Quasi-distributed Interference Coordination for HSPA HetNet

Chi Zhang, Yongyu Chang, Shuqi Qin, and Dacheng Yang

The heterogeneous network (HetNet) has been discussed in detail in the Long-Term Evolution (LTE) and LTE Advanced standards. However, the standardization of High-Speed Packet Access HetNet (HSPA HetNet) launched by 3GPP is pushing at full steam. Interference coordination (IC), which is responsible for dealing with the interference in the system, remains a subject worthy of investigation in regard to HSPA HetNet. In this paper, considering the network framework of HSPA HetNet, we propose a quasi-distributed IC (QDIC) scheme to lower the interference level in the co-channel HSPA HetNet. Our QDIC scheme is constructed as slightly different energy-efficient non-cooperative games in the downlink (DL) and uplink (UL) scenarios, respectively. The existence and uniqueness of the equilibrium for these games are first revealed. Then, we derive the closed-form best responses of these games. A feasible implementation is finally developed to achieve our QDIC scheme in the practical DL and UL. Simulation results show the notable benefits of our scheme, which can indeed control the interference level and enhance the system performance.

Keywords: HSPA heterogeneous network, quasi-distributed interference coordination, non-cooperative game, energy-efficient, game equilibrium.

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I. Introduction

As the requirements for wireless mobile communication are growing rapidly along with the desire for relatively lower cost operation, the heterogeneous network (HetNet), in which low-power nodes (LPNs) are configured throughout the existing macro layout, is gradually becoming an effective approach to cost-efficiently increase both the capacity and coverage. While HetNet has been carefully discussed in the Long-Term Evolution (LTE) and LTE Advanced (LTE-A) standards, the standardization for High-Speed Packet Access (HSPA) HetNet launched by 3GPP is pushing at full steam, according to a recent 3GPP study [1].

In the co-channel HSPA HetNet (CcHH) scenario in which all LPNs are configured with the same frequency as the macrocell layout, coping with the annoying co-channel interference is usually a challenging task. Specifically, due to the large transmit power difference between the macro and LPN transmitters, the potential imbalance problem [2] between the uplink (UL) and downlink (DL) will inevitably lead to undesirable interference issues, which naturally motivates us to find out some appropriate interference coordination (IC) strategies to mitigate the interference in CcHH.

In the discussion of LTE/LTE-A HetNet, some related works on IC [3]-[8] have already been investigated. Works [3] and [4] developed the concept of the protected band in the frequency domain. In the protected band, which is only used by the edge LPN users, macro transmitters will be mute to control the interference with the edge LPN users. Some studies [5]-[7] proposed that by dynamically silencing some of the macro transmitters during some subframes, the lower macro-interference environment can be provided to the edge LPN users. Some system-level performance evaluation results of existing IC schemes for HetNet have been given in the LTE-A system [8].

Most of the above-mentioned methods belong to centralized IC (CIC) schemes, which request that transmitters first share their local information through the X2 interface in LTE/LTE-A HetNet, and, based on the exchanged information, each transmitter is then able to carry out the reasonable resource allocation and scheduling to control the interference. In CcHH, however, the high-speed interface between the transmitters is not defined, so the CIC scheme can only be implemented through the central control unit, that is, the radio network controller (RNC) in HSPA. Since exchanging information by the RNC is time-consuming, it is necessary to develop distributed IC or quasi-distributed IC (QDIC) schemes in CcHH to reduce interference.

The contribution of this paper is to propose a QDIC scheme that involves power adjustment to lower the interference level in CcHH. To achieve the quasi-distributed nature, we model our QDIC strategy as slightly different energy-efficient non-cooperative games (EENGs) in the DL and UL scenarios, respectively. In an EENG, based on some local restriction and information from the local receiver, each transmitter adjusts its transmit power to maximize its own utility in a quasi-distributed way. The introduction of energy-efficiency ensures that each transmitter can hold a conservative amount of power that is adequate to reach the required quality of service (QoS). The reduced power is not only beneficial to reduce interference but also helpful to save energy. We clarify the existence and uniqueness of the equilibrium for this game. Then, a closed-form best response of this game is derived. Finally, a feasible implementation is developed to apply our QDIC scheme in practice.

The remainder of this paper is organized as follows. In section II, we describe the system model and analyze the interference conditions in CcHH. In section III, our QDIC scheme is proposed and a feasible implementation is introduced in practice. In section IV, some simulation results are provided and discussed. Finally, we give some concluding remarks in section V.

II. System Model and Interference Analysis

1. System Model

We mainly consider a CcHH deployment, which consists of N macro cells. Every macro cell is separated into three sectors, each of which has one macro NodeB (MNB). Meanwhile, each macro sector cell is randomly and uniformly underlaid with M outdoor co-channel LPN cells operating at the same frequency as the macro layout. There is one LPN NodeB (LNB) located at the center of each LPN cell. Both the MNB and LNB are equipped with two antennas. We denote the sets of MNBs and LNBs as $\mathcal{N}$ and $\mathcal{M}$, respectively. Within each macro sector, there are K user equipment devices (UEs) configured with two antennas. According to the DL pilot strength, each UE must choose either the MNB or the LNB as its serving NodeB (SNB). If one UE selects an MNB or LNB as its SNB, this UE will be regarded as an MUE or LUE. The set of UEs that have been scheduled by their SNBs in the whole system is denoted by $\mathcal{K}$.

For the DL, we assume that each NodeB can only serve one UE at each transmission time interval (TTI). If UEk_l is scheduled by its SNBl, the DL signal-to-interference-plus-noise ratio (SINR) at UEk_l caused by its SNBl is expressed as

$$\gamma_{l,k_l,d}\left(p_{l,d},\mathbf{p}_{-l,d}\right)=\frac{p_{l,d}G_{l,k_l,d}}{\sigma^2_{k_l,d}+\sum_{l'\in\mathcal{N}\cup\mathcal{M},l'\neq l}p_{l',d}G_{l',k_l,d}}, \quad (1)$$

where $p_{l,d}$ is the DL transmit power of NodeBl and $\mathbf{p}_{-l,d}$ is the NodeB DL power vector that excludes NodeBl's power. $G_{l,k_l,d}$ is the DL channel gain between UEk_l and NodeBl, and $\sigma^2_{k_l,d}$ denotes the DL Gaussian noise at UEk_l. Thus, the DL data rate of UEk_l from its SNBl is given by

$$r_{l,k_l,d}\left(p_{l,d},\mathbf{p}_{-l,d}\right)=B\log_2\left(1+\frac{\gamma_{l,k_l,d}\left(p_{l,d},\mathbf{p}_{-l,d}\right)}{\Gamma}\right), \quad (2)$$

where B is the bandwidth and Γ denotes the SINR gap between the channel capacity and a practical coding and modulation scheme. For coded quadrature amplitude modulation HSPA, the gap can be given as $\Gamma=\Gamma\left(e_b\right)=-\ln\left(5e_b\right)/1.5$ (e_b is the required BER) [9]. For the general BER, $e_b<0.1$, $\Gamma>0$ can be guaranteed.

