i}^{(t+1)}\sum_{j=1}^{K_0}a_j\left|\mathbf{h}_{q0,j}^H\widetilde{\mathbf{w}}_{q,i}\right|^2$.
3) Drop FUE-$(q,i^\star)$ by setting $[\Sigma_q^{(t+1)}]_{i^\star,i^\star} = 0$ and return to step 2).

The convergence of this iterative power update procedure is addressed in the following proposition.

Proposition 1: The power updates (11) *and* (17) *will converge to a fixed-point where the SINR requirements of the MUEs and the admitted FUEs are maintained, and the power constraints are complied.*

Proof: Firstly, rewrite the power updates (11) and (17) as

$$\mathbf{p}_0^{(t+1)} = \mathbf{G}_0^{-1}\left(\sum_{q=1}^{Q}\mathbf{G}_{q0}\mathbf{p}_q^{(t)} + \mathbf{1}\sigma^2\right) \tag{18}$$

$$\mathbf{p}_q^{(t+1)} = \Sigma_q^{(t+1)}\mathbf{G}_q^{-1}\left(\mathbf{G}_{0q}\mathbf{p}_0^{(t)} + \sum_{r\neq q}^{Q}\mathbf{G}_{rq}\mathbf{p}_r^{(t)} + \mathbf{1}\sigma^2\right), \quad q = 1,\ldots Q, \tag{19}$$

where $[\mathbf{G}_{0q}]_{i,j} = \left|\mathbf{h}_{0q,i}^H\widetilde{\mathbf{v}}_j\right|^2$, $[\mathbf{G}_{q0}]_{i,j} = \left|\mathbf{h}_{q0,i}^H\widetilde{\mathbf{w}}_{q,j}\right|^2$, and $[\mathbf{G}_{rq}]_{i,j} = \left|\mathbf{h}_{rq,i}^H\widetilde{\mathbf{w}}_{r,j}\right|^2$. Since the update of $\mathbf{p}_q^{(t+1)}$ involves the admission control for the FUEs by setting $\Sigma_q^{(t+1)}$, one has $\mathbf{1}^T\mathbf{p}_q^{(t+1)} \leq P_q$ to enforce the power constraint at the FBS-q. In addition, $\sum_{j=1}^{K_0}a_j\sum_{i\in\mathcal{S}_q}p_{q,i}^{(t+1)}\left|\mathbf{h}_{q0,j}^H\widetilde{\mathbf{w}}_{q,i}\right|^2 = \mathbf{1}^T\mathbf{G}_0^{-1}\mathbf{G}_{q0}\mathbf{p}_q^{(t+1)} \leq I_q$ and $\sum_{q=1}^{Q}I_q \leq I_{\max}$, which then guarantees the compliance of the power constraint at the MBS: $\mathbf{1}^T\mathbf{p}_0^{(t+2)} \leq I_{\max} + \mathbf{1}^T\mathbf{G}_0^{-1}\mathbf{1}\sigma^2 = P_0$ at all time.

For deterministic Σ_q's, it is straightforward to prove that the power update functions (18) and (19) are *standard* functions [39]. Thus, the power update (18)–(19) is guaranteed to converge to a fixed-point [39], if it exists. If a fixed-point does not exist, $\mathbf{p}_q^{(t)} \xrightarrow{t\to\infty} \infty, \forall q$. However, constraining $\mathbf{p}_q^{(t)}$ by setting $\Sigma_q^{(t)}$, $q = 1,\ldots,Q$ ensures the boundedness of the power update, which then guarantees the existence of a fixed-point. At the fixed-point, it can be deduced from equation (18) that the SINR at the MUE-i is exactly $\gamma_{0,i}$.

Similarly, equation (19) indicates that SINR at FUE-(q, i) is $\gamma_{q,i}$ when $\Sigma_q^{(t)} \overset{t\to\infty}{=} \mathbf{I}$, *i.e.*, all the FUEs in the admissible set $\mathcal{S}_q$ are admitted. If $\Sigma_q^{(t)} \overset{t\to\infty}{\neq} \mathbf{I}$, one or more elements in $\mathbf{p}_q$ will be 0, which indeed reduces the intra-user interference between the FUEs at femtocell-q. Thus, the SINR at an admitted FUE must be at least its target requirement. ∎

Algorithm 3 Joint Beamforming Design and Admission Control With Limited Coordination

1 At the MBS: calculate the weight vector $\mathbf{a}$ and the cross-tier ICI limits I_q's;

2 At FBS-q: compose the set of admissible FUEs $\mathcal{S}_q$ using either the inflation-based or the deflation-based approach with the informed I_q as its cross-tier ICI limit;

3 At the MBS and FBSs: iterative power update as given in (18) and (19) until convergence;

We summarize the three-step algorithm for joint admission control and beamforming optimization with limited coordination in Algorithm 3.

