Joint Power Coordination for Spectral-and-Energy Efficiency in Heterogeneous Small Cell Networks: A Bargaining Game-Theoretic Perspective

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***Abstract*—Extensive deployment of small cells in heterogenous cellular networks introduces both challenges and opportunities. Challenges come with the reuse of the limited frequency resource for improving spectral efficiency, which always introduces serious mutual inter- and intracell interference between or among small cells and macrocells. The opportunities refer to more potential chances of inter- and intratier cooperations among small cells and macrocells. Energy efficiency will be a critical performance requirement for future green communications, especially when small cells are densely deployed to enhance the quality of user's experience. We exploit the potential cooperation diversities to combat the interference and energy management challenges. To capture the complicated interference interaction and also the possible coordination behavior among small cells and macrocells, this paper proposes a novel bargaining cooperative game (BCG) framework for energy efficient and interference-aware power coordination in a dense small cell network. In particular, a new adjustable utility function is employed in the BCG framework to jointly address both the spectral efficiency and energy efficiency issues. Using the BCG framework, we then derive the closed-form power coordination solutions and further propose a joint interference-aware power coordination scheme (Joint) with the considerations of both interference mitigation and energy saving. Moreover, a simplified algorithm (Simplified) is presented to combat the heavy signaling overhead, which is one of the significant challenges in the scenario of extensive deployment of small cells. Finally, numerical results are provided to illustrate the effectiveness of the proposed Joint and Simplified schemes.**

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I. Introduction

WITH the prevalence of smart mobile devices, such as smart phones, tablets and ultra-portable laptops, and the subsequent explosive growth of mobile applications, people now enjoy the benefits of accessing diverse data services, such as video, online gaming and group chatting on the move. To support the ever-increasing communication service demand with satisfied user experience, the capacity of wireless communication networks needs to increase accordingly. In general, communication capacity could be increased in the following three directions, improving the air interface in the physical layer, acquiring new spectrum, and improving the network architecture [1], [2].

A heterogenous network (HetNet), where multiple smallcell eNodeBs (SeNBs) are overlaid on the coverage of a macrocell eNodeB (MeNB), has been regarded as a very promising technique for traffic offloading, coverage optimization, spectral efficiency (SE) improvement and also capacity enhancement in future cellular wireless networks. Here, the smallcell is a general term adopted in LTE networks to refer to femtocells and picocells with coverage radius in the range of 10–300 m [3]–[5]. There are three different frequency channel deployment cases, where multiple SeNBs and the MeNB can fully share, partially share, or orthogonally use the spectrum resource. When deployed in an orthogonally used or partially shared frequency band, the cell deployment strategy, resource allocation strategy among small cells and interference cancelation strategy should be properly designed. When deployed in the fully shared band as macro cells (co-channel case), further issues such as mobile association, interference and radio resource management between macro and small cells should be looked into carefully. In this work, we concentrate on the co-channel case, which is the full spectrum sharing case.

Although HetNets hold great promises for achieving higher SE by exploiting both spatial and universal frequency reuse, coexistence of multiple SeNBs and MeNB in the same coverage area of a HetNet makes the mutual interference control a significant problem [6]. Therefore, interference-aware power coordination among SeNBs and MeNB serves as a critical issue for mitigating both inter-tier and intra-tier interference and thus ensuring SE performance which is highly related to Signal-to-Interference plus Noise Ratio (SINR) [7]–[11]. The conventional convex optimization-based power control schemes usually rely on a central controller to achieve the optimal power allocation, which always incurs significant signaling overhead and thus is not really suitable for the distributed LTE HetNets scenario. Certainly, there are several distributed utility-maximization-based power control schemes [9]–[11]. The work in [7] indicates that self-configuration and self-optimization techniques are suited for power control and interference avoidance in the distributed HetNets. It is notable that game theory provides a natural model to handle multiple and interactively interfered entities attempting to make a decision and seeking a solution state that distributively maximizes each entity's utility [12]–[15]. In this work, we focus on the game-theoretic approach in formulating the complicated interactions among MeNB and multiple SeNBs in a HetNet.

A. Research Activities Based on Game Theory

Available works on game theory-based power coordination and SE optimization in HetNets usually adopt a non-cooperation game-theoretic approach. In [12], a non-cooperative game theory-based method was developed for transmit power adaptation and inter-cell interference reduction. The work in [13] adopted a potential game approach for performance analysis of downlink multi-cell orthogonal frequency-division multiple access (OFDMA) systems. Through a femto-tier non-cooperative game formulation, authors in [14] explored the optimal power allocation under the generalized interference constraints. It is noted that the solutions presented in [12]–[14] are essentially all based on the Nash non-cooperative game approach. On the other hand, by considering the MeNB as leader and SeNBs as followers, and allowing the leader to sell its withstanding interference quota to followers, several non-cooperative Stackelberg game-theoretic methods have been presented for avoiding high interference power from SeNBs to the MeNB [15]–[17]. The work in [15] investigated the downlink power allocation in OFDMA femtocell networks, the work in [16] dealt with the pricing function design, and the work in [17] intended to protect the leader MeNB by pricing the interference from SeNBs's users.

Note that the above strategic non-cooperative Nash game [12]–[14] and hierarchical Stackelberg game [15]–[17] for power coordination in HetNets, although simple can reflect the hierarchical relationship between MeNB and SeNBs. These strategies all fail to capture the inherent coordination behaviors among SeNBs and MeNB and thus usually lead to non-optimal power coordination solutions. Recently, some techniques have been introduced to improve the Pareto-optimality of the above non-cooperative game theoretic formulations, such as pricing [16]–[18], virtual referee [19], new repeated game [20] and pricing of interference [21]–[23]. However, an accurate pricing usually requires excessive information exchange or aggregation, and thus incurs significant wireless/wired backhauling overhead in HetNets. Also, adopting pricing may lead to a slow convergent or even divergent power coordination algorithm.

On one hand, node players in a non-cooperative game are rational and selfish to maximize their individual utility, which always leads to a non-Pareto optimal solution [24]. For instance, in the power coordination formulation, any small cell's power level increase will not always improve the SINR performance since the other small cells will implement the same strategy, thus introducing more interference to each other. On the other hand, it is obvious that it can not guarantee the fairness among different small cells. However, cooperative game theory can improve the Pareto-optima, which has been proved by Nash in the economic field, and extensively be used in the wireless communication community. Bargaining cooperative game is defined via an axiomatic way, and the social optimal solution is proved to be achieved by maximizing a Nash-product-formed utility function [25]–[29].

As discussed in [25], another limitation of available game-based power coordination for HetNets is that most of the previous research attempts mainly focused on spectrum sharing and interference avoidance for ensuring the SE performance, while the energy efficiency (EE), another critical performance metric in HetNets, has been largely neglected in available SE-oriented power coordination solutions [13]–[18]. Some recent works indicate that the energy efficiency will be a significant requirement of future HetNets, especially when SeNBs/MeNB are densely deployed to ensure quality of experience [30]. In [31], heterogeneous networks, cognitive radios and smart grid were jointly applied to improve energy efficiency. The work in [32] investigated a non-cooperative game approach for energy-efficient power optimization, while the work in [33] addressed the fundamental tradeoff between EE and SE in downlink OFDMA networks. The work in [34] explored the trade-off between traffic offloading from the MeNB and the energy consumption of SeNBs in a cognitive small cell network.

From the above literature scan, we can see that while the power coordination plays a pivotal role in both interference management for enhancing SE and energy utilization for improving EE, little research efforts have been devoted to exploring their inherent interaction under one unified bargaining cooperative game model with the consideration of both SE and EE issues.