For the UL, we redefine the UL SINR of UEk at its SNBl^k as follows:

$$\gamma_{l^k,k,u}\left(p_{k,u},\mathbf{p}_{-k,u}\right)=\frac{p_{k,u}G_{l^k,k,u}}{\sigma^2_{l^k,u}+\sum_{k'\in\mathcal{K},k'\neq k}p_{k',u}G_{l^k,k',u}}, \quad (3)$$

where $p_{k,u}$ is the UL transmit power of UEk and $\mathbf{p}_{-k,u}$ is the UE UL power vector that excludes UEk's power. $G_{l^k,k,u}$ is the UL channel gain between UEk and NodeBl^k, and $\sigma^2_{l^k,u}$ denotes the UL Gaussian noise at NodeBl^k. Therefore, the UL data rate of UEk at its SNBl^k is

$$r_{l^k,k,u}\left(p_{k,u},\mathbf{p}_{-k,u}\right)=B\log_2\left(1+\frac{\gamma_{l^k,k,u}\left(p_{k,u},\mathbf{p}_{-k,u}\right)}{\Gamma}\right). \quad (4)$$

2. Interference Analysis

In this subsection, we will analyze the typical interference conditions in a CcHH scenario. Figures 1(a) and 1(b) show the emergence of typical UL and DL interference in CcHH.

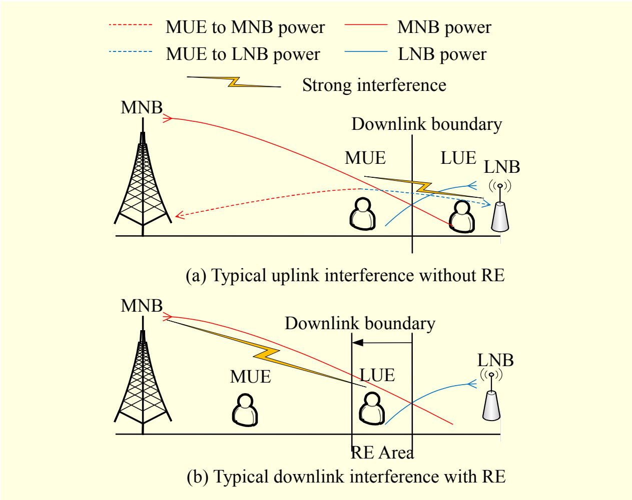

Fig. 1. Interference in CcHH.

A. Uplink Interference

For the uplink interference (UI), when an MUE is close to the DL boundary defined as the point beyond which UE should perform its serving cell change, this UE could still have a better UL to the nearest LNB than to its serving MNB due to the UL-DL imbalance problem. Therefore, this LNB could be the victim of excessive interference from this MUE, and some LUEs served by this LNB may suffer from the degradation in UL performance.

B. Downlink Interference

For the downlink interference (DI), we consider the application of range expansion (RE) [10], which is able to improve the coverage and offloading capacity of LPN cells. To compensate for the UL-DL imbalance and enhance the HetNet performance, RE is introduced to perform cell selection for UEs. With RE, UE*k* will select NodeBl^k as its SNB according to the following rule:

$$l^k = \arg \max_{l \in \mathcal{N} \cup \mathcal{M}} \left(\varphi_{l,k} + \Delta_l \right), \tag{5}$$

where $\varphi_{l,k}$ is the received signal code power [11] measured at UE*k* on the DL pilot channel from NodeB*l*. Δ_l represents the extra bias for NodeB*l* and satisfies the following condition:

$$\Delta_l [\text{dB}] = \begin{cases} \delta \ (\delta > 0), & l \in \mathcal{M}, \\ 0, & l \in \mathcal{N}. \end{cases} \tag{6}$$

In HSPA, we can achieve this bias by setting the cell individual offset, which is a Radio Resource Control parameter [12]. As the bias increases, the number of UEs camped on LNBs will increase, which implicitly expands the coverage of LPNs.

When RE technology is applied in CcHH and LUE*k* is located in the RE area (shown in Fig. 1(b)), due to the large transmit power imbalance between MNB and LNB, the desired signal strength from the serving LNB of LUE*k* will probably be weaker than the interference from LUE*k*'s nearest non-serving MNB. In this case, LUE*k* may experience degradation in DL performance.

Based on the above discussion, we can conclude that it is necessary to put emphasis on applying and enhancing the IC scheme in CcHH to control the interference level. Additionally, considering that the centralized IC strategy will bring undesired complexity in a practical system, we will pay attention to the distributed/quasi-distributed IC scheme to make it applicable in practice.

III. Quasi-distributed Interference Coordination

In this section, a game-theoretic approach is used to develop our QDIC strategy for both the DL and UL in CcHH. To save power consumption and reduce the level of interference in the system, we impose the energy-efficient requirement to limit the transmit power of the NodeBs and UEs.

1. Downlink Quasi-distributed Interference Coordination

A. Downlink Game Formulation

To implement the DL IC in a quasi-distributed way, we propose a DL EENG (D-EENG) to achieve our QDIC in the DL. We define the following DL game:

$$\Omega_d = \left[\mathcal{N} \cup \mathcal{M}, \left\{ \mathcal{P}_{l,d} \right\}, \left\{ u_{l,d}(\cdot) \right\} \right]. \tag{7}$$

All NodeBs in set $\mathcal{N} \cup \mathcal{M}$ act as players. $\mathcal{P}_{l,d}$ is the strategy space of the DL transmit power for NodeB*l*. Let $\mathcal{P}_{l,d} = [\underline{p}_{l,d}, \overline{p}_{l,d}]$ be a convex compact set with NodeB*l*'s maximum and minimum DL power budgets denoted by $\overline{p}_{l,d}$ and $\underline{p}_{l,d}$, respectively. $u_{l,d}(\cdot)$ is the DL utility function for NodeB*l*. Considering the energy-efficient aspect, we define the utility as [13]

$$u_{l,d}\left(k_l, p_{l,d}, \mathbf{p}_{-l,d}\right) = \frac{r_{l,k_l,d}\left(p_{l,d}, \mathbf{p}_{-l,d}\right)}{p_{l,d} + p_{c,d}}, \tag{8}$$

where $p_{c,d}$ is the DL circuit power, which is regarded as the general energy consumption of device electronics in the DL. Thus, for each NodeB$l \in \mathcal{N} \cup \mathcal{M}$, D-EENG is constructed as follows:

$$\begin{aligned} (\textbf{D-EENG}) \ & \max_{p_{l,d} \in \mathcal{P}_{l,d}} u_{l,d}\left(k_l, p_{l,d}, \mathbf{p}_{-l,d}\right) \\ \textbf{s.t.} \ & \gamma_{l,k_l,d}\left(p_{l,d}, \mathbf{p}_{-l,d}\right) \geq \lambda_{l,k_l,d} \end{aligned}. \tag{9}$$

The constraint in (9) is explained as the QoS restriction, which implies that UEk_l scheduled by NodeB*l* should have a DL SINR $\gamma_{l,k_l,d}(p_{l,d}, \mathbf{p}_{-l,d})$ no less than the target SINR $\lambda_{l,k_l,d}$

to protect the link quality.

In (9), given the scheduling UEk_l and DL transmit power $\mathbf{p}_{-l,d}$ of other NodeBs, NodeBl has to adjust its own power to maximize its own utility as well as satisfy the QoS restriction regardless of other NodeBs' choices.

B. Downlink Power Optimization

For NodeB$l \in \mathcal{N} \cup \mathcal{M}$, when its scheduled UE$k_l$ and other NodeBs' power have been determined, the initial target of (9) will become

$$\begin{aligned} & p_{l,d}^* = f_{l,d}\left(k_l, \mathbf{p}_{-l,d}\right) = \arg\max_{p_{l,d} \in \mathcal{P}_{l,k_l,d}} u_{l,d}\left(k_l, p_{l,d}, \mathbf{p}_{-l,d}\right), \\ & \mathcal{P}_{l,k_l,d} = \left[\underline{p}_{l,k_l,d}, \overline{p}_{l,d}\right], \end{aligned} \tag{10}$$

where $f_{l,d}(k_l, \mathbf{p}_{-l,d})$ is called the best response correspondence (BRC) of NodeBl in the DL. While the maximum DL power for NodeB is constant in the system, the minimum DL power, $\underline{p}_{l,k_l,d}$, of NodeBl for UEk_l actually originates from the QoS restriction. Rewriting the constraint inequality in (9), we get

$$p_{l,d} \geq \frac{\lambda_{l,k_l,d}\left(\sigma_{k_l,d}^2 + \sum_{l' \in \mathcal{N} \cup \mathcal{M}, l' \neq l} p_{l',d} G_{l',k_l,d}\right)}{G_{l,k_l,d}} \triangleq p_{l,k_l,d}^{\dagger}. \tag{11}$$

Therefore, we have the expression of $\underline{p}_{l,k_l,d}$:

$$\underline{p}_{l,k_l,d} = \min\left(p_{l,k_l,d}^{\dagger}, \overline{p}_{l,d}\right). \tag{12}$$

Next, we will explore the existence of a Nash equilibrium for game (10). The Nash equilibrium for (10) is strictly defined as follows [14].