Remark 4: Each step of Algorithm 3 can be implemented in a fully distributed manner at the MBS and each FBS. The only intercell message exchange required is the sending of the design parameters $\mathbf{a}$ and I_q from the MBS to FBS-q in step 1) of the algorithm. Then, the admission control and power update procedure in step 2) and 3) of the algorithm can be carried out separately at each FBS *without* the need of MBS-FBS coordination. The CSI requirement is also less stringent than the full coordination approach in Algorithms 1 and 2. Specifically, the MBS only needs to know the CSI to the MUEs, whereas each FBS needs to know CSI to the FUEs within its cell coverage. Still, each FBS requires the CSI to the MUEs to control its cross-tier ICI.

D. ADAPTIVE ALLOCATION OF THE CROSS-TIER ICI LIMITS

In step 1) of Algorithm 3, the MBS needs to partition the amount of tolerable cross-tier ICI $I_{\max}$ into I_q's and allocate to the FBSs. Since I_q directly impacts the admission control decision at FBS-q, efficient partitioning of $I_{\max}$ potentially enhances the number of FUEs admitted across the Q femtocells. Clearly, the most straightforward way in partitioning I_q's is to give each FBS an equal share of $I_{\max}$, *i.e.*, $I_q = I_{\max}/Q$. Such allocation is then fixed during steps 2) and 3) of Algorithm 3. While the equal ICI limit allocation is simple to implement, it might be inefficient in many situations due to the nonuniform placements of FBSs and MUEs. For example,

- If an FBS is placed where no MUEs is located in the vicinity, the transmissions to its connected FUEs will generate negligible cross-tier ICI. An equal portion of $I_{\max}$ is probably redundant for the very FBS and should be re-allocated for other FBSs.
- If an FBS is placed nearby an MUE, a stringent cross-tier ICI limit may force the FBS to drop all of its FUEs.

Thus, the cross-tier ICI limits I_q's should be allocated adaptively to enhance the admission control decision at each FBS. Since the original two-step optimization problem (6)–(7) is nonconvex, obtaining an optimal allocation of the cross-tier ICI limits via dual decomposition [40] is not easy and well beyond the scope of this work.

In this section, we propose a heuristic iterative algorithm to adaptively allocate the cross-tier ICI limits among the multiple FBSs. Since each FBS does not know its final cross-tier ICI limit allocation; at first, each FBS composes its set of admissible FUEs using the limit $I_{\max}$, instead of $I_{\max}/Q$. At a current round of ICI allocation, say round-n, the MBS informs FBS-q its cross-tier ICI limit $I_q^{(n)}$, the MBS and FBSs iteratively update its power allocation strategies (18)–(19) until convergence. FBS-q then feeds back to the MBS its current inducing cross-tier ICI, denoted as $J_q^{(n)} \triangleq \sum_{j=1}^{K_0} a_j \sum_{i\in\mathcal{S}_q} p_{q,i} \left|\mathbf{h}_{q0,j}^H \widetilde{\mathbf{w}}_{q,i}\right|^2$. If FBS-$q$ has to drop an FUE from its admissible set $\mathcal{S}_q$ to ensure $J_q^{(n)} \leq I_q^{(n)}$, the FBS will also make a request to the MBS to increase its limit $I_q^{(n+1)}$ in the next round. The MBS then composes a set of FBSs making the ICI allocation request at round-n, denoted as $\mathcal{R}^{(n)}$.

In the following round of ICI allocation, if FBS-q does not belong to the set $\mathcal{R}^{(n)}$, $I_q^{(n+1)}$ will be set as $J_q^{(n)} + \epsilon$, where ϵ is a minute portion of $I_{\max}$. The remaining of the total cross-tier ICI limit $I_{\max}$ is shared equally among the FBSs in $\mathcal{R}^{(n)}$. Should more FUEs be admitted by the FBSs in $\mathcal{R}^{(n)}$, the amount of cross-tier and co-tier ICI in the network will certainly be increased. Thus, the small ICI limit gap ϵ allocated to the FBS-q, $\forall q \notin \mathcal{R}^{(n)}$ enables the FBS to compensate for the increased ICI without necessarily dropping any FUEs in its admissible set $\mathcal{S}_q$. The ICI allocation procedure stops at time-n if the number of requests do not reduce compared to time-$(n-1)$, *i.e.*, $|\mathcal{R}^{(n)}| \geq |\mathcal{R}^{(n-1)}|$. We summarize the above iterative procedure in Algorithm 4 as follows:

Remark 5: The re-allocation of the cross-tier ICI limits in step 11) of Algorithm 4 is to maintain $\sum_{q=1}^{Q} I_q^{(n+1)} \leq I_{\max}$. Thus, the QoS at the MUEs and the power constraint at the MBS are always guaranteed. Step 11) also provides the exit conditions for the algorithm when no more request is made or the number of requests does not decrease relatively to the previous round. We observe in simulations that the MBS only re-adjusts its allocation a few times to reach the exit conditions.

Remark 6: Compared to Algorithm 3, steps 1) and 2) of Algorithm 4 are similar to that of Algorithm 3. With deterministic I_q's at the exit conditions, the iterative step 7) in Algorithm 4 is similar to step 3) in Algorithm 3. Thus, Algorithm 4 is also guaranteed to converge. In terms of complexity, most of the computations in the two algorithms lie on step 2), where the optimization is taken to compose the admissible sets $\mathcal{S}_q$'s. The iterative power updates and the ICI re-allocation step only require simple matrix manipulations. However, Algorithm 4 demands more signaling exchange for the adaptive allocation of the cross-tier ICI limits I_q's.

Algorithm 4 Adaptive Allocation of Cross-Tier ICI Limits for Joint Beamforming Design and Admission Control With Limited Coordination

<u>*At the MBS:*</u> calculate the weight vector $\mathbf{a}$ and the total cross-tier ICI limit $I_{\max}$;
<u>*At FBS-q:*</u> compose the set of admissible FUEs $\mathcal{S}_q$ with $I_{\max}$ as its cross-tier ICI limit;
Initialize $I_q^{(0)} = I_{\max}/Q$;
repeat
- Set $n \leftarrow n+1$;
- MBS informs FBS-q the cross-tier ICI limit $I_q^{(n)}$;
- <u>*At the MBS and FBSs:*</u> iterative power update (18)–(19) until convergence;
- FBS-q informs the MBS its inducing cross-tier ICI $J_q^{(n)}$;
If $\Sigma_q \neq \mathbf{I}$ and $J_q^{(n)} \leq I_q^{(n)}$, **then** FBS-q makes a request to the MBS;
- MBS composes the set $\mathcal{R}^{(n)}$ of FBSs making the requests;
If $\mathcal{R}^{(n)} = \emptyset$ or $|\mathcal{R}^{(n)}| \geq |\mathcal{R}^{(n-1)}|$, **then** exit; **else** re-allocate the cross-tier ICI limits as

$$I_q^{(n+1)} = J_q^{(n)} + \epsilon, \forall q \notin \mathcal{R}^{(n)} \tag{20}$$

$$I_r^{(n+1)} = \frac{I_{\max} - \sum_{q \notin \mathcal{R}^{(n)}} I_q^{(n+1)}}{|\mathcal{R}^{(n)}|}, \forall r \in \mathcal{R}^{(n)}. \tag{21}$$

until *convergence*;

Remark 7: The proposed framework in Algorithm 4 is also applicable when additional FBSs are deployed. Ideally, the deployment of new FBSs should not disturb the normal operation of the macrocell cell and existing femtocells [17]. Instead of re-optimizing the whole network, the MBS can adaptively allocate the cross-tier ICI limits among the existing FBS and the newly deployed ones. Specifically, the cross-tier ICI limit allocated to an existing FBS, say FBS-q, is based on its current inducing ICI level, where $I_q = J_q + \epsilon$. The remaining of the total cross-tier ICI limit $I_{\max}$ is then allocated equally to the newly deployed femtocells. Subsequently, these newly deployed FBS can make the decision on their admission control and beamformers with the informed cross-tier ICI limits. The transmit powers across the MBS, existing FBSs, and newly deployed FBSs are then iteratively updated in a distributed manner until convergence.