B. Dense Deployment Challenges and Opportunities

Extreme deployment of small cells in heterogenous cellular networks introduce both challenges and opportunities. Challenges come with reuse of the limited frequency resource for improving spectral efficiency, which always introduce serious mutual inter-and intra-interference between or among small cells and macrocells. The opportunities refer to more potential chances of inter-and intra-tier cooperations among small cells and macrocells [35]. In [36], authors investigated the network spectrum efficiency of dense small cell networks to gain insight on the small cell deployment strategy in the separate frequency band deployment case. Authors in [1] regarded network densification as the key mechanism for wireless evolution over the next decade. Hwang et al. [2] presented a holistic view on hyper-dense HetNets, which includes fundamental preference in future wireless systems, and technical challenges and recent technological advancements made in such networks. In [37], a new design framework of cooperative green heterogeneous networks was presented, which is aimed at balancing and optimizing spectrum efficiency, energy efficiency, and quality of service (QoS) in 5G wireless communication systems. In [38] some cooperative distributed radio resource management algorithms for time synchronization, carrier selection, and power control were discussed for hyper-dense small cell deployment. In [39] two promising practical use cases were studied for simple multicell cooperation for LTE-Advanced heterogeneous network scenarios with macro and small cells. In [40], the multicell cooperation solutions were surveyed for improving the energy efficiency of cellular networks. Authors in [41] proposed a semi-distributed interference management scheme based on joint clustering and resource allocation for small cells. We note that potential cooperation diversities have not been well explored under the bargaining cooperative game-theoretic framework for hyper-dense small cell networks.

C. Contribution and Organization of This Work

To address these research limitations, this paper proposes a novel bargaining cooperative game (BCG) framework for interference-aware power coordination in a HetNet [35]. We first introduce the system model and interference interaction model in Section II, and then define a new adjustable utility function and propose a bargaining cooperative game (BCG) framework for interference-aware power coordination in Section III. In Section IV, we derive the closed-form power coordination solutions and further design a joint interference-aware power coordination scheme with the considerations of both interference mitigation and energy saving. Moreover, a simplified algorithm (Simplified) is presented to combat the heavy signaling overhead, which is one of the challenges in the scenario of extreme deployment of small cells. Numerical results are provided in Section V to illustrate the convergence property and the efficiency of our new power coordination scheme. Finally, we conclude this work in Section VI.

II. SYSTEM MODEL AND INTERFERENCE MODEL

This section introduces the system model and interference interaction model considered in this study.

A. System Model

As illustrated in Fig. 1, we consider a two-tier macro-small HetNet, where multiple SeNBs are overlaid on the coverage of an existing macrocell controlled by a MeNB. The spectrum is shared by both tiers and is universally reused in both tiers. Here, a small cell is a general term adopted in LTE networks to refer to femtocells and picocells with coverage radius in the range of 10–300 m [3], [4].

In Fig. 1, both SeNB and MeNB may respectively suffer from significant performance degradation due to both inter- and intra-tier interference. For instance, serious mutual interference may occur between the downlink communication pairs of MeNB $\rightarrow$ MUE$_1$ and SeNB$_2$ $\rightarrow$ SUE$_2$. Here, MUE and SUE represent the Macrocell User Equipment and Small cell User Equipment, respectively. Similarly, MUE$_2$ may

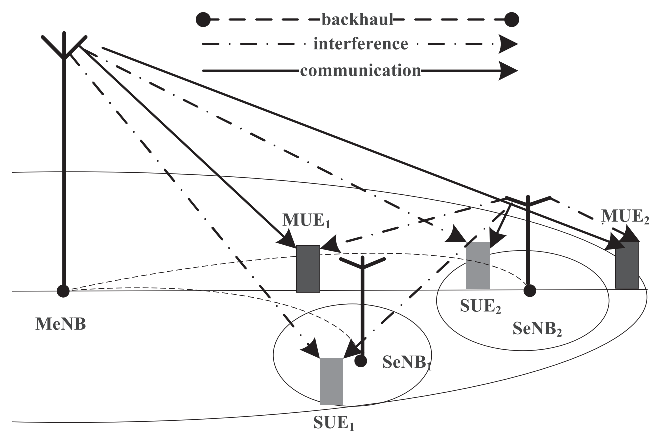

Fig. 1. A two-tier macro-small HetNet.

experience more serious interference from its nearest SeNB since it is located far away from its associated MeNB but near to one specific SeNB. Therefore, it is critical to have an interference-aware power coordination among SeNBs and MeNB to mitigate both inter-tier and intra-tier interference, and thus to enhance SINR-related spectral efficiency performance. An efficient power coordination scheme between MeNB and SeNB will be largely determined by their association users, their aggregate interference power and locations.

B. Interference-Based Interaction Model

We assume that N SeNBs coexist with MeNB$_0$ in the considered HetNet, and we use $\mathcal{N} = \{1, \ldots, N\}$ to denote the SeNB set with the total number of N SeNBs, $\mathcal{M}$ is the set of the M MUEs that are associated with the MeNB$_0$, and $\mathcal{N}_f$ is defined as the set of N_f small cell user equipments (SUEs) that are served by the SeNB$_f$, $f \in \mathcal{N}$. Thus, the SINR of MUE$_m$, $m \in \mathcal{M}$ associated to MeNB$_0$ is determined as

$$\gamma_{0,m} = \frac{p_0 g_{0,m}}{\sum_{f=1}^{N} p_f g_{f,m} + \sigma_{0,m}^2}, \tag{1}$$

where p_0 is the downlink transmission power of MeNB$_0$, $g_{0,m}$ is the channel gain of MeNB$_0$ with its associated MUE$_m$, p_f is the downlink transmission power of SeNB$_f$, $g_{f,m}$ is the channel gain from SeNB$_f$ to MUE$_m$, and $\sigma_{0,m}^2$ is the background noise power. Here, $\sum_{f=1}^{N} p_f g_{f,m} + \sigma_{0,m}^2$ represents the total interference power plus noise perceived by MUE$_m$, in which the first term corresponds to the interference power introduced by all the N SeNBs.

Note that $\kappa_{0,m}$, the gain-to-interference-plus-noise ratio (GINR) of the MUE$_m$, is determined as

$$\kappa_{0,m} = \frac{g_{0,m}}{\sum_{f=1}^{N} p_f g_{f,m} + \sigma_{0,m}^2}. \tag{2}$$

TABLE I
SUMMARY OF THE KEY NOTATIONS AND DEFINITIONS

Notation	Meaning
f, n, m	Index of SeNB, SUE and MUE, respectively
κ_0, κ_f	Aggregated GINR of MeNB_0 and SeNB_f
p_0, p_f	Downlink transmit power of MeNB_0 and SeNB_f
η_0, η_f	Energy efficiency function of MeNB_0 and SeNB_f
π_0, π_f	Spectral efficiency function of MeNB_0 and SeNB_f
u_0, u_f	Utility function of MeNB_0 and SeNB_f
α_0, α_f	Balance coefficient between EE and SE of MeNB_0 and SeNB_f