Definition 1. DL power vector $\mathbf{p}_d^* = \left(p_{l,d}^*\right), l \in \mathcal{N} \cup \mathcal{M}$ is a Nash equilibrium of game (10) if, for each $l \in \mathcal{N} \cup \mathcal{M}$, $u_{l,d}(k_l, p_{l,d}^*, \mathbf{p}_{-l,d}) \geq u_{l,d}(k_l, p_{l,d}', \mathbf{p}_{-l,d})$ for all $p_{l,d}' \in \mathcal{P}_{l,d}$.

To justify the existence of equilibrium for (10), we should find out whether utility $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d})$ in (10) is quasi-concave. We now give the definition of quasi-concavity [15].

Definition 2. Function $f(x)$ is known as strictly quasi-concave on convex set Z if, for each $\beta \in \mathbb{R}$, set $Z_\beta = \{x \in Z \mid f(x) \geq \beta\}$ is convex.

Based on Definition 2, we state and prove Lemma 1 to describe the quasi-concavity of utility $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d})$.

Lemma 1. $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d})$ is strictly quasi-concave in $p_{l,d}$.

Proof. Define auxiliary set Z_β:

$$\begin{aligned} & Z_\beta = \left\{p_{l,d} \in \mathcal{P}_{l,k_l,d} \mid u_{l,d}\left(k_l, p_{l,d}, \mathbf{p}_{-l,d}\right) \geq \beta\right\}, \beta \in \mathbb{R} \\ & \mathcal{P}_{l,k_l,d} = \left[\min\left(p_{l,k_l,d}^{\dagger}, \overline{p}_{l,d}\right), \overline{p}_{l,d}\right] \end{aligned}. \tag{13}$$

If $\beta \leq 0$, $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d}) \geq \beta$ will always hold because $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d}) \geq 0$, which means Z_β is a convex set. If $\beta > 0$, for any $p_{l,d}^1, p_{l,d}^2 \in Z_\beta$, we get (ignoring $\mathbf{p}_{-l,d}$ in the following expressions)

$$r_{l,k_l,d}\left(p_{l,d}^1\right) - \beta\left(p_{l,d}^1 + p_{c,d}\right) \geq 0, \tag{14}$$

$$r_{l,k_l,d}\left(p_{l,d}^2\right) - \beta\left(p_{l,d}^2 + p_{c,d}\right) \geq 0. \tag{15}$$

For any $t \in (0,1)$, define $\tilde{p}_{l,d} = (1-t)p_{l,d}^1 + tp_{l,d}^2$. Rewriting $(1-t)\times(14)+t\times(15)$, we have

$$(1-t) r_{l,k_l,d}\left(p_{l,d}^1\right) + t r_{l,k_l,d}\left(p_{l,d}^2\right) - \beta\left(\tilde{p}_{l,d} + p_{c,d}\right) \geq 0. \tag{16}$$

Since $r_{l,k_l,d}(p_{l,d})$ is quasi-concave in $p_{l,d}$, we get

$$r_{l,k_l,d}\left(\tilde{p}_{l,d}\right) \geq (1-t) r_{l,k_l,d}\left(p_{l,d}^1\right) + t r_{l,k_l,d}\left(p_{l,d}^2\right). \tag{17}$$

From (16) and (17), we can observe that

$$r_{l,k_l,d}\left(\tilde{p}_{l,d}\right) - \beta\left(p_{c,d} + \tilde{p}_{l,d}\right) \geq 0 \Rightarrow \tilde{p}_{l,d} \in Z_\beta, \tag{18}$$

which implies that set Z_β is convex. Based on Definition 2, we have Lemma 1 actually. ■

To facilitate the subsequent expressions, we define the following:

$$\begin{aligned} & A_{l,k_l,d} \triangleq \frac{G_{l,k_l,d}}{\Gamma\left(\sigma_{k_l,d}^2 + \sum_{l' \in \mathcal{N} \cup \mathcal{M}, l' \neq l} p_{l',d} G_{l',k_l,d}\right)}, \\ & \eta_{l,k_l,d} \triangleq A_{l,k_l,d} p_{c,d} - 1 > -1. \end{aligned} \tag{19}$$

Based on Lemma 1, we prove the existence of equilibrium and the BRC for power allocation in Theorem 1.

Theorem 1. If every NodeB has scheduled the serving UE, there exists equilibrium $\mathbf{p}_d^* = (p_{l,d}^*), l \in \mathcal{N} \cup \mathcal{M}$ in (10). For NodeBl, the corresponding BRC to this equilibrium of DL transmit power $p_{l,d}^*$ for its scheduling UEk_l should meet

$$p_{l,d}^* = \begin{cases} \min\left(\hat{p}_{l,k_l,d}, \overline{p}_{l,d}\right), \ \hat{p}_{l,k_l,d} > \underline{p}_{l,k_l,d}, \\ \min\left(p_{l,k_l,d}^{\dagger}, \overline{p}_{l,d}\right), \ \hat{p}_{l,k_l,d} \leq \underline{p}_{l,k_l,d}, \end{cases} \tag{20}$$

where $\hat{p}_{l,k_l,d}$ satisfies

$$\hat{p}_{l,k_l,d} = \begin{cases} \left(\dfrac{\eta_{l,k_l,d}}{A_{l,k_l,d} W_{-1}\left(\eta_{l,k_l,d}/e\right)} - \dfrac{1}{A_{l,k_l,d}}\right)^+, \ \eta_{l,k_l,d} < 0, \\ \left(\dfrac{\eta_{l,k_l,d}}{A_{l,k_l,d} W_0\left(\eta_{l,k_l,d}/e\right)} - \dfrac{1}{A_{l,k_l,d}}\right)^+, \ \eta_{l,k_l,d} \geq 0, \end{cases} \tag{21}$$

where $(\cdot)^+ \triangleq \max(\cdot, 0)$. $W_0(\cdot)$ and $W_{-1}(\cdot)$ are the real-valued principal and lower branches of the Lambert-W function [16].

Proof.

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1) Existence of equilibrium. For each NodeBl, given its scheduling UEk_l and other NodeBs' DL power, $\mathbf{p}_{-l,d}$, we write $u_{l,d}(p_{l,d})$ simply for $u_{l,d}(k_l, p_{l,d}, \mathbf{p}_{-l,d})$. Based on [17], game (10) will have Nash equilibrium if, for any NodeBl and its scheduling UEk_l, (i) strategy space $\mathcal{P}_{l,k_l,d}$ of (10) is a nonempty, compact, and convex subset of some Euclidean space and (ii) $u_{l,d}(p_{l,d})$ is continuous and quasi-concave in $p_{l,d}$. Lemma 1 has depicted the quasi-concavity of $u_{l,d}(p_{l,d})$ in $p_{l,d}$. So, both (i) and (ii) are met, which results in the existence of equilibrium for game (10).