V. SCHEME III: MULTIUSER ADMISSION CONTROL AND ZERO-FORCING BEAMFORMING WITH NO COORDINATION

This section is concerned with a simple admission control and beamforming strategy in which no coordination or signaling between the MBS and FBSs is required. Due to the lack of MBS-FBS coordination, each FBS does not necessarily know the limit on its inducing cross-tier ICI. Instead, each FBS needs to suppress its cross-tier ICI to maintain the QoS at the MUEs. However, if an FBS is to fully eliminate its cross-tier ICI by spatial precoding, it might not have any spatial dimensions available for scheduling its own FUEs. On the other hand, should the FBS cancel the cross-tier ICI only to nearby MUEs, it is not only able to serve the FUEs within its coverage region, but also circumvent the undesirable *dead zone* issue to the nearby MUEs.

Considering the optimization at femtocell-q, let us denote $\mathcal{F}_{0,q} \subset \mathcal{F}_0$ as the set of MUEs in the expanded coverage region of FBS-q. Our proposed beamforming design is to maintain no cross-tier ICI to the MUEs in $\mathcal{F}_{0,q}$, *i.e.*, $\mathbf{h}_{q0,j}^H \mathbf{w}_{q,i} = 0, \forall j \in \mathcal{F}_{0,q}$. Thus, $\mathbf{w}_{q,i}$'s must be in the null space created by $\hat{\mathbf{H}}_{q0} \triangleq \left[\{\mathbf{h}_{q0,j}\}_{j \in \mathcal{F}_{0,q}}\right]^H$. Denote the singular value decomposition of the $|\mathcal{F}_{0,q}| \times M_q$ matrix $\hat{\mathbf{H}}_{q0}$ as

$$\hat{\mathbf{H}}_{q0} = \mathbf{U}_q \Sigma_q \mathbf{V}_q^H = \mathbf{U}_q \left[\tilde{\Sigma}_q,\ \mathbf{0}\right] \begin{bmatrix} \tilde{\mathbf{V}}_q^H \\ \hat{\mathbf{V}}_q^H \end{bmatrix}, \tag{22}$$

any precoding vector $\mathbf{w}_{q,i}$ in the form of $\hat{\mathbf{V}}_q \hat{\mathbf{w}}_{q,i}$ would make $\hat{\mathbf{H}}_{q0} \mathbf{w}_{q,i} = \mathbf{0}$, where $\hat{\mathbf{w}}_{q,i}$ is an arbitrary length-$(M_q - |\mathcal{F}_{0,q}|)$ vector. Thus, we have $M_q - |\mathcal{F}_{0,q}|$ spatial degrees of freedom for FUE scheduling at femtocell-q. In addition to zero-forcing the cross-tier ICI to the MUEs within its expanded coverage region, FBS-q can also utilize ZF precoding to suppress all intracell interference to its scheduled FUEs.

Note that $\hat{\mathbf{h}}_{qq,i} \triangleq \hat{\mathbf{V}}_q^H \mathbf{h}_{qq,i}$ can be regarded as the equivalent channel vector from FBS-q to FUE-(q,i). Because the FBSs are not transmitting yet, the total IPN at FUE-(q,i) can be measured as $\left\|\mathbf{V}^H \mathbf{h}_{0q,i}\right\|^2 + \sigma^2$ and fed back to FBS-q. Denote $\hat{\mathbf{H}}_{qq} = [\hat{\mathbf{h}}_{qq,1}, \ldots, \hat{\mathbf{h}}_{qq,K_q}]^H$ and $\hat{\mathbf{W}}_q = [\hat{\mathbf{w}}_{q,1}, \ldots, \hat{\mathbf{w}}_{q,K_q}]$. Given the equivalent channel $\hat{\mathbf{H}}_{qq,i}$, the total IPN at its FUEs, and the power budget P_q, the next step is to jointly design the ZF precoder $\hat{\mathbf{W}}_q$ and compose the set of potentially admitted FUEs $\mathcal{S}_q$ at FBS-q. For a given set $\mathcal{S}_q$, the ZF precoder $\hat{\mathbf{W}}_q$ can be obtained by channel inversion

$$\hat{\mathbf{W}}_q(\mathcal{S}_q) = \hat{\mathbf{H}}_{qq}(\mathcal{S}_q)^H \left(\hat{\mathbf{H}}_{qq}(\mathcal{S}_q)\hat{\mathbf{H}}_{qq}(\mathcal{S}_q)^H\right)^{-1} \mathbf{\Delta}^{1/2}, \tag{23}$$

where $\mathbf{\Delta} = \mathrm{diag}(\{\delta_i\}_{i \in \mathcal{S}_q})$ contains the power scaling factors for scheduled FUEs. In order to meet the target SINR $\gamma_{q,i}$ at FUE-(q,i), with $i \in \mathcal{S}_q$, δ_i can be determined as

$$\delta_i = \gamma_i \left(\left\| \mathbf{V}^H \mathbf{h}_{0q,i} \right\|^2 + \sigma^2 \right). \tag{24}$$