Thus, (1) can be simplified as

$$\gamma_{0,m} = p_0 \kappa_{0,m}. \tag{3}$$

Based on (3), the sum capacity π_0 of all MUEs associated with MeNB_0 is given by

$$\pi_0 = \sum_{m=1}^{M} \log_2(1 + p_0 \kappa_{0,m}), \tag{4}$$

where the shared spectrum of the MeNB_0 with N SeNBs is normalized to be one in order to reflect the spectral efficiency performance in the unit of bit/s/Hz. Similarly, for SUE_n associated with SeNB_f, $n \in \mathcal{N}_f$, $f \in \mathcal{N}$, its GINR $\kappa_{f,n}$ is determined as

$$\begin{aligned} \kappa_{f,n} &= \frac{g_{f,n}}{\sum\limits_{f'=1, f' \neq f}^{N} p_{f'} g_{f',\{f,n\}} + p_0 g_{0,\{f,n\}} + \sigma_{f,n}^2} \\ &= \frac{g_{f,n}}{p_0 g_{0,\{f,n\}} + \varpi_{f,n}}, \end{aligned} \tag{5}$$

where $\varpi_{f,n} = \sum\limits_{f'=1, f' \neq f}^{N} p_{f'} g_{f',\{f,n\}} + \sigma_{f,n}^2$ is the aggregated interference from other SeNBs f' plus the noise power. Now, its SINR $\gamma_{f,n}$ is given by

$$\gamma_{f,n} = p_f \cdot \kappa_{f,n}, \tag{6}$$

where $\sum\limits_{f'=1, f' \neq f}^{N} p_{f'} g_{f',\{f,n\}}$ represents the co-tier interference power from all the other $\text{SeNB}_{f'}$, $f' \in \mathcal{N}$, $f' \neq f$, $p_0 g_{0,\{f,n\}}$ is the cross-tier interference from the MeNB_0, and $\sigma_{f,n}^2$ is noise power. Therefore, the sum capacity achieved by the SeNB_f is evaluated as:

$$\pi_f = \sum_{n=1}^{N_f} \log_2(1 + p_f \kappa_{f,n}). \tag{7}$$

III. BARGAINING COOPERATIVE GAME

In this section, we first formulate a bargaining cooperative game (BCG) framework to capture the inherent coordination behaviors among SeNBs and MeNB, then a Nash-product optimization is formulated to achieve the interference-aware power coordination in the BCG framework.

A. BCG Among MeNB and SeNBs

It is known that the optimal Nash bargaining solution (NBS)-based control will achieve an optimal tradeoff between Nash fairness and Nash axiomatic efficiency from the Nash axiomatic theory [30]. To capture the inherent coordination behaviors among SeNBs and MeNB, we formulate here a BCG framework for interference-aware power coordination.

Definition 1: Bargaining cooperative game (BCG)

$$G^{\text{BCG}} = \left\langle \left\{ \text{MeNB}_0, \text{HeNB}_f,\ f \in \mathcal{N} \right\}; \left\{ p_0, p_f,\ f \in \mathcal{N} \right\}; u \right\rangle,$$

where the players are the MeNB_0 and multiple SeNB_f, $f \in \mathcal{N}$; the available actions are $p_0 \leq p_0^{max}$, $p_f \leq p_f^{max}$, $f \in \mathcal{N}$; most important tuple of such a game is the utility function design, where we employ the Nash-product function of $u = u_0 \prod\limits_{f=1}^{N} u_f$ with u_0 and u_f being the utility function denoted for MeNB_0 and SeNB_f, respectively.

Remark 1: Socially optimal utility function in the Nash-product form defined in the presented BCG framework guarantees both efficiency and fairness, which has been proved in [27], [28]. On the individual utility function, both (4) and (7) as well as their variations have been widely adopted as the utility function in the current literature on game theory-based power coordination and SE optimization for HetNets. However, energy efficiency (EE), a critical issue especially when multiple SeNBs are densely overlaid on the macrocell to enhance quality of user experience, has been largely neglected in these SE-oriented game-theoretic formulations.

How to reasonably design utility functions of u_0 and u_f for MeNB_0 and SeNB_f is critical for the interference-aware power coordination BCG framework [42]. To jointly address both SE and EE, and achieve an optimal tradeoff between them, we introduce u_0 and u_f, both of which are with a new adjustable α parameter.

Definition 2: The utility function u_f of a player SeNB_f, $f \in \mathcal{N}$, is defined as

$$u_f = \left(\eta_f - \eta_f^0\right)^{\alpha_f} \left(\pi_f - \pi_f^0\right)^{1-\alpha_f}, \tag{8}$$

where $\eta_f = \frac{\pi_f}{p_f + p_f^{\text{cst}}}$ is the energy efficiency function, which represents the ratio of the sum capacity π_f of all SeNB_f's associated users to the total power consumption $p_f + p_f^{\text{cst}}$ including the constant circuit power consumption p_f^{cst} and the transmission power consumption p_f. In addition, η_f^0 and π_f^0 represent the minimum requirements of the energy efficiency and spectral efficiency, respectively. The coefficient $0 \leq \alpha_f \leq 1$ is adopted here to strike a balance between SE and EE.

Similar normalized utility function was presented in [42], where the defined utility functions in the following are different from them on two aspects: first, our utility function is more general; second, we introduce the Nash bargaining cooperative game theoretic perspective to investigate them.

Definition 3: The utility function u_0 of MeNB_0 is defined as

$$u_0 = \left(\eta_0 - \eta_0^0\right)^{\alpha_0} \left(\pi_0 - \pi_0^0\right)^{1-\alpha_0}, \tag{9}$$

with $\eta_0 = \frac{\pi_0}{p_0 + p_0^{\text{cst}}}$ being the EE function, π_0 being the SE function, η_0^0 and π_0^0 being the minimum requirements of EE and SE, and $0 \leq \alpha_0 \leq 0$ being the balance coefficient between SE and EE.

Remark 2: The balance coefficients α_f and α_0 are determined by the total number and also distribution of all users associated with SeNB$_f$ and MeNB$_0$, respectively. If a player (e.g., the SeNB) is with less number of users, the player will coordinate the downlink power to care more about energy efficiency; otherwise, it will care more about the spectral efficiency. On one extreme, if $\alpha_f = 1$, then the player is wholly energy efficiency-oriented; on the other extreme, if $\alpha_f = 0$, then the player is wholly spectral efficiency-oriented. In this work, to guarantee the fairness between the spectrum efficiency and the energy efficiency, we choose $\alpha_f = 0.5$ and $\alpha_0 = 0.5$ in the following sections.

Remark 3: In summary, two typical features of the proposed BCG framework contain that, first, the BCG modeling for interference-aware power coordination well characterize the inter/intra interference relationships among MeNB and multiple SeNBs, which will yield more efficient and fair cooperative strategy. Second, a unified utility function design combining with EE and SE is formulated to investigate the tradeoff between them.

B. BCG-Based Optimal Power Coordination Problem

Thus, the BCG-based optimal power coordination can be achieved by solving the following Nash-product optimization problem

$$\mathbf{P1}: \max_{p_0 \leq p_0^{max}, p_f \leq p_f^{max}} \quad u_0 \prod_{f=1}^{N} u_f \tag{10a}$$

$$\text{subject to} \quad \eta_0 - \eta_0^0 \geq 0, \tag{10b}$$

$$\pi_0 - \pi_0^0 \geq 0, \tag{10c}$$

$$\eta_f - \eta_f^0 \geq 0, \ f \in \mathcal{N}, \tag{10d}$$

$$\pi_f - \pi_f^0 \geq 0, \ f \in \mathcal{N}. \tag{10e}$$

Objective (10a) is the Nash-product function of u_0 and u_f being the utility functions denoted for MeNB$_0$ and SeNB$_f$, respectively shown as (8) and (9). Constraints (10b), (10c), (10d) and (10e) are required by the BCG framework, where η_0^0, π_0^0, η_f^0 and π_f^0 are the disagreement points of cooperative players in the cooperative game-theoretic notations, which are the minimum outcomes required by the players, e.g., MeNB$_0$ and any SeNB$_f$, for involving in the BCG. Otherwise, they will not participate in the BCG. On the other hand, η_0^0 and π_0^0 are the minimum EE and SE requirements of MeNB, respectively, and η_f^0 and π_f^0 are the minimum EE and SE requirements of MeNB$_0$ and SeNB$_f$, respectively. Without loss of generality, $\eta_0^0 = 0$, $\pi_0^0 = 0$, $\eta_f^0 = 0$ and $\pi_f^0 = 0$ are the mainstream assumptions in the cooperative game-theoretic formulations. This can help to simplify the following analysis, derive the closed-form equilibrium solutions, and design distributed algorithm [24], [27], [28].