2) BRC of transmit power. The partial derivative of utility $u_{l,d}(p_{l,d})$ with respect to $p_{l,d}$ is

$$\frac{\partial u_{l,d}\left(p_{l,d}\right)}{\partial p_{l,d}} = \frac{B\phi_{l,k_l,d}\left(p_{l,d}\right)}{\left(p_{l,d}+p_{c,d}\right)^2}, \tag{22}$$

$$\phi_{l,k_l,d}\left(p_{l,d}\right) = \frac{A_{l,k_l,d}\left(p_{l,d}+p_{c,d}\right)}{\ln 2\left(1+p_{l,d}A_{l,k_l,d}\right)} - \log_2\left(1+p_{l,d}A_{l,k_l,d}\right). \tag{23}$$

$\phi_{l,k_l,d}\left(p_{l,d}\right)$ actually determines the sign of (22). So, we get

$$\frac{\partial \phi_{l,k_l,d}\left(p_{l,d}\right)}{\partial p_{l,d}} = -\frac{A_{l,k_l,d}^2\left(p_{l,d}+p_{c,d}\right)}{\ln 2\left(1+p_{l,d}A_{l,k_l,d}\right)^2} < 0, \tag{24}$$

which implies that $\phi_{l,k_l,d}(p_{l,d})$ is monotonically decreasing in $p_{l,d}$. Then, we try to check the relevant limits of $\phi_{l,k_l,d}(p_{l,d})$. When $p_{l,d} \to 0$, we have

$$\lim_{p_{l,d}\to 0}\phi_{l,k_l,d}\left(p_{l,d}\right) = \frac{p_{c,d}A_{l,k_l,d}}{\ln 2} > 0. \tag{25}$$

On the contrary, if $p_{l,d} \to \infty$, we get

$$\lim_{p_{l,d}\to\infty}\phi_{l,k_l,d}\left(p_{l,d}\right) = \frac{1}{\ln 2} - \lim_{p_{l,d}\to\infty}\log_2\left(1+p_{l,d}A_{l,k_l,d}\right) < 0. \tag{26}$$

According to (24) through (26), we can assert there exists power $\hat{p}_{l,k_l,d} \in (0,\infty)$, making $\phi_{l,k_l,d}(\hat{p}_{l,k_l,d}) = 0$. Rearranging this formula, we obtain (27), which is a transcendental equation.

$$A_{l,k_l,d}\left(\hat{p}_{l,k_l,d}+p_{c,d}\right) = \xi_{l,k_l,d}\ln\xi_{l,k_l,d}, \tag{27}$$

$$\xi_{l,k_l,d} = 1+\hat{p}_{l,k_l,d}A_{l,k_l,d}. \tag{28}$$

With the aid of the real-valued Lambert-W function $W(\cdot)$ [16], we can derive $\hat{p}_{l,k_l,d}$ as follows:

$$\hat{p}_{l,k_l,d} = \left(\frac{\eta_{l,k_l,d}}{A_{l,k_l,d}W\left(\eta_{l,k_l,d}/e\right)} - \frac{1}{A_{l,k_l,d}}\right)^+. \tag{29}$$

If $\eta_{l,k_l,d} \geq 0$, Lambert-W function $W(\cdot) = W_0(\cdot)$ is injective, which leads to a single value for $\hat{p}_{l,k_l,d}$ in (29). When $\eta_{l,k_l,d} < 0$, function $W(\cdot)$ is not injective and holds two real-valued branches ($W(\cdot)$ and $W_{-1}(\cdot)$). Considering energy-efficiency, we prefer the lower $\hat{p}_{l,k_l,d}$, which can be achieved by $W_{-1}(\cdot)$ in (29) according to the definition of the Lambert-W function. So, we can derive the closed-form solution of $\hat{p}_{l,k_l,d}$ in (21).

When $\hat{p}_{l,k_l,d} \leq \underline{p}_{l,k_l,d}$, then $\phi_{l,k_l,d}(p_{l,d}) < 0$ always holds in $p_{l,d}$ and $u_{l,d}(p_{l,d})$ is strictly decreasing in $p_{l,d}$, which implies $\underline{p}_{l,k_l,d} = \min(p^{\dagger}_{l,k_l,d}, \overline{p}_{l,d})$ will maximize $u_{l,d}(p_{l,d})$. When $\underline{p}_{l,k_l,d} < \hat{p}_{l,k_l,d} < \overline{p}_{l,d}$, then $\phi_{l,k_l,d}(p_{l,d}) \geq 0$ holds at $p_{l,d} \leq \hat{p}_{l,k_l,d}$ and $\phi_{l,k_l,d}(p_{l,d}) < 0$ holds at $p_{l,d} > \hat{p}_{l,k_l,d}$. So, $u_{l,d}(p_{l,d})$ is first strictly increasing and then strictly decreasing in $p_{l,d}$, which implies $\hat{p}_{l,k_l,d}$ can maximize $u_{l,d}(p_{l,d})$. When $\hat{p}_{l,k_l,d} > \overline{p}_{l,d}$, then $\phi_{l,k_l,d}(p_{l,d}) > 0$ always holds in $p_{l,d}$ and $u_{l,d}(p_{l,d})$ is strictly increasing in $p_{l,d}$, which implies $\overline{p}_{l,d}$ can maximize $u_{l,d}(p_{l,d})$. Summarizing the above findings, we can finally get the BRC expression of transmit power in (20). ■

Based on Theorem 1, when the DL power of all NodeBs meets (20) and (21), the network will achieve the equilibrium state. Next, the uniqueness of equilibrium for game (10) will be explored. We first state and prove a lemma to illustrate that the DL BRC in (10) is a standard function [18].

Lemma 2. The DL BRC $f_{l,d}(k_l, \mathbf{p}_{-l,d})$ for NodeBl in (10) is a standard function in $\mathbf{p}_{-l,d}$, that is, $f_{l,d}(k_l, \mathbf{p}_{-l,d})$ satisfies the following properties.

- Positivity:

There always exists $f_{l,d}(k_l, \mathbf{p}_{-l,d}) > 0$.

- Monotonicity:

If $\mathbf{p}_{-l,d} \succ \mathbf{p}'_{-l,d}$, then $f_{l,d}(k_l, \mathbf{p}_{-l,d}) \succ f_{l,d}(k_l, \mathbf{p}'_{-l,d})$.

- Scalability:

For $\mu > 1$, there exists $\mu f_{l,d}(k_l, \mathbf{p}_{-l,d}) > f_{l,d}(k_l, \mu\mathbf{p}_{-l,d})$.

Proof.

1) Positivity. For every NodeBl, since $f_{l,d}(k_l, \mathbf{p}_{-l,d})$ is a meaningful power, we get $f_{l,d}(k_l, \mathbf{p}_{-l,d}) > 0$, which results in the positivity.

2) Monotonicity. Rewriting $A_{l,k_l,d}$ in (19), we have

$$\begin{aligned} A_{l,k_l,d} &\triangleq \frac{G_{l,k_l,d}}{\Gamma\left(\sigma_{k_l,d}^2 + I_{l,k_l,d}\right)}, \\ I_{l,k_l,d} &\triangleq \sum\nolimits_{l'\in\mathcal{N}\cup\mathcal{M}, l'\neq l} p_{l',d}G_{l',k_l,d}. \end{aligned} \tag{30}$$

$I_{l,k_l,d} = I_{l,k_l,d}(\mathbf{p}_{-l,d})$, which is related to parameter $\mathbf{p}_{-l,d}$, is the DL interference from other UEs to UEk_l served by NodeBl.

