Femtocell Access Strategies in Heterogeneous Networks using a Game Theoretical Framework

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***Abstract*—In recent years, femtocell plays an important role in wireless networks not only for its spectrum reuse but also for its low power consumption. However, there exist several critical issues that need to be investigated, especially for the interferences between the macrocell BSs (mBSs) and femtocell BSs (fBSs). The level of interference mainly depends on the access strategies of fBSs. Two major access policies are considered in femtocell network, including the closed access mode and open access mode. The closed access mode only permits authorized subscribers to utilize the fBS; while all users are allowed to connect to the fBS by adopting the open access mode. Closed access will intuitively be advantageous to the femtocell subscribers, however, interference from the fBS to mBS's users can become severe in the closed access mode than in open access mode. System performance of the entire heterogeneous network (HetNet) can be improved if fBS is operated in the open access mode. In order to relax the inflexible access strategies, hybrid access policy is considered in this paper which allows nonsubscribers to possess limited connections to the fBS. Two cell selection games for distinct scenarios are theoretically modeled to formulate the behaviors of nonsubscribers, and the existences of pure strategy Nash equilibria are also proven under feasible utility functions. From the perspectives of subscribers, HetNet system, and operator, numerical results suggest the adoption of hybrid access mode to provide higher flexibility for the performance enhancement.**

***Index Terms*—Heterogeneous networks, femtocell access, game theory.**

I. Introduction

LONG-TERM evolution-advanced (LTE-A) techniques are proposed by the 3rd generation partnership project (3GPP) to provide higher spectrum efficiency and data rate. According to the technical report from 3GPP [1], the downlink and uplink peak data rates are respectively required to achieve 1 Gbps and 500 Mbps in order to fulfill the quality-of-service (QoS) requirement for the user equipment (UE). For achieving these objectives, imposing additional low-power base stations (BSs) into the original networks naturally becomes a feasible solution for increasing the spectrum efficiency and data rate. On the other hand, according to the statistical data in [2], it is expected that there will be nearly 90% of data services and 60% of phone calls taken place in indoor environments. Hence, femtocell BSs (fBSs) with the properties of short-range, low-power, low-cost, and plug-and-play are designed to connect into the end user's broadband line in order to provide high throughput and QoS for the UEs. Moreover, installation of fBSs can share the traffic load of its coexisting macrocell BSs (mBSs) [3].

For the macrocell/femtocell heterogeneous networks (HetNets), it has been studied in [4] that co-channel deployment of frequency spectrum can achieve higher system throughput than independent channel deployment because of spectrum reuse. However, critical challenge associated with femtocell technology is the co-channel interference if the fBSs utilize the same frequency spectrum as the overlay mBSs, especially in the case that fBSs are operated in the closed access mode. Note that the closed and open access modes are two different access methods for the femtocell. The closed access mode only allows specific UEs that possess proper authorization, i.e., *subscribers*, to access the corresponding fBS. In general, *subscribers* are the UEs who purchase closed access fBS in order to improve their own throughput; while the *nonsubscribers* are prohibited to access the closed accessed fBS. On the other hand, the open access mode provides all the UEs with the permission to connect and access the fBS. One severe problem for this type of HetNets is that the fBS will produce strong interference to those UEs that are situated close by this fBS but not connect to it. Apparently, this problem tends to occur in closed access mode since those *nonsubscribers* close to the fBS are not allowed to access it. Note that for the closed access mode, *nonsubscribers* are defined as the UEs who are not permitted to access the fBS; while *subscribers* represent those UEs that are authorized and allowed to connect with the fBS.

Different existing research works have been proposed to alleviate the interference problem for HetNets. Distributed utility functions are designed in [5], [6] to achieve minimum signal to interference plus noise ratio (SINR) for the femtocells, and the authors prove the existence of Nash equilibrium (NE) based on those utility functions. Novel preamble structure and self-organized power control scheme are proposed in [7] such that *nonsubscribers* can detect the signals from the mBS even if they are located close to fBS. By estimating the path loss between the fBS and mBS, a power control scheme for femtocell has been designed in [8] to reduce the interference with mBS. Considering the tradeoffs between the co-channel and independent channel deployments, a hybrid spectrum usage scheme has been proposed in [9] to take advantage of their corresponding merits for interference mitigation. Based on the LTE-A system, a simple and fast distributed resource allocation scheme is proposed in [10]

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associated with cell splitting, range expansion, and semi-static resource negotiation. By adopting the cognitive radio (CR) approach to sense the resource usage of mBS, a CR resource management scheme is proposed in [11] to deal with the interference problem between the fBS and mBS. For HetNets, the work in [12] divided the cell selection and resource allocation problem into two subproblems based on gaming models. The proposed distributed approaches drive UEs to converge to NEs. Considering cooperation between UEs, [13] proposed cooperative power game and obtained the coalition as a stable solution for the access control problem in HetNets. Moreover, game-theoretical model is constructed in [14] to analyze interaction between customers and operators. The authors proved the existence of Wardrop equilibrium and showed that the operator can maximize their revenue by predicting customers' behaviors.