C. Problem Simplification

It is noted that the problem (10) is a general BCG-structured optimization problem and complicated to be analyzed. Taking into account the real network features of some constraints, e.g., the minimum outcomes required by the players, e.g., MeNB$_0$ and any SeNB$_f$, we first make some simplifications on the objective function and constraint conditions. Here, since extensive works have concentrated on the SINR-related optimization functions in [9]–[11], we also use the SINR functions (3) and (6) instead of the capacity formula (4) and (7) in utility functions of (8) and (9) during the following analysis.

Corollary 1: With SINR definition instead of capacity function in the utility function and the assumptions of $\eta_0^0 = 0$ and $\pi_0^0 = 0$ for MeNB, and $\eta_f^0 = 0$ and $\pi_f^0 = 0$ for any SeNB f, the Nash-product-based power optimization problem of **P1** in (10) is simplified as

$$\mathbf{P2}: \max_{p_0 \leq p_0^{max}, p_f \leq p_f^{max}} \left\{ \phi = \kappa_0 p_0^{1-\alpha_0} \prod_{f=1}^{N} \kappa_f p_f^{1-\alpha_f} \right\}, \tag{11}$$

where $\kappa_0 = \sum_{m=1}^{M} \kappa_{0,m}$ and $\kappa_f = \sum_{n=1}^{N_f} \kappa_{f,n}$ are the aggregate GINRs from all MeNB's or SeNB$_f$ served MUEs/SUEs, respectively.

Proof: With SINR definition (3) in the utility function (9), the sum SINR achieved by the MeNB$_0$ is

$$\pi_0 = \sum_{m=1}^{\mathcal{M}} p_0 \kappa_{0,m} = p_0 \kappa_0, \tag{12}$$

where $\kappa_0 = \sum_{m=1}^{M} \kappa_{0,m}$ is the aggregate GINR from all its served MUEs. Similarly, With SINR definition (6) in the utility function (8), the sum SINR achieved by the SeNB$_f$ is

$$\pi_f = \sum_{n=1}^{N_f} p_f \kappa_{f,n} = p_f \kappa_f, \tag{13}$$

where $\kappa_f = \sum_{n=1}^{N_f} \kappa_{f,n}$ is the aggregate GINR from all its served SUEs of SeNB$_f$.

Therefore, according to the utility function denoted in Definition 3, the simplified utility functions for the MeNB$_0$ is given by

$$u_0 = \eta_0^{\alpha_0} \left(\pi_0^{1-\alpha_0} \right) = \left(\frac{\pi_0}{p_0} \right)^{\alpha_0} \left(\pi_0^{1-\alpha_0} \right) = \frac{\pi_0}{p_0^{\alpha_0}}, \tag{14}$$

with the assumptions of $\eta_0^0 = 0$, $\pi_0^0 = 0$, and $p_0^{\text{cst}} = 10$. Also, according to the utility function denoted in Definition 2, the finally simplified utility functions for the any SeNB$_f$ is given by

$$u_f = \eta_f^{\alpha_f} \left(\pi_f^{1-\alpha_f} \right) = \left(\frac{\pi_f}{p_f} \right)^{\alpha_f} \left(\pi_f^{1-\alpha_f} \right) = \frac{\pi_f}{p_f^{\alpha_f}} \tag{15}$$

with $\pi_f^0 = 0$ and $\pi_f^0 = 0$ for any SeNB$_f$.

We can see that the utility functions are greatly simplified, which will facilitate the following analysis. Therefore, the Nash-product-based power optimization problem of **P1** in (10) is simplified as

$$\phi = u_0 \prod_{f=1}^{N} u_f \overset{(14)}{\underset{(15)}{=}} \frac{\pi_0}{p_0^{\alpha_0}} \prod_{f=1}^{N} \frac{\pi_f}{p_f^{\alpha_f}}, \tag{16}$$

$$\overset{(12)}{\underset{(13)}{=}} \kappa_0 p_0^{1-\alpha_0} \prod_{f=1}^{N} \kappa_f p_f^{1-\alpha_f}, \tag{17}$$

which is easily obtained with simple mathematical derivations and (14), (15) in (16) and (12), (13) in (17), respectively. This concludes the proof. ■

Corollary 2: The problem **P2** in (11) is equivalently reformulated as

$$\textbf{P3}: \quad \max \quad \varphi \tag{18a}$$

$$\text{subject to} \quad p_0 \leq p_0^{max}, \tag{18b}$$

$$p_f \leq p_f^{max}, \tag{18c}$$

where the new objective function $\varphi = \ln(\phi)$, and it is the logarithmic function of (17).

Proof: The primal objective function (17) is easily verified to be convex with respect to the optimization variables of p_0 and p_f. Since the logarithmic function does not change the convexity, the problem **P3** in (18) is naturally an equivalent reformulation of the primal problem **P2** in (11). ■

Here, we should keep in mind that κ_0 and κ_f are the functions of their respectively perceived inter-tier interference power. Therefore, the problem for MeNB is given by

$$\textbf{P-MeNB}: \quad \max \quad (1-\alpha_0)\log p_0 + \sum_{f=1}^{N} \log\kappa_f, \tag{19a}$$

$$\text{subject to} \quad p_0 \leq p_0^{max}, \tag{19b}$$

and for any SeNB_f, the problem is

$$\textbf{P-SeNB}: \quad \max \quad \log\kappa_0 + \sum_{f=1}^{N} (1-\alpha_f)\log p_f, \tag{20a}$$

$$\text{subject to} \quad p_f \leq p_f^{max}. \tag{20b}$$

At this time, the problem turns into how to solve the sub-problems of (19) and (20).

IV. BCG Analysis and Power Coordination

With the help of the above BCG framework, we first illustrate the overall flow of BCG analysis, then we derive the closed-form power coordination solutions by solving the sub-problems of (19) and (20) for MeNB_0 and SeNB_f, respectively.

A. Overall Flow of Implementation of BCG Framework

We assume that there exists a wired backhaul connecting the MeNB to the SeNBs, which enables them to exchange interference-related information required for the cooperative power coordination, the same assumption can be found in [18]. We note that the general power coordination problem in the presence of mutual interference between MeNB and SeNBs is intractable even under the premise of an ideal information exchange.

- First, MeNB and SeNBs initialize their transmit powers at time t, e.g., $p_0^{(t)}$, $p_f^{(t)}$, $p_{f'}^{(t)}$ respectively for the MeNB_0, SeNB_1 and SeNB_2.
- Then, serious interference is caused to each other, e.g., each MUE_m receives the interference power from both SeNB_1 and SeNB_2. MUE_m constructs the GINR function $\kappa_{0,m}$ using (2). Similarly, SeNB_f achieves the GINR function of $\kappa_{f,n}$ using (5). These GINR functions are exchanged for assisting the distributed power coordinations.
- MeNB and SeNBs update the power under the BCG framework, using the detailed update functions, e.g., $p_0^{(t+1)}$, $p_f^{(t+1)}$, $p_{f'}^{(t+1)}$ respectively for the MeNB_0, SeNB_1 and SeNB_2.
- The above two steps will continue until the convergence is achieved, which is measured by $|p_0^{(t+1)} - p_0^{(t)}| \leq \varepsilon$, and $|p_f^{(t+1)} - p_f^{(t)}| \leq \varepsilon$, $f \in \mathcal{N}$, for any tiny ε.