If BRC for NodeBl in (10) is $p^*_{l,d} = f_{l,d}(k_l, \mathbf{p}_{-l,d}) = \overline{p}_{l,d}$, on the basis of Theorem 1, $\partial p^*_{l,d}/\partial I_{l,k_l,d} = 0$ will always hold no matter what $\mathbf{p}_{-l,d}$ is. Similarly, if the BRC is $p^*_{l,d} = p^{\dagger}_{l,k_l,d}$, we get $\partial p^*_{l,d}/\partial I_{l,k_l,d} = \lambda_{l,k_l,d}/G_{l,k_l,d} > 0$, regardless of $\mathbf{p}_{-l,d}$.

Thus, the above analysis has justified part of the monotonicity.

When the BRC is $p^*_{l,d} = \hat{p}_{l,k_l,d}$, we rearrange (27) as

$$\begin{aligned}&\hbar_{l,k_l,d}\left(\hat{p}_{l,k_l,d}, I_{l,k_l,d}\right)=0\\&=G_{l,k_l,d}\left(\hat{p}_{l,k_l,d}+p_{c,d}\right)-\left(\frac{G_{l,k_l,d}}{A_{l,k_l,d}}+\hat{p}_{l,k_l,d}G_{l,k_l,d}\right)\ln\xi_{l,k_l,d}.\end{aligned} \tag{31}$$

By means of the implicit function theorem, there is

$$\frac{\partial\hat{p}_{l,k_l,d}}{\partial I_{l,k_l,d}}=-\frac{\frac{\partial\hbar_{l,k_l,d}\left(\hat{p}_{l,k_l,d},I_{l,k_l,d}\right)}{\partial I_{l,k_l,d}}}{\frac{\partial\hbar_{l,k_l,d}\left(\hat{p}_{l,k_l,d},I_{l,k_l,d}\right)}{\partial\hat{p}_{l,k_l,d}}}=\frac{\Gamma\left(\alpha_{l,k_l,d}-\ln\left(1+\alpha_{l,k_l,d}\right)\right)}{G_{l,k_l,d}\ln\left(1+\alpha_{l,k_l,d}\right)}, \tag{32}$$

where $\alpha_{l,k_l,d}=\hat{p}_{l,k_l,d}A_{l,k_l,d}>0$. Since $0-\ln(1+0)=0$ and $x-\ln(1+x)$ holds the positive first-order derivative if $x > 0$, we can affirm $\partial\hat{p}_{l,k_l,d}/\partial I_{l,k_l,d}>0$. So, by now, we have examined the whole monotonicity.

3) Scalability. If the BRC is $p^*_{l,d}=\overline{p}_{l,d}$, for $\mu > 1$, we have $\mu f_{l,d}(k_l,\mathbf{p}_{-l,d})=\mu\overline{p}_{l,d}>\overline{p}_{l,d}\geq f_{l,d}(k_l,\mu\mathbf{p}_{-l,d})$, which justifies part of the scalability.

When $p^*_{l,d}$ is either $\hat{p}_{l,k_l,d}$ or $p^{\dagger}_{l,k_l,d}$, we define function $\tilde{F}(\mu)\triangleq\mu f_{l,d}(k_l,\mathbf{p}_{-l,d})-f_{l,d}(k_l,\mu\mathbf{p}_{-l,d})$ and try to prove $\tilde{F}(\mu)>0,\forall\mu>1$. Observing that $\tilde{F}(1)=0$, we only have to confirm that $\tilde{F}(\mu)$ is non-decreasing in $\mu > 1$, which is equivalent to $\partial\tilde{F}(\mu)/\partial\mu\geq 0,\forall\mu>1$. Meanwhile, we get

$$\frac{\partial^2 p^*_{l,d}}{\partial I^2_{l,k_l,d}}=\begin{cases}\dfrac{\hat{p}_{l,k_l,d}\left(\alpha_{l,k_l,d}-\left(1+\alpha_{l,k_l,d}\right)\ln\left(1+\alpha_{l,k_l,d}\right)\right)}{\left(1+\alpha_{l,k_l,d}\right)\left(\left(\sigma^2_{k_l,d}+I_{l,k_l,d}\right)\ln\left(1+\alpha_{l,k_l,d}\right)\right)^2}, & p^*_{l,d}=\hat{p}_{l,k_l,d},\\ 0, & p^*_{l,d}=p^{?}_{l,k_l,d}.\end{cases} \tag{33}$$

As $0-(1+0)\ln(1+0)=0$ and $\overline{h}(x)\triangleq x-(1+x)\ln(1+x)$ holds the negative first-order derivative if $x > 0$, we can confirm $\overline{h}(x)<0$, which means $\partial^2 p^*_{l,d}/\partial I^2_{l,k_l,d}\leq 0$. So we get

$$\frac{\partial^2\tilde{F}(\mu)}{\partial\mu^2}=-\mathbf{p}^2_{-l,d}\frac{\partial^2 p^*_{l,d}}{\partial I^2_{l,k_l,d}}\geq 0, \tag{34}$$

which implies that $\partial\tilde{F}(\mu)/\partial\mu$ is non-decreasing in μ. So, we only have to prove the following formula for any $\mathbf{p}_{-l,d}$:

$$\tilde{f}_{l,d}\left(k_l,\mathbf{p}_{-l,d}\right)=\frac{\partial\tilde{F}(\mu)}{\partial\mu}|_{\mu=1}=f_{l,d}\left(k_l,\mathbf{p}_{-l,d}\right)-\mathbf{p}_{-l,d}\frac{\partial p^*_{l,d}}{\partial I_{l,k_l,d}}\geq 0. \tag{35}$$

According to (33) again, we obtain

$$\frac{\partial\tilde{f}_{l,d}\left(k_l,\mathbf{p}_{-l,d}\right)}{\partial\mathbf{p}_{-l,d}}=-\mathbf{p}_{-l,d}\frac{\partial^2 p^*_{l,d}}{\partial I^2_{l,k_l,d}}\geq 0. \tag{36}$$

From (36), we can say that $\tilde{f}_{l,d}(k_l,\mathbf{p}_{-l,d})$ is non-decreasing in $\mathbf{p}_{-l,d}$. Meanwhile, we also have $\tilde{f}_{l,d}(k_l,\mathbf{0})=f_{l,d}(k_l,\mathbf{0})>0$. Therefore, (35) actually follows, and we have examined the whole scalability. ■

On the basis of Lemma 2, we give the next theorem to state the uniqueness of equilibrium.

Theorem 2. If each NodeB has determined the scheduling UEs, there exists a unique equilibrium for game (10).

Proof. When the BRC of a non-cooperative game is a standard function, according to [18], this game will have a unique equilibrium. So, based on Lemma 2, we can confirm that game (10) holds a unique equilibrium. ■

Both the uniqueness of equilibrium and closed-form BRC in Theorem 1 provide the basis for the one-shot implementation.

C. Downlink Practical Implementation

In this part, we will investigate the feasibility of our proposed QDIC scheme in the practical HSPA HetNet system. Besides, an easy approach will be proposed to implement our QDIC scheme in practice.

In our original game (10), the BRC power of NodeB*l* for the scheduling UEk_l is connected with other NodeBs' power allocation, $\mathbf{p}_{-l,d}$, that is locally unavailable for NodeB*l*. Nevertheless, we observe that $\mathbf{p}_{-l,d}$ actually affects the BRC in the form of other NodeBs' DL interferences, $I_{l,k_l,d}$, in (30), which can be locally obtained by Node*l*. Therefore, $I_{l,k_l,d}$ surely contains sufficient information of $\mathbf{p}_{-l,d}$ to identify the BRC for NodeB*l* in a quasi-distributed way.