As a result, the allocated power for FUE-(q,i) is given by

$$p_{q,i}(\mathcal{S}_q) = \left[\left(\hat{\mathbf{H}}_{qq}(\mathcal{S}_q)\hat{\mathbf{H}}_{qq}(\mathcal{S}_q)^H \right)^{-1} \right]_{i,i} \delta_i. \tag{25}$$

To compose the set $\mathcal{S}_q$ under the power constraint $\sum_{i \in \mathcal{S}_q} p_{q,i}(\mathcal{S}_q) \leq P_q$, we can apply the inflation-based approach to sequentially admit the FUEs as follows:

1) Initialize: $\mathcal{S}_q = \emptyset$.
2) **While** $|\mathcal{S}_q| < M - |\mathcal{F}_{0,q}|$: **For** $j \in \mathcal{F}_q$, let $\mathcal{S}_q^j = \mathcal{S}_q \cup \{j\}$, compute the ZF precoder $\hat{\mathbf{W}}_q(\mathcal{S}_q^j)$ as given

in (23) and (24), and the allocated power $p_{q,i}(\mathcal{S}_q^j)$ as given in (25).

3) Select the FUE-(q, j) as follows: Find

$$j^\star = \arg\min_{j\in\mathcal{F}_q} \sum_{i\in\mathcal{S}_q^j} p_{q,i}(\mathcal{S}_q^j). \tag{26}$$

If $\sum_{i\in\mathcal{S}_q^{j^\star}} p_{q,i}(\mathcal{S}_q^{j^\star}) > P_q$, **then** stop; **else** admit FUE-$(q, j^\star)$ as

$$\mathcal{S}_q = \mathcal{S}_q \cup \{j^\star\}; \quad \mathcal{F}_q = \mathcal{F}_q \backslash \{j^\star\}, \tag{27}$$

and return to step 2).

Compared to the inflation-based approach with SOCP in Section IV-B, the above procedure is much simpler to implement. This is because the ZF precoder only involves simple matrix manipulations.

Similar to the analysis in Section IV-C, once the FBSs start transmitting, the MBS may increase its transmit power to compensate for the cross-tier ICI. Likewise, each FBS also needs to boost its transmit power to deal with new sources of cross-tier and co-tier ICI. To maintain the SINR target for admitted FUEs, the same power update mechanism in Equation (17) can be applied at FBS-q. Moreover, to keep its transmit power below P_q, certain FUEs in $\mathcal{S}_q$ might be dropped by fine-tuning $\mathbf{\Sigma}_q$. The MBS and FBSs then iteratively update their transmit powers using (18) and (19), respectively, in a fully distributed manner without any coordination.

Remark 8: Due to the boundedness on the transmit power at the FBSs, the iterative power update (18)–(19) is guaranteed to converge, according to Proposition 1. Moreover, the SINR requirements of the MUEs and the admitted FUEs are also satisfied at convergence. While the transmit power at each FBS, say FBS-q, is kept below its limit P_q, there is no such guarantee on the transmit power at the MBS. This is because the FBSs do not coordinate to keep the total cross-tier ICI below $I_{\max}$ in the considered joint ZF beamforming and admission control scheme. Thus, if the MBS is to exceed its power limit P_0 to maintain the MUE's QoS, the MBS can simply broadcast an alarm beacon. Upon receiving the beacon, any FBS within the macrocell coverage then needs to back off its transmit power.[3] A simple power back-off strategy at a particular FBS is to remove the FUE which consumes the highest power level at the FBS. Effectively, the cross-tier ICI will be reduced and the QoS at MUEs can be quickly restored. However, concurrent FUE removals across all the FBSs can yield poor performance because too many FUEs could be unnecessarily removed. Instead, we propose a probabilistic removal scheme to slow down this FUE removal procedure. Specifically, when receiving the beacon, FBS-q only sets $[\mathbf{\Sigma}_q]_{i^\star,i^\star} \to 0$ with a pre-defined probability ρ, where $i^\star = \arg\max_{i\in\mathcal{S}_q} p_{q,i}$. The FUEs are dropped across the femtocells until no more beacon is sent/received. We summarize the proposed admission control and ZF beamforming scheme in the following algorithm.

[3] While no coordination is assumed between the MBS and the FBSs, being the secondary users, the FBSs are still required to maintain the operation at the MUEs.