In summary, three procedures are included in the overall flow of implementation of BCG framework, which are initialization, power coordination and convergence determination. Here, information exchange is important in the cooperative game-theoretic formulations. Here, the MeNB needs to know the interference information of all the SeNBs as the arrows indicate. Also, each SeNB needs the information of both the MeNB and other SeNBs. Finally, we will propose a simplified scheme to reduce the information exchange overhead. At this time, the most critical procedure is how to update the next transmit power. To deal with this problem, we solve the above-defined problems.

B. Closed-form Power Coordination Solution for MeNB_0

Corollary 3: The closed-form power solution of MeNB_0, which is given by

$$p_0^\star = \frac{1-\alpha_0}{\sum_{f=1}^{N} \sum_{n=1}^{N_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \frac{\kappa_{f,n}^2}{\kappa_f} + \lambda_0}, \tag{21}$$

where $\lambda_0 \left(p_0 - p_0^{max}\right) = 0$.

Proof: For the problem denoted as **P1**, introducing the Lagrangian parameters λ_0 for the power mask, which yields

$$L_0 = (1-\alpha_0)\log p_0 + \sum_{f=1}^{N} \log\kappa_f - \lambda_0 \left(p_0 - p_0^{max}\right). \tag{22}$$

First, we derive the first-order derivation of (22) with respect to p_0 of MeNB_0, and we get

$$\begin{aligned} \frac{\partial L_0}{\partial p_0} &= \frac{1-\alpha_0}{p_0} + \sum_{f=1}^{N} \frac{1}{\kappa_f} \frac{\partial \kappa_f}{\partial p_0} - \lambda_0, \\ &= \frac{1-\alpha_0}{p_0} + \sum_{f=1}^{N} \frac{\nu_f}{\kappa_f} - \lambda_0, \end{aligned} \tag{23}$$

where $\nu_f = \frac{\partial \kappa_f}{\partial p_0}$. According to the definition of κ_f in (10) and $\kappa_{f,n}$ in (6), we obtain

$$\begin{aligned}\nu_f = \frac{\partial \kappa_f}{\partial p_0} &= \frac{\partial}{\partial p_0}\left\{\sum_{n=1}^{N_f} \kappa_{f,n}\right\} = \sum_{n=1}^{N_f} \frac{\partial \kappa_{f,n}}{\partial p_0} \\ &= -\sum_{n=1}^{N_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \kappa_{f,n}^2. \end{aligned} \tag{24}$$

Substitute (24) into (23), we have

$$\begin{aligned}\frac{\partial L_0}{\partial p_0} &= \frac{1-\alpha_0}{p_0} + \sum_{f=1}^{N} \frac{1}{\kappa_f}\frac{\partial \kappa_f}{\partial p_0} - \lambda_0 \\ &= \frac{1-\alpha_0}{p_0} - \sum_{f=1}^{N}\sum_{n=1}^{N_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \frac{\kappa_{f,n}^2}{\kappa_f} - \lambda_0, \end{aligned} \tag{25}$$

further, we achieve the closed-form power solution of MeNB_0, which is given by

$$p_0^\star = \frac{1-\alpha_0}{\sum_{f=1}^{N}\sum_{n=1}^{\mathcal{N}_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \frac{\kappa_{f,n}^2}{\kappa_f} + \lambda_0}. \tag{26}$$

■

Remark 4: From (26), we can conclude that

- If the MeNB_0 cares more about energy efficiency, that is with larger α_0, then it should use less power $p_0^\star$, which is in line with the practical situation.
- If more SeNBs (larger N) with more served SUEs in each SeNB_f (larger N_f) are deployed in the coverage of MeNB_0; meanwhile, when these SeNBs are located very close to MeNB_0, the MeNB_0 should apply much less power, which indicates that our scheme contains a full account of the opponent's preferences.
- If the GINR of all SeNB_f are good enough (larger than κ_f), then the MeNB_0 can use a much larger power to enhance its capacity.

C. Closed-form Power Coordination Solution for SeNB_f

Corollary 4: We achieve a closed-form power solution of eNB, which is given by

$$p_f{}^\star = \frac{1-\alpha_f}{\sum_{m=1}^{M} \frac{g_{f,m}}{g_{0,m}} \frac{\kappa_{0,m}^2}{\kappa_0} + \lambda_f}. \tag{27}$$

Proof: Similarly, we derive the first-order derivation of (19) with respect to p_f of SeNB_f, and get

$$\begin{aligned}\frac{\partial \varphi}{\partial p_f} &= \frac{1}{\kappa_0}\frac{\partial \kappa_0}{\partial p_f} + \frac{1-\alpha_f}{p_f} - \lambda_f \\ &= \frac{\nu_0}{\kappa_0} + \frac{1-\alpha_f}{p_f} - \lambda_f, \end{aligned} \tag{28}$$

where $\nu_0 = \frac{\partial \kappa_0}{\partial p_f}$. According to the definition of κ_0 in (12) and $\kappa_{0,m}$ in (2), we attain

$$\nu_0 = \frac{\partial \kappa_0}{\partial p_f} = \sum_{m=1}^{M} \frac{\partial \kappa_{0,m}}{\partial p_f} = -\sum_{m=1}^{M} \frac{g_{f,m}}{g_{0,m}} \kappa_{0,m}^2. \tag{29}$$

Substitute (29) into (28), we have

$$\frac{\partial \varphi}{\partial p_f} = \frac{1-\alpha_f}{p_f} - \frac{1}{\kappa_0}\sum_{m=1}^{M} \frac{g_{f,m}}{g_{0,m}} \kappa_{0,m}^2 - \lambda_f. \tag{30}$$

Further, we achieve the closed-form power solution of eNB, which is given by

$$p_f{}^\star = \frac{1-\alpha_f}{\sum_{m=1}^{M} \frac{g_{f,m}}{g_{0,m}} \frac{\kappa_{0,m}^2}{\kappa_0} + \lambda_f}. \tag{31}$$

■

Remark 5: From (31), we can conclude that

- If the SeNB_f cares more about energy efficiency, that is with larger α_f, then it should use less power $p_f^\star$, which is in line with the practical situation.
- If more MUEs (larger M) served by the MeNB_0, meanwhile, specific SeNB_f is located very close to MeNB_0, then the SeNB_f should use much less power, which also indicates that our scheme contains a full account of the opponent's preferences.
- If the GINR of all MUEs are good enough (larger than κ_0), then the SeNB_f can use much larger power to enhance its capacity.

V. Distributed Interference-Aware Power Coordination

In this section, we focus on the design of a distributed algorithm to approximately realize optimal solutions. We consider distributed algorithms with possible signalling information exchange between the multiple SeNB_f and the MeNB_0, with which each of them acts independently to optimize its own power allocation.

A. Distributed Power Coordination with Heavy Signaling Overhead

We propose a joint interference-aware power coordination scheme based on the derived closed-form solutions in (26) and (31). The performance of the designed algorithm is significantly determined by the heavy signaling overhead information.

A1: Joint Power Coordination Between MeNB and SeNBs with Interference Awareness

- Initialization: MeNB_0 and SeNB_f, $f \in \mathcal{N}$ choose power levels of $p_0(0)$ and $p_f(0)$; meanwhile, predefined the Lagrangian parameters are $\lambda_0^{(t)}$ and $\lambda_f^{(t)}$, $f \in \mathcal{N}$ at t step.