Specifically, at TTI$t-1$, every schedulable UEk_l of NodeB*l* measures and reports its DL interference term, $I_{l,k_l,d}\langle t-1\rangle$, to NodeB*l*. At TTI*t*, if UEk_l is scheduled and the DL transmit power of NodeB*l* for UEk_l is going to be determined, the following predicted utility is recommended.

$$\hat{u}_{l,d}\left(k_l\langle t\rangle,p_{l,d}\langle t\rangle\right)=\frac{B\log_2\left(1+\hat{\gamma}_{l,k_l,d}\left(p_{l,d}\langle t\rangle\right)/\Gamma\right)}{p_{l,d}\langle t\rangle+p_{c,d}}, \tag{37}$$

where $\hat{\gamma}_{l,k_l,d}\left(p_{l,d}\langle t\rangle\right)$ is the predicted DL SINR for UEk_l:

$$\hat{\gamma}_{l,k_l,d}\left(p_{l,d}\langle t\rangle\right)=\frac{G_{l,k_l,d}p_{l,d}\langle t\rangle}{\sigma^2_{k_l,d}+I_{l,k_l,d}\langle t-1\rangle}. \tag{38}$$

Based on (37) and (38), the initial D-EENG in (9) becomes

$$\begin{aligned}&\max_{p_{l,d}\langle t\rangle\in\left[\underline{p}_{l,k_l,d}\langle t\rangle,\overline{p}_{l,d}\right]}\hat{u}_{l,d}\left(k_l\langle t\rangle,p_{l,d}\langle t\rangle\right),\forall l\in\mathcal{N}\cup\mathcal{M},\\&\textbf{s.t.}\quad\hat{\gamma}_{l,k_l,d}\left(p_{l,d}\langle t\rangle\right)\geq\lambda_{l,k_l,d}\langle t\rangle,\end{aligned} \tag{39}$$

where minimum power budget $\underline{p}_{l,k_l,d}\langle t\rangle$ satisfies

$$\underline{p}_{l,k_l,d}\langle t\rangle=\min\left(p^{\dagger}_{l,k_l,d}\langle t\rangle,\bar{p}_{l,d}\right),$$
$$p^{\dagger}_{l,k_l,d}\langle t\rangle=\frac{\lambda_{l,k_l,d}\langle t\rangle\left(\sigma^2_{k_l,d}+I_{l,k_l,d}\langle t-1\rangle\right)}{G_{l,k_l,d}}. \tag{40}$$

With (37) through (40), when using Theorem 1 to get the BRC power of NodeBl for UEk_l at TTIt, we only need to replace item $I_{l,k_l,d}$ of $A_{l,k_l,d}$ in (30) with measured interference $I_{l,k_l,d}\langle t-1\rangle$. Therefore, the whole procedure of QDIC for the practical DL HSPA HetNet system can be encapsulated in Algorithm 1.

Algorithm 1. D-QDIC algorithm.
For each NodeBl and its scheduling UEk_l at TTIt,
do
i) **Initialize** $p^*_{l,d}=0$, $\bar{p}_{l,d}$
ii) **Input** $I_{l,k_l,d}\langle t-1\rangle$ and $\lambda_{l,k_l,d}\langle t\rangle$
iii) **Calculate** $p^{\dagger}_{l,k_l,d}\langle t\rangle$ and $\underline{p}_{l,k_l,d}\langle t\rangle$ based on (40)
iv) **Compute** $p^*_{l,d}$ for UE k_l according to (20), (21), $p^{\dagger}_{l,k_l,d}\langle t\rangle$, $\underline{p}_{l,k_l,d}\langle t\rangle$, and $I_{l,k_l,d}\langle t-1\rangle$.

In Algorithm 1, at TTIt, each NodeB independently calculates its own BRC based on the reported interference item of the last TTIt–1 from its scheduled UE. Therefore, at each TTI, there is no need to compute BRC iteratively for each NodeB because it only knows the reported interference information of the last TTI, which is completely determinate. So, each NodeB can only get its BRC once based on this determinate information, which has relatively lower complexity during each TTI.

2. Uplink Quasi-distributed Interference Coordination

A. Uplink Game Formulation

Similar to the DL game, the UL energy-efficient non-cooperative game (U-EENG) can be defined as

$$\Omega_u=\left[\mathcal{K},\{\mathcal{P}_{k,u}\},\{u_{k,u}(\cdot)\}\right]. \tag{41}$$

The UEs scheduled by their SNBs in set $\mathcal{K}$ act as the players. $\mathcal{P}_{k,u}$ is the strategy space of the UL transmit power for UE k. Let $\mathcal{P}_{k,u}=\left[0,\bar{p}_{k,u}\right]$ be a convex compact set with UEk's maximum UL power denoted by $\bar{p}_{k,u}$. $u_{k,u}(\cdot)$ is the UL utility function for UEk, which can be similarly defined as the energy-efficient form:

$$u_{k,u}\left(l^k,p_{k,u},\mathbf{p}_{-k,u}\right)=\frac{r_{l^k,k,u}\left(p_{k,u},\mathbf{p}_{-k,u}\right)}{p_{k,u}+p_{c,u}}, \tag{42}$$

where $P_{c,u}$ is the UL circuit power and $r_{l^k,k,u}(p_{k,u},\mathbf{p}_{-k,u})$ is defined in (4). l^k is the SNB of UEk. Therefore, for all UEs $k\in\mathcal{K}$, U-EENG is modeled as

$$(\textbf{U-EENG})\ \max_{p_{k,u}\in\mathcal{P}_{k,u}} u_{k,u}\left(l^k,p_{k,u},\mathbf{p}_{-k,u}\right). \tag{43}$$

The subtle difference between U-EENG and D-EENG mainly reflects in the absence of QoS restriction in U-EENG, which is attributable to the participation of NodeB in the power control procedure. In the HSPA UL, more precisely, the QoS assurance is mainly dominated by NodeB rather than UE itself, which motivates us to remove the QoS constraint from the U-EENG model. Instead, in the later subsection, an interaction process between NodeB and UE will be established to cooperate with our QDIC scheme in the UL HSPA.

B. Uplink Power Optimization

For UE$k\in\mathcal{K}$, when the powers of other scheduled UEs have been determined, the original problem (43) will become

$$p^*_{k,u}=f_{k,u}\left(l^k,\mathbf{p}_{-k,u}\right)=\arg\max_{p_{k,u}\in\mathcal{P}_{k,u}} u_{k,u}\left(l^k,p_{k,u},\mathbf{p}_{-k,u}\right), \tag{44}$$

where $f_{k,u}(l^k,\mathbf{p}_{-k,u})$ is the BRC of UEk in the UL. Again, to facilitate the next expressions, we define:

$$I_{l^k,k,u}\triangleq\sum\nolimits_{k'\in\mathcal{K},k'\neq k}p_{k',u}G_{l^k,k',u},$$
$$A_{l^k,k,u}\triangleq\frac{G_{l^k,k,u}}{\Gamma\left(\sigma^2_{l^k,u}+I_{l^k,k,u}\right)}, \tag{45}$$
$$\eta_{l^k,k,u}\triangleq A_{l^k,k,u}p_{c,u}-1>-1.$$

Then, similar to Theorem 1, we provide the following theorem to state the existence of equilibrium and the BRC of the UL transmit power for (44).