Algorithm 5 Joint Admission Control and ZF Beamforming With No Coordination

1 At FBS-q, $\forall q$: compose the set of admissible FUEs $\mathcal{S}_q$ using the inflation-based approach with ZF precoding, while nulling the cross-tier ICI to the FUEs within its extended coverage region;
2 Power update across MBS and FBSs;
3 **repeat**
4 - Set $t \longleftarrow t+1$;
5 - *At the MBS:* update $\mathbf{p}_0^{(t+1)}$ as given in (18). **If** $\mathbf{1}^T\mathbf{p}_0^{(t+1)} > P_0$, **then** send an alarm beacon;
6 - *At FBS-q:* update $\mathbf{p}_q^{(t+1)}$ as given in (19), where $\mathbf{\Sigma}^{(t+1)}$ is set to enforce $\mathbf{1}^T\mathbf{p}_q^{(t+1)} \le P_q$. **If** a beacon is received, **then** with a pre-defined probability ρ, set $[\mathbf{\Sigma}_q]_{i^\star,i^\star} \to 0$, where $i^\star = \arg\max_{i\in\mathcal{S}_q} p_{q,i}^{(t+1)}$;
7 **until** *convergence*;

Remark 9: The above Algorithm 5 can be applied to the HetNets where the FBSs cannot acquire the CSI to the MUEs. In these cases, $\hat{\mathbf{V}}_q$'s are simply set as identity matrices. The FBSs then can rely on the power control step 2)-6) of Algorithm 5 to manage the cross-tier ICI and maintain the QoS at the MUEs.

TABLE 2. Simulation parameters and settings.

Parameter	Value
Carrier frequency f_c	2.5 GHz
AWGN power	-104 dBm
MBS transmit power	43 dBm
FBS transmit power	33 dBm
Shadowing	6 dB
Wall-loss	5 dB

VI. SIMULATION RESULTS

This section presents simulation results to illustrate the performances of the proposed algorithms in terms of the average number of FUEs served and the average sum transmit power per FUE served. The simulation parameters, based on the LTE-Advanced physical layer architecture [41], are summarized in Table 2. We consider a HetNet where the coverage of each femtocell (with radius of 50m) is within the macrocell coverage (with radius of 500m). The expanded coverage region is set with the radius of 150m from the FBS. Each channel vector is generated from i.i.d. Gaussian random variables using the path loss model. The path loss in dB is defined as $PL(d_{ij}) = A_i \log_{10}(d_{ij}) + B_i + C\log_{10}(f_c/5) + W_l n_{ij} + S$, where d_{ij} is the distance from the BS to the UE under consideration; (A_i, B_i) are set as $(18.7, 46.8)$ and $(42, 31.46)$ for the UEs locating inside and outside the femtocells, respectively; $C = 20$; W_l is the wall-loss set at 5 dB; n_{ij} is the number of walls between the BS and the UE; and S models the shadowing effect. We assume that each FBS/MBS is equipped with 4 antennas. There are 4 randomly located MUEs being served by the MBS at the SINR requirement of 15 dB. Our objective is to serve as many FUEs out of 6 randomly located FUEs under the coverage of each FBS.

In the first set of simulations, we consider the HetNet with one femtocell whose FBS is located at a distance 200m from the MBS. Note that the cross-tier ICI limit $I_{\max}$ can be fully allocated to the sole FBS. Our objective in these simulations is to compare the performances of the optimal exhaustive search to the three solution approaches: Scheme I with full MBS-FBS coordination (Algorithms 1 and 2), Scheme II with limited MBS-FBS coordination (Algorithm 3), and Scheme III with no MBS-FBS coordination (Algorithm 5). In Scheme III, we consider 2 scenarios: ''Scheme III - ICI Suppression'' is applied when the FBS knows the CSI to its nearby MUEs and tries to suppress its cross-tier ICI, and ''Scheme III - Power Control'' is applied when the FBS does not know the CSI to the FUEs and relies only to power control to manage its cross-tier ICI as in step 2) of Algorithm 5.