- Implementation:
  - MeNB:
    - Each SeNB$_f$ gathers the information of GINR

$$\hat{\kappa}_f(t) = \sum_{n=1}^{\mathcal{N}_f} \hat{\kappa}_{f,n}(t)$$

      from all its associated SUEs, where $\hat{\kappa}_{f,n}(t) = \frac{\hat{\gamma}_{f,n}(t)}{p_f(t)}$. Here, the GINR of each SUE$_n$ in SeNB$_f$ is estimated by its current achieved SINR $\hat{\gamma}_{f,n}(t)$ and its received power $p_f(t)$.
    - Then, MeNB$_0$ will adjust the power at the next step $t+1$ using

$$p_0(t+1) = \frac{1-\alpha_0}{\sum_{f=1}^{N}\sum_{n=1}^{\mathcal{N}_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \frac{\kappa_{f,n}^2(t)}{\kappa_f(t)} + \lambda_0(t)}$$

      with the fixed setting of α_0, and the estimated channel state information.
    -

$$\lambda_0^{(t+1)} = \lambda_0^{(t)} + \left\{ p_0^{(t)} - p_0^{\max} \right\}$$

  - SeNB:
    - The MeNB$_0$ computes

$$\hat{\kappa}_0(t) = \sum_{m=1}^{M} \hat{\kappa}_{0,m}(t),$$

      where $\hat{\kappa}_{0,m}(t) = \frac{\hat{\gamma}_{0,m}(t)}{p_0(t)}$ is the GINR of each MUE$_m$ served by the MeNB$_0$.
    - Each SeNB$_f$ will adjust the power using

$$p_f(t+1) = \frac{1-\alpha_f}{\sum_{m=1}^{M} \frac{g_{f,m}}{g_{0,m}} \frac{\kappa_{0,m}^2(t)}{\kappa_0(t)} + \lambda_f(t)}$$

      with the fixed setting of α_f, and the estimated channel state information.
    -

$$\lambda_f^{(t+1)} = \lambda_f^{(t)} + \left\{ p_f^{(t)} - p_f^{\max} \right\}$$

- Termination: These listed steps $2 \sim 3$ will continue until the final convergence.

The proposed algorithm requires the interference context information exchange of all the involved players. The information exchange overhead required for this power coordination is likely to be prohibitive for moderate-sized small cell deployment. It challenges the scalability of the large number of small cell deployment.

B. A Low-Cost Sub-Optimal Solution

In this subsection, we propose a low-cost sub-optimal algorithm with the simplified specific power update function in **A1**, where we consider the real interference features of two-tier macro-small HetNets. The basic analysis assumptions include that MeNB$_0$ is always the maximum interferer for any SeNB$_f$, and there always exists one SeNB$_f$ maximum interferer for the MeNB$_0$ due to the SeNB location distribution.

As denoted in (5), $\kappa_{f,n}$ is the function of $\varpi_{f,n}$, and $\varpi_{f,n}$ is the aggregated interference from all other SeNBs $f' \in \mathcal{N}$, $f' \neq f$ plus the noise power. In (5), if we assume that $p_0 g_{0,\{f,n\}} \gg \varpi_{f,n}$, then $\kappa_{f,n} = \frac{g_{f,n}}{p_0 g_{0,\{f,n\}}}$, that is $\frac{g_{0,\{f,n\}}}{g_{f,n}} = \frac{1}{p_0 \kappa_{f,n}}$. At this time, the power update of MeNB$_0$ is

$$\begin{aligned} p_0(t+1) &= \frac{1-\alpha_0}{\sum_{f=1}^{N}\sum_{n=1}^{\mathcal{N}_f} \frac{g_{0,\{f,n\}}}{g_{f,n}} \frac{\kappa_{f,n}^2(t)}{\kappa_f(t)} + \lambda_0(t)} \\ &\approx \frac{1-\alpha_0}{\sum_{f=1}^{N}\sum_{n=1}^{\mathcal{N}_f} \frac{1}{p_0(t)\kappa_{f,n}(t)} \frac{\kappa_{f,n}^2(t)}{\kappa_f(t)} + \lambda_0(t)} \\ &= \frac{1-\alpha_0}{\frac{1}{p_0(t)} \sum_{f=1}^{\mathcal{N}} \frac{1}{\kappa_f(t)} \sum_{n=1}^{\mathcal{N}_f} \kappa_{f,n}(t) + \lambda_0(t)} \\ &= \frac{1-\alpha_0}{\frac{\mathcal{N}}{p_0(t)} + \lambda_0(t)}, \end{aligned} \tag{32}$$

where $\kappa_f(t) = \sum_{n=1}^{N_f} \kappa_{f,n}(t)$. We should consider the inter-layer interference during the design of a suitable power control, in particular in the dense small cell networks. However, here we have the following typical scenarios.

Remark 6: In a practical HetNet, there is always one maximum SeNB$_f$ interferer for the MeNB$_0$, therefore, we have

$$\begin{aligned} \gamma_{0,m} &= \frac{p_0 g_{0,m}}{\sum_{f=1}^{N} p_f g_{f,m} + \sigma^2} \\ &= \frac{p_0 g_{0,m}}{p_f g_{f,m} + \sum_{f'=1}^{N-1} p'_f g_{f',m} + \sigma^2} \\ &= \frac{p_0 g_{0,m}}{p_f g_{f,m} + \varpi_m} \\ &\approx \frac{p_0}{p_f} \frac{g_{0,m}}{g_{f,m}}, \end{aligned} \tag{33}$$

with the index f as the selected maximum SeNB$_f$ interferer for the MeNB$_0$ during the following analysis. In (33), we consider the inter-layer interference, and here (33) represents the achieved SINR of the MUE in the macrocell, where we assume that there is a dominant inter-layer interference SeNB source that introduces the most interference to the MeNB's user. With (33), we attain

$$\frac{g_{0,m}}{g_{f,m}} = \gamma_{0,m} \frac{p_f}{p_0}. \tag{34}$$

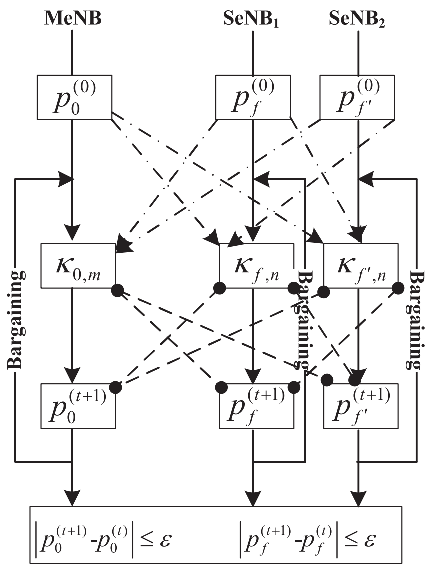

Fig. 2. Implementation of the proposed BCG framework.

At this time, the power update of SeNB$_f$ is

$$\begin{aligned} p_f(t+1) &= \frac{1-\alpha_f}{\sum_{m=1}^{\mathcal{M}} \frac{g_{f,m}}{g_{0,m}} \frac{\kappa_{0,m}^2(t)}{\kappa_0(t)} + \lambda_f(t)} \\ &\approx \frac{1-\alpha_f}{\sum_{m=1}^{\mathcal{M}} \frac{p_0}{p_f} \frac{1}{\gamma_{0,m}} \frac{\kappa_{0,m}^2(t)}{\kappa_0(t)} + \lambda_f(t)} \\ &= \frac{1-\alpha_f}{\frac{1}{\kappa_0(t) p_f} \sum_{m=1}^{\mathcal{M}} \kappa_{0,m}(t) + \lambda_f(t)} \\ &= \frac{1-\alpha_f}{\frac{1}{p_f(t)} + \lambda_f(t)}, \end{aligned} \tag{35}$$

where $\kappa_0 = \sum_{m=1}^{\mathcal{M}} \kappa_{0,m}$. With the above remarks, the completely distributed sub-optimal power coordination algorithm is attained.