Theorem 3. If every NodeB has scheduled its UL serving UEs, there exists equilibrium $\mathbf{p}^*_u=(p^*_{k,u}),k\in\mathcal{K}$ in (44). For UEk, the corresponding BRC to this equilibrium of UL transmit power $p^*_{k,u}$ should satisfy

$$p^*_{k,u}=\min\left(\hat{p}_{l^k,k,u},\bar{p}_{k,u}\right), \tag{46}$$

where $\hat{p}_{l^k,k,u}$ meets

$$\hat{p}_{l^k,k,u}=\begin{cases}\left(\dfrac{\eta_{l^k,k,u}}{A_{l^k,k,u}W_{-1}\left(\eta_{l^k,k,u}/e\right)}-\dfrac{1}{A_{l^k,k,u}}\right)^+, & \eta_{l^k,k,u}<0,\\[2ex] \left(\dfrac{\eta_{l^k,k,u}}{A_{l^k,k,u}W_0\left(\eta_{l^k,k,u}/e\right)}-\dfrac{1}{A_{l^k,k,u}}\right)^+, & \eta_{l^k,k,u}\geq 0,\end{cases} \tag{47}$$

where $W_0(\cdot)$ and $W_{-1}(\cdot)$ are the real-valued principal and lower branches of the Lambert-W function.

Proof. It is similar to the proof of Theorem 1. ■

Furthermore, just like Theorem 2, the next theorem is provided to illustrate the uniqueness of equilibrium for (44).

Theorem 4. If each NodeB has determined the scheduling UEs for the UL transmission, there exists a unique equilibrium for (44).

Proof. It is similar to the proof of Theorem 2. ■

For the UL, Theorem 3 and Theorem 4 can be jointly applied to guarantee the one-shot pattern to achieve the BRC solution of game (44).

C. Uplink Practical Implementation

In game (44), $\mathbf{p}_{-k,u}$ affects $p^*_{k,u}$ in the form of other UEs' UL interference, $I_{l^k,k,u}$, in (45) at the SNBl^k of UEk. Therefore, UEs can get the interference information locally to implement the UL QDIC (U-QDIC).

More precisely, at TTIt−1, NodeBl^k measures and reports UL interference item $I_{l^k,k,u}\langle t-1\rangle$ to its serving UEk. At the next TTIt, if UEk is scheduled to implement the UL transmission and its UL transmit power is going to be identified, the following predicted utility is proposed for use.

$$\hat{u}_{k,u}\left(l^k, p_{k,u}\langle t\rangle\right) = \frac{B\log_2\left(1+\hat{\gamma}_{l^k,k,u}\left(p_{k,u}\langle t\rangle\right)/\Gamma\right)}{p_{k,u}\langle t\rangle + p_{c,u}}, \quad (49)$$

where $\hat{\gamma}_{l^k,k,u}\left(p_{k,u}\langle t\rangle\right)$ is the predicted UL SINR for UEk:

$$\hat{\gamma}_{l^k,k,u}\left(p_{k,u}\langle t\rangle\right) = \frac{G_{l^k,k,u}p_{k,u}\langle t\rangle}{\sigma^2_{l^k,u} + I_{l^k,k,u}\langle t-1\rangle}. \quad (50)$$

From (49) and (50), the original U-EENG in (43) becomes

$$\max_{p_{k,u}\langle t\rangle\in\left[0,\bar{p}_{k,u}\right]} \hat{u}_{k,u}\left(l^k, p_{k,u}\langle t\rangle\right), \forall k\in\mathcal{K}. \quad (51)$$

With the help of (49) through (51), when using Theorem 3 to get the BRC power of UEk at TTIt, we just need to replace item $I_{l^k,k,u}$ of $A_{l^k,k,u}$ in (45) with measured interference $I_{l^k,k,u}\langle t-1\rangle$.

In the practical UL HSPA+ system, on the other hand, UE is required to determine the transmit power level and data rate for the UL transmission by the procedure called enhanced dedicated channel transport format combination (E-TFC) selection. As for the existing E-TFC selection, the UL transmit power of UEk is restricted by maximum UL power $\bar{p}_{k,u}$ and the serving grant, which is sent from its SNBl^k. That is, UEk first gets UL transmit power $p^{rec}_{k,u}$, which is recommended by its SNBl^k in the form of a serving grant. Then, UEk chooses the smaller one between $\bar{p}_{k,u}$ and $p^{rec}_{k,u}$ as its transmit power, $\tilde{p}_k$. Finally, UE selects an E-TFC to maximize the amount of data that can be transmitted at the given power, $\tilde{p}_k$ [19]. The determined relationship between E-TFC and the transmit power is predefined in [20].

However, when the proposed U-QDIC is introduced into the current mechanism, it is necessary to focus on the influence that is brought to the existing E-TFC selection. Based on the above-mentioned considerations, we develop Algorithm 2, which embeds the proposed scheme in the current E-TFC selection procedure.

Algorithm 2. U-QDIC algorithm.
For each scheduled UEk at TTIt,
do
i) **Initialize** $p^*_{k,u}=0$, $\bar{p}_{k,u}$
ii) **Input** $I_{l^k,k,u}\langle t-1\rangle$ and serving grant from its SNBl^k
iii) **Compute** $p^*_{k,u}$ for UEk according to (46), (47), and $I_{l^k,k,u}\langle t-1\rangle$
iv) **Compute** $p^{rec}_{k,u}$ based on the serving grant acquired in ii)
v) **Get** the UL transmit power according to $\tilde{p}_k = \min(\min(p^*_{k,u}, p^{rec}_{k,u}), \bar{p}_{k,u})$
vi) **Implement** the conventional E-TFC selection procedure

Like Algorithm 1, Algorithm 2 is achieved in a one-shot fashion due to its implementation process.

IV. System-Level Simulation

1. Simulation Configurations

In the next subsection, we will provide some system-level simulation results to evaluate our proposed scheme in the DL and UL respectively. The simulation configurations are mainly based on [21]. We consider a CcHH that consists of 19 hexagonal wrap-around cells with three sectors per cell in the macro layer. The system bandwidth is 5 MHz and the carrier frequency is 2 GHz. M outdoor LNBs are uniformly dropped within each macro sector. The minimum distance between the MNB and LNB is 75 m. The channel fading is modeled as PA3 fast fading and log-normal shadowing fading. Path loss $v_{l,k}$ between NodeBl to UEk is

$$v_{l,k}\,[\text{dB}] = \begin{cases} 128.1+37.6\lg\left(d_{l,k}\right), & l\in\mathcal{N}, \\ 140.7+36.7\lg\left(d_{l,k}\right), & l\in\mathcal{M}, \end{cases} \quad (52)$$

where $d_{l,k}$ (km) is the distance between NodeBl and UEk.

We consider a situation in which the UE density is nonuniform and the total number of UEs per macro sector is K=16. We drop a configured percentage (p^{hotspot} = 50%) of UEs (hotspot UE) into a configured radius (R = 40 m) of each LPN cell while dropping the remaining UEs randomly and uniformly into the entire macro geographical area. The UE placement procedure is defined in detail in [21]. Each UEk holds the maximum power ($\bar{p}_{k,u}$ = 24 dBm) and applies the full buffer

Table 1. Other parameters.

Parameter	Macro layout	LPN layout
Inter-site distance	500 m	> 40 m
Min access distance	35 m	10 m
Shadow fading std. dev.	8 dB	10 dB
RE bias value	0 dB	3 dB
Max NodeB power	43 dBm	30 dBm
NodeB antenna pattern	3GPP 2D antenna	Omnidirectional

traffic model. The UE noise figure is 9 dB and the thermal noise density is –174 dBm/Hz. The circuit power for the DL and UL is 100 mW. The target RoT at each NodeB for the UL is 6 dB. Other parameters are listed in Table 1.

For the DL, we mainly consider four cases in our simulation:

- **Greedy power (GP).** Every NodeB transmits at its available power as much as possible.
- **Tight power (TP).** Every NodeB transmits at the tight power which is estimated to tightly meet the serving UE's QoS.
- **Pricing.** Use the pricing-based game [14] in the DL. As the pricing utility is different, our utility is used to evaluate the utility value generated from the pricing-based scheme for the consistent comparison in utility.
- **D-QDIC.** Each NodeB implements our D-QDIC scheme.