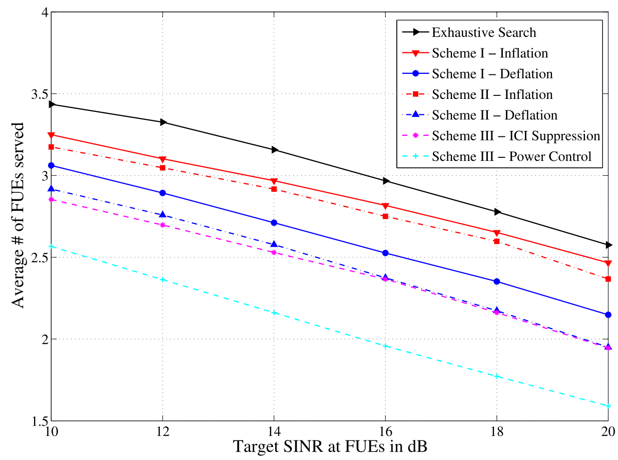

FIGURE 2. Average number of FUEs served *vs.* target SINR at the FUEs served with *d* = 200 m.

Figures 2 and 3 display the average number of FUEs served and the average sum transmit power per FUE served *versus* the target SINR at the FUEs. As can be seen in Figure 2, the increasing target SINR undoubtedly reduces the number of FUEs admitted. Interestingly, the inflation-based admission control approaches can yield the performances very close to the optimal exhaustive search. Within the same inflation-based admission control, a higher level of coordination results in a higher number of FUEs being served. However, the inflation-based Algorithm 3 with limited coordination performs comparably to the fully centralized Algorithm 1. Due to the suboptimal ZF beamforming and the lack of MBS-FBS coordination, Algorithm 5 is noticeably outperformed by the inflation-based Algorithm 3, where the beamformers are optimally obtained from SOCP. Nevertheless, being aware of nearby MUEs and performing cross-tier ICI suppression, the ZF-based admission control scheme can obtain a superior performance over the scheme with power control only.

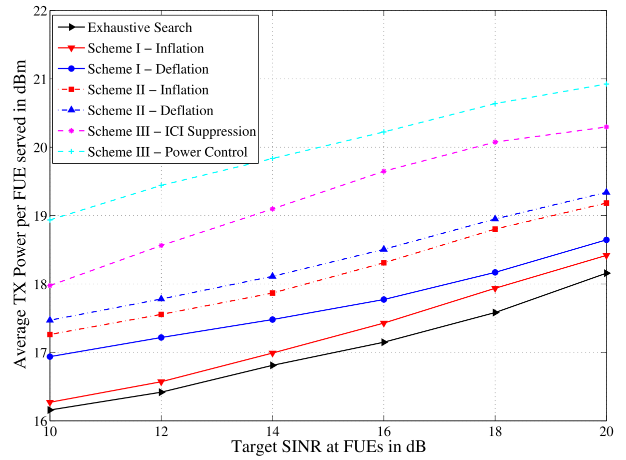

FIGURE 3. Average sum transmit power per FUE served *vs.* target SINR at the FUEs served with *d* = 200 m.

From Figure 3, an increase in the sum transmit power consumption at the MBS and FBS is observed when the QoS requirement of admitted FUEs becomes higher. Clearly, the algorithms in Scheme I outperform their counterparts in Schemes II and III, because the former jointly coordinate the beamforming optimization across the network. However, only less than 1 dB advantage in power usage is observed by using full MBS-FBS coordination. It is worth mentioning that this extra performance comes at the drawbacks of increased computational complexity and signaling due to the higher level of coordination.

In the next simulation, we consider the network where 10s of femtocells are deployed within the coverage of an MBS. Figure 4 displays the number of FUEs served *versus* the number of femtocells being deployed and compares the results obtained from the equal cross-tier ICI allocation (in conjunction with Algorithm 3), the adaptive cross-tier ICI allocation (Algorithm 4), and scheme with no cross-tier ICI allocation (Algorithm 5). Due to the excessive computation to implement the exhaustive search, as well as Algorithms 1 and 2, the optimal results and the ones obtained with full MBS-FBS coordination are not given in the figure. As observed from the figure, when more femtocells are being deployed, more FUEs are being served subject to the MBS-FBS coordination. Interestingly, the performance of the joint ZF beamforming and admission control scheme scales at much lower rate than other schemes and tends to saturate at high numbers of femtocells. This is because the proposed algorithms in Scheme III do not effectively coordinate all cross-tier ICI sources, whose effect becomes more pronounced with more femtocells being deployed. In fact, if only power control is