Remark 7: Substituting (32) and (35) to **A1**, we present a simplified algorithm (Simplified) with less signaling overhead, termed as **A2**. We omit the detailed description of **A2** as the basic steps are similar to **A1**; however, the presented **A2** is with the derived closed-form solutions of (32) and (35) as the most featured characteristics.

Remark 8: Significant information exchange is the most important drawback of the proposed BCG framework. Here, the MeNB needs to know the interference information from N SeNBs and each SeNB is with N_f SUEs. Each SeNB needs to know the interference information from all the other $N-1$ SeNBs and M MUEs of the only MeNB. These have been shown with the arrows in Fig. 2. Therefore, in the proposed "Joint" algorithm, the MeNB and each SeNB need to exchange the information in the amount of $O(N \times N_f)$ and $O(M + (N-1) \times N_f)$, respectively. However, in the proposed "Simplified" algorithm, the MeNB and each SeNB only need to exchange information in the amount of $O(N_f)$ and $O(M)$, respectively. Therefore, the proposed "Simplified" algorithm well reduce the interference information exchange compared to the proposed "Joint" algorithm.

TABLE II
SYSTEM SIMULATION PARAMETERS

Simulation Parameter	**Value**
Deployment scenario	Dense SeNBs 5×5 grid model
Number of MUEs	100
Carrier frequency and bandwidth	2GHz and 10MHz
Macro cell inter site distance (ISD)	500m
Minimum distance between SeNB and eNB	75m
Minimum distance between UE and eNB	35m
Minimum distance between UE and SeNB	3m
Minimum distance among SeNBs	40m cluster radius

VI. SIMULATION RESULTS

In this section, simulation results based on a practical LTE-A scenario are provided to illustrate the convergence property and effectiveness of the proposed Joint and Simplified schemes compared to others.

The MeNB is with omnidirectional antenna, $\mathtt{ISD} = 500$ m, and $p_0^{\max} = 46$ $\mathtt{dBm}$. We set the MeNB in the center of its coverage, and dense deployment of small cells are overlaid around the macrocell edge. We layout the coverage of the macrocell, and then generate a $50m \times 50m$ rectangular area, in which multiple SeNBs are deployed. Therefore, multiple SeNBs are deployed in 5×5 grid model with $p_x^{\max} = 20$ $\mathtt{dBm}$. Here, the used path loss models and shadowing standard deviations are according to the Table A.2.1.1.2-3 for the Femtocells in 5x5 grid model of 3GPP-TR 36.814 [11]. We refer to Femto as one example of SeNB in our simulations. In detail, the path loss model from Femto to UEs inside the same cluster is $L = 127 + 30\log_{10}$R, while other links are $L = 128.1 + 37.6\log_{10}$R for 2 GHz, where R is in the unit of km. Meanwhile, the shadowing standard deviations are 10 dB for the link between the SeNB and the SUE, and 8 dB for other links. The settings of α_f and α_0 are related to the number of associated users of each small cell and the channel fading parameter. How α_f and α_0 actually affect SE and EE was studied in our previous conference work in [33] as mentioned. In this work, to guarantee the fairness between the SE and the EE, we set them as 0.5 in the simulation sections. Other simulation parameters can be found in Table II.

1) Convergence Verification: The convergence property is very important to the proposed distributed interference-aware power coordination (Joint) due to its intrinsic two-stage bargaining process. However, the proof of the convergence is nontrivial, in particular, in the much denser small cell networks. Here, we also found that the power coordination process is a fixed point iteration process, which is guaranteed to converge via the folk theorem [24]. The initialization of the powers are 46 dBm for the MeNB and 23 dBm for all the other 20 involved SeNBs. We illustrate convergence behavior in Fig. 3.

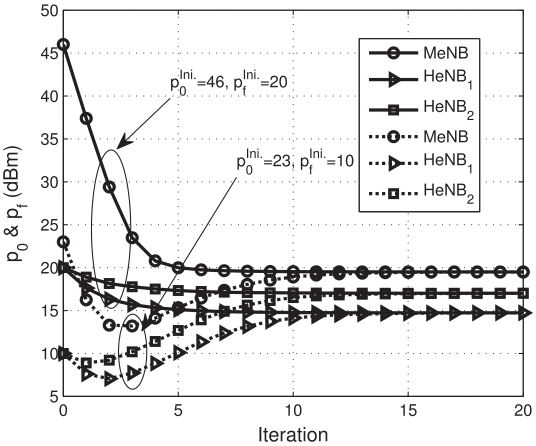

Fig. 3. Convergence verification with arbitrary initializations.

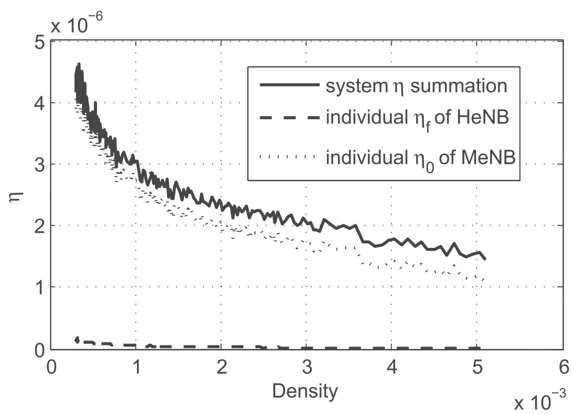

Fig. 4. Energy efficiency of the proposed Joint scheme.

In fact, we choose different simulation scenarios and set different simulation parameters, and finally we always can see that our proposed joint power coordination can guarantee the convergence behavior. As illustrated in Fig. 3, both p_0 and p_f will fast converge after 7–11 iterations under the considered initial conditions. For instance, we depict two cases; Case 1: $p_0^{\text{Iin.}} = 46\ \mathtt{dBm}$, $p_f^{\text{Iin.}} = 20\ \mathtt{dBm}$; and Case 2: $p_0^{\text{Iin.}} = 23\ \mathtt{dBm}$, $p_f^{\text{Iin.}} = 10\ \mathtt{dBm}$. For the two cases, our proposed algorithm can always ensure a fast convergence to the unique optimal power coordination solutions for the specific settings.

2) Algorithm Characteristics: We identify the characteristics of the proposed Joint scheme with respect to the increasing density of small cells. In our work, the node density is defined as the number of small cells deployed per area, which is in the unit of the number of small cells per m^2. We depict the area energy efficiency (η) and area spectral efficiency (π), respectively. They are respectively shown in Fig. 4 and Fig. 5.

Here, to measure the performance of the proposed scheme, we choose the area energy and spectral efficiency as the metrics. For instance, the area spectral efficiency (π) equals to the ratio of the total spectral efficiency to the area of the investigated region. In detail, we depict the system π summation, and

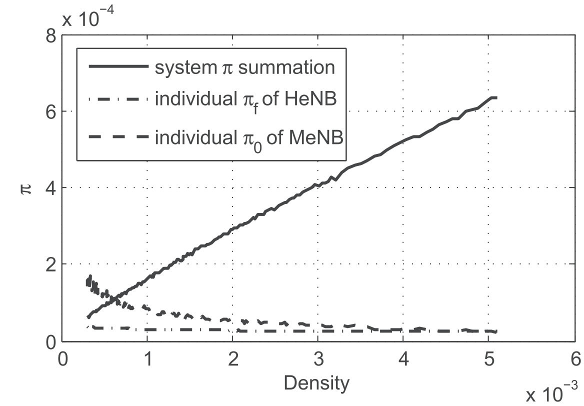

Fig. 5. Spectral efficiency of the proposed Joint scheme.

the individual π of SeNB and MeNB, respectively. They are respectively defined as

$$\text{system } \pi \text{ summation} = \frac{\sum_{f=1}^{N} \pi_f + \pi_0}{3.14\, r^2},$$

$$\text{individual } \pi \text{ of SeNB} = \frac{\sum_{f=1}^{N} \pi_f}{N \cdot 3.14\, r^2},$$

$$\text{individual } \pi \text{ of MeNB} = \frac{\pi_0}{3.14\, r^2},$$

where r is the radius setting, for instance, $r = 289$ m.