For the UL, we mainly consider three cases in our simulation:

- **No U-QDIC.** Every UE implements E-TFC selection without using our U-QDIC scheme.
- **Pricing.** Use the pricing-based game [14] in the UL.
- **U-QDIC.** Every UE implements our U-QDIC algorithm.

2. Simulation Results

For the DL case, Fig. 2 shows the utility and interference condition. As GP is the most energy-intensive case, it inevitably has the lowest utility. The interference in GP is very severe because of its high power level. Contrarily, TP enhances the utility and interference performance because it uses the feasible minimum power. Compared with TP, our D-QDIC can further improve the utility since our scheme has considered not only saving the power but also ensuring the practical serving QoS, which is ignored by TP. Although the interference in D-QDIC is slightly stronger than that in TP, we can still expect the better throughput performance of D-QDIC. In addition, the pricing-based scheme has the slightly worse performance of utility and interference compared with our D-QDIC scheme.

Figures 3(a) and 3(b) depict the average DL throughput of the sector cell and UE, respectively. It can be seen that our D-

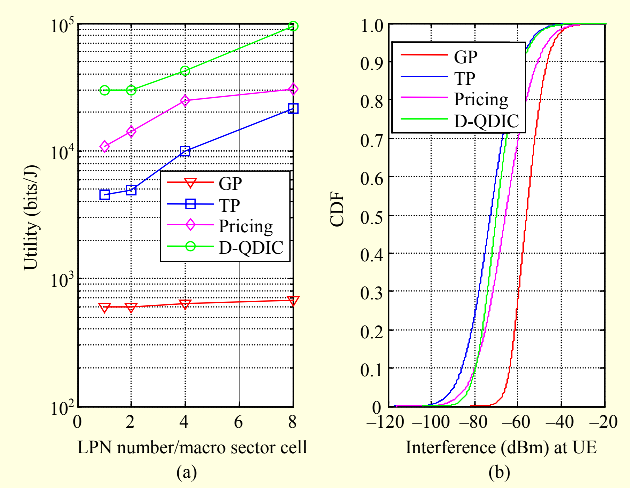

Fig. 2. (a) Average DL utility vs. M. (b) Interference CDF at UE side ($M = 4$).

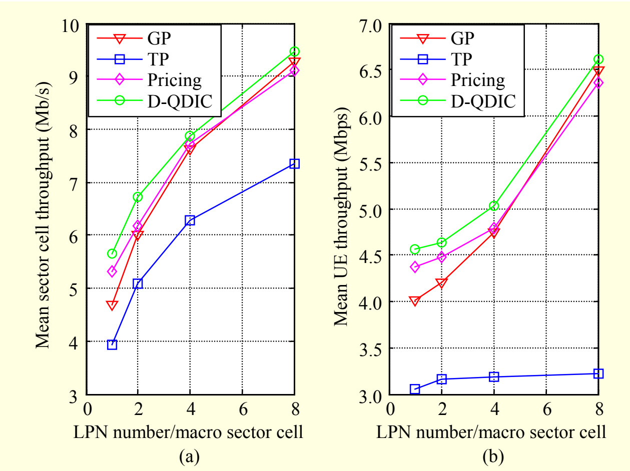

Fig. 3. (a) Average aggregated sector DL throughput vs. M. (b) Average UE DL throughput vs. M.

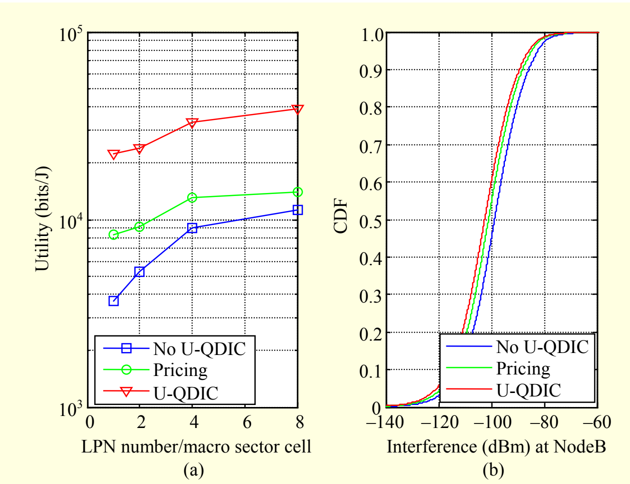

Fig. 4. (a) Average UL utility vs. M. (b) Interference CDF at NodeB side (M=4).

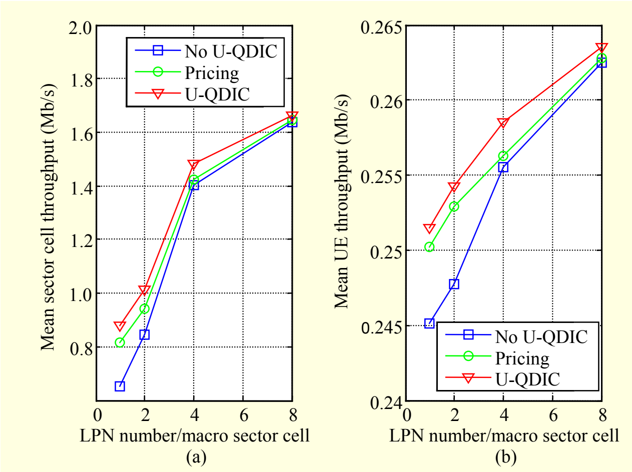

Fig. 5. (a) Average aggregated sector UL throughput vs. *M*. (b) Average UE UL throughput vs. *M*.

QDIC scheme has the best throughput performance compared with GP and TP. From the above results, we also observe that although TP has the best interference condition in Fig. 2(b), it does not provide adequate power to ensure the practical serving QoS, which leads to the dissatisfactory throughput performance. So, our D-QDIC scheme can not only enhance the efficiency of power resource but also mitigate the interference and improve the throughput performance for the DL. Also, the throughput performance of pricing is somewhat worse than that of our D-QDIC scheme.

For the UL case, Fig. 4 illustrates the utility and interference situation. Since our proposed U-QDIC has considered further limiting the UL transmit power in the process of E-TFC selection, the interference level for U-QDIC is naturally lower than that when U-QDIC has not been used in E-TFC selection. Meanwhile, the lower power caused by U-QDIC makes the average utility higher compared with the non-U-QDIC case. Besides, the pricing scheme in the UL also performs slightly worse than our proposed strategy.

Figures 5(a) and 5(b) show the average UL throughput of the sector cell and UE, respectively. Similar to the DL results, when E-TFC selection has been implemented along with our U-QDIC, both cell and UE average throughputs are increased compared with both the non-U-QDIC and pricing scheme, which can be attributed to the lower interference level shown in Fig. 4(b). Therefore, for the UL case, our scheme can also alleviate the interference and improve the system performance.

V. Conclusion and Future Work

In this paper, we proposed a QDIC scheme to deal with the interference in CcHH. Our QDIC scheme was modeled as a slightly different energy-efficient non-cooperative game. We justified the existence and uniqueness of the equilibrium for the game. Then, a closed-form best response of the game was derived. Finally, we developed a feasible implementation to apply our QDIC scheme in practice. We also provided simulation results to illustrate the advantages of our QDIC scheme.

In future work, our QDIC scheme can be extended into LTE/LTE-A HetNet to reduce the big burden coming from the information sharing in the existing CIC schemes. Considering the different resource structure of LTE/LTE-A, some related issues, such as the joint distributed power allocation based on game theory in both the time and frequency domains, remain to be reconsidered in the future extensions.

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