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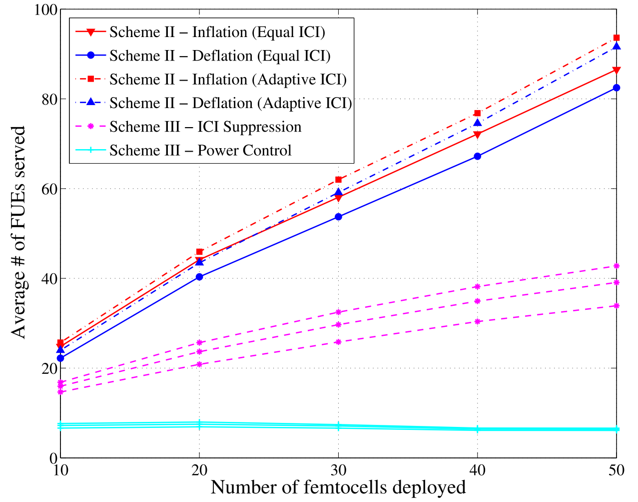

FIGURE 4. Average number of FUEs served *vs.* number of femtocell deployed.

employed at the FBSs, the number of admitted FUEs tends to decrease in denser femtocell deployment. It is also observed in the figure that applying adaptive cross-tier ICI allocation schemes do help to increase the number of FUEs served by the FBSs. On the other hand, dropping the FUEs at a slower rate (smaller ρ) allows more FUEs to be admitted in Scheme III.

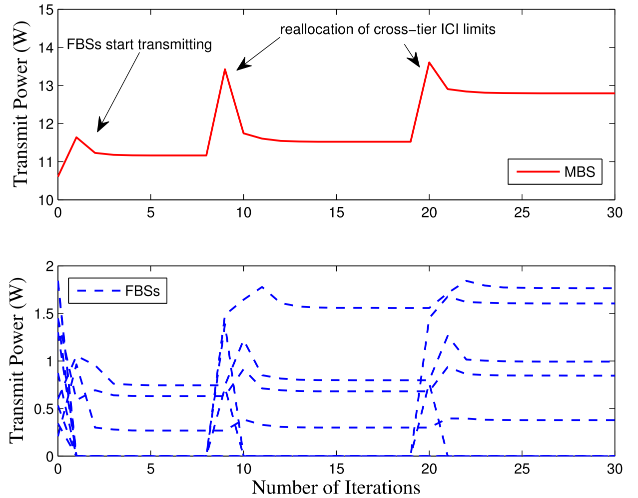

FIGURE 5. The convergence of Algorithm 4 with adaptive allocation of the cross-tier ICI limits and iterative MBS-FBS power updates.

Finally, for a specific channel realization, Figure 5 illustrates the convergence of the adaptive allocation of cross-tier ICI limits and iterative MBS-FBS power updates steps in the proposed Algorithm 4. Presumptively, each FBS has already composed the set of admissible FUEs. By setting $\mathbf{\Sigma}_q$'s, the power update step in Algorithm 5 is similar to that in Algorithm 3. Since Algorithm 3 can be considered as part of Algorithm 4, the figure also illustrates the convergence of Algorithm 3 and 5, as proved in Proposition 1. It is observed that once the FBS starts transmitting, the MBS has to increase its transmit power to compensate for cross-tier ICI. The power updates between the MBS and the FBSs converge within a few iterations. Once the FBS re-allocates the cross-tier ICI limits, some of FBSs can boost its transmit power and admit more FUEs. In overall, Algorithm 4 converges quickly within of 10 iterations and a couple of cross-tier ICI re-allocations. It is noted that the transmit powers at the MBS and the FBSs are maintained below their limits of 20 W (43 dBm) and 2 W (13 dBm), respectively, at all time.

VII. CONCLUSION

This work has studied the joint multiuser downlink beamforming design and admission control in MISO HetNets. With the objective of serving as many FUEs as possible while protecting the operation at the macrocell, we have proposed three main solution approaches: centralized with full MBS-FBS coordination (Scheme I), distributed with limited MBS-FBS coordination (Scheme II), and distributed with no MBS-FBS coordination (Scheme III). In Scheme I, the multiuser admission control and beamforming optimization are jointly performed by a centralized unit. In Scheme II, the admission control and beamforming decision is made independently at each FBS while maintaining the inducing cross-tier ICI limits. We also proposed an adaptive scheme in allocating the cross-tier ICI limits among the FBSs. In Scheme III, each FBS attempts to suppress all the cross-tier ICI to the MUEs within its expanded coverage region by means of ZF precoding. Simulation results have showed a similar performance by the distributed algorithms to that of the centralized counterparts in terms of number of FUEs served as well as the optimal exhaustive search. With a small penalty on the network power usage, the distributed algorithms in Schemes II offer much less complexity to the optimization of the HetNets. Simulation results have also showed an improvement in the number of FUEs served by using the proposed distributed algorithm with adaptive allocation of cross-tier ICI limits.

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