Comparing Fig. 4 to Fig. 5, we conclude that both the individual η and π of SeNB and MeNB decrease with respect to the density. This is caused by increasing the interference to each other when more small cells are involving in the joint interference-aware power coordination scheme (Joint) with the considerations of both interference mitigation and energy saving. For the system η and π summation, there is something different. The system η summation decreases with increasing the small cell density. However, the system π summation approximately appears to be a linear increase with the small cell density. It is reasonable since we consider the energy consumption when calculating the system η summation. Higher density means higher energy consumption; that is why the lower the system η summation; however, higher density directly means more of the system π summation. Therefore, it is natural to conclude that the higher small cell density is not always for improving the system performance; there should be a good tradeoff number when considering both η and π.

3) Improved Performance: To reflect the performance advantages on both EE and SE, we compute the EE and SE (cumulative distribution function, CDF) of MeNB and the averaged EE and SE of the SeNBs, which are shown in Fig. 6, respectively. Here, the benchmark case is implemented as: only the MeNB can coordinate its power to maximize its own utility without considerations of the strategic effects to SeNBs. Therefore, the benchmark case is a typical non-cooperative game. It is essentially a iteration process with the achieved SINR as the metric, which can be found in [33].

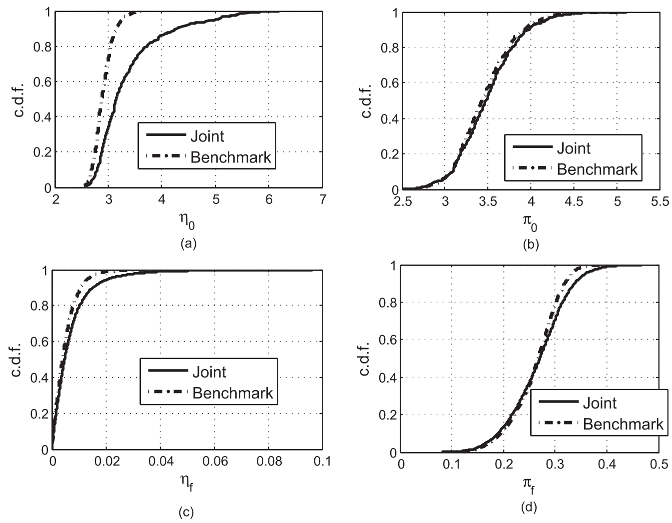

Fig. 6. The CDF of EE (a) and SE (b) for the MeNB, and the CDF of EE (c) and SE (d) for the SeNB.

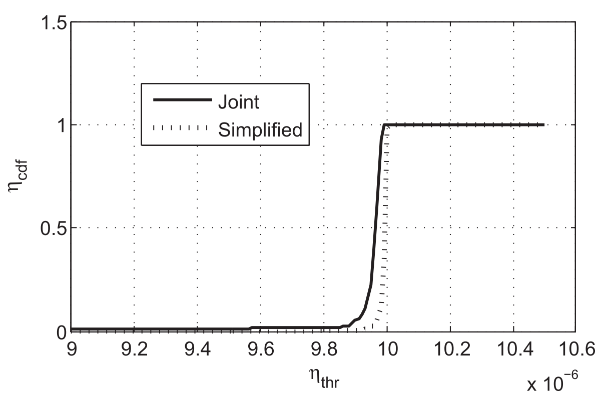

Fig. 7. Energy efficiency performance of the simplified algorithm.

From Fig. 6 we can see that the energy efficiency of both the MeNB and the SeNB is well improved using our proposed algorithm; however, the spectral efficiency can be further improved. This situation is due to the following reasons. First, always the interference power introduced by the SeNBs to MeNB is small, and therefore, the power adjustments of SeNBs will not do much better to the MeNB's SE. On the other hand, the MeNB's SE is significantly dependent on the MeNB's transmission power. Less power consumption always leads to less SE; however, it will do good to save energy, that leads to improved EE. Therefore, it is safe to conclude that for MeNB sacrificing a little SE will largely save energy. The biggest beneficiary of the power coordination between MeNB and SeNBs is the SeNB, as shown in Fig. 6.

4) Performance of Simplified Algorithm: The proposed joint interference-aware power coordination scheme (Joint) will be fully implemented with the considerations of both interference mitigation and energy saving. However, it requires heavy signaling overhead. That is why, a simplified algorithm (Simplified) is presented to combat the heavy signaling overhead. Here, the approximate performance of the presented algorithm has also been studied.

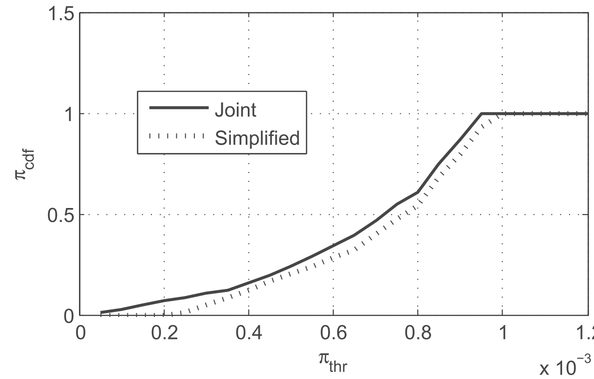

Fig. 8. Spectral efficiency performance of the simplified algorithm.

Here, we measure the approximate performance of the Simplified scheme via the cumulative distribution function. Again, we illustrate both the energy and spectral efficiency performance of the simplified algorithm compared to that of the Joint scheme, which are respectively shown in Fig. 7 and Fig. 8. We conclude that the proposed Simplified scheme can well approach the performance of that of the Joint scheme. The Simplified scheme will help reduce information exchange, and deal with the most drawback in the cooperative game-theoretic formulations in the settings of this work.

VII. Conclusion

To achieve both spectral efficiency and energy efficiency in one mathematical modeling, this paper proposed an α balanced coefficient-related adjustable utility function and a novel bargaining cooperative game (BCG) framework for interference-aware power coordination in a HetNet. We derived the closed-form power coordination solutions under a simplified framework to well understand the resource conflicts and interference coordinations. Simulation results indicate that the proposed joint power coordination scheme has a good capability in both interference mitigation and energy saving. Meanwhile, the proposed Simplified scheme can approach the performance of that of the Joint scheme.

In future, we will formulate the effects of other players, other strategic behaviors and interactions using the mean field game, and we will prove the existence, uniqueness, and convergence, which is really suitable for the hyper-multi-agent game-theoretic formulations of ultra-dense networks [44], and [45]. However, this work is different from them on at least two aspects: first, in the dense scenario, we identify the dominant interference source for both macrocell and each small cell in the cooperative game formulations. We think this meets the practical communication scenarios, that is always there is one main interference source for the player due to different locations of different players; however, they assume that there is no dominant player in the mean-field game. On the other hand, mean-field game is essentially the non-cooperative game, which can not achieve the social optimal solutions.

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