Furthermore, the impacts from different access policies for femtocell networks have been studied in many existing works. Assuming that the distributions of UEs' locations follow homogeneous spatial poisson point process, the uplink capacity analysis and interference avoidance strategy were proposed in [15] for the HetNets. It has been described in [15] [16] and 3GPP [17] that open access mode can alleviate the interference and improve throughput for the entire network under feasible numbers of fBSs and UEs. Moreover, the gaming model for different access strategies from economic aspects are established in [18]. The authors conclude that it is beneficial to both operators and users if open access mode is adopted. Although the open access mode was suggested to increase the entire network throughput, this mode is an obvious obstruction to promote the popularization of femtocells since users will not be interested in installing fBSs but accessed by other users. Customer surveys [19] have shown that open access mode is a main drawback to persuade users to purchase the fBSs and also pay for the expense of backhaul network. The tradeoffs between closed and open access modes for both the *subscribers* and entire network system were investigated in [20], and the uplink performances were also evaluated. The authors in [21] suggested the necessity to adopt hybrid access mode since both the closed and open access modes suffer from various disadvantages. The hybrid access mode has been proposed in [22], [23] to allow limited numbers of *nonsubscribers* to connect to fBS in order to reduce co-channel interference. The authors in [23] proposed a solution to increase overall performance with the guarantee of required network throughput for *subscribers*. However, these hybrid access schemes consider the tradeoff between the *subscribers* throughput and total network throughput, which consequently sacrifice the maximum achievable performance of *subscribers*.

A crucial issue in HetNet will be investigated in this paper: which femtocell access strategy is recommended considering performance from the perspectives of *subscribers*, entire HetNet, and operator? To address the answer, *subscribers'* throughput, HetNet system throughput, and operator's revenue will be compared under closed, open, and hybrid access modes. In order to describe selfish behavior of individual UE, the cell selection schemes for *nonsubscribers* to access the fBS are formulated based on a theoretical gaming model. Both channel capacity and payment to the operator are considered for the utility function. Two different network scenarios are considered in our problem including co-channel spectrum deployment and independent channel deployment. Based on the defined cell selection games, the existence of a pure strategy NEs will be illustrated and proven. Noted that the proof for existence of NEs under a simplified network scenario which considers only large-scale fading was first presented in our previous work in [24].

Moreover, the concept of primary users (PUs) and secondary users (SUs) in CR approach, e.g., [25], [26], is applied to resolve the prioritized access issue for co-channel HetNet. In co-channel scenario, fBS utilizes the same spectrum as mBS, which may produce strong interference to mBS's UEs. In order to reduce this potential interference, the UEs that connect to the mBS are defined as the primary UEs (PUEs); while connected to fBS are defined as the secondary UEs (SUEs). Since PUEs have higher priorities to access spectrum than SUEs, SUEs can be served by fBS only if PUEs are not significantly interfered by fBS. While prioritized access issue is solved, interference to mBS's UEs can therefore be mitigated. Based on proposed two cell selection games, three main conclusions from numerical results of this paper are summarized as follows:

- Hybrid access mode is superior to closed access mode no matter which perspective, *subscribers*, entire HetNet, or operator revenue, is considered.
- Open access mode can result in higher capacity for the entire HetNet and greater revenue for operator compared to both the hybrid and closed access modes.
- *Subscribers* can obtain higher capacity in the hybrid access mode compared to both the open and closed access modes.

Notice that the *subscribers* can benefit more from hybrid access mode compared to closed access mode. This results is considered novel and different from general intuition that *subscribers* should possess higher capacity in closed access mode. With the adoption of hybrid access, the performance of entire network is slightly sacrificed; while the throughput of subscriber can be significantly augmented. Therefore, it can be concluded in this paper that hybrid access mode is a more suitable solution considering the performance of *subscribers*, performance of entire HetNet system, and operator's revenue compared to both the open and closed access modes. Note that some existing works, e.g., [22], [23], have also suggested hybrid access mode rather than closed access mode. However, none of these work considers the capacity of *subscribers*, the capacity of HetNets, and operator's revenue at the same time. Moreover, for cell selection in the HetNets, game theoretical models have never been utilized in existing research works to describe selfish behaviors of UEs. Most of existing works only focus on maximization of system capacity.

The rest of this paper is organized as follows. Cell selection game *I* which considers frequency reuse and large-scale fading are established in Section II. On the other hand, independent channel with both large-scale and small-scale fading are adopted for cell selection game *II* in Section III. Section IV illustrates performance evaluation for open, closed, and hybrid access modes. Conclusions are drawn in Section V.

II. Construction of Cell Selection Game I

In this section, cell selection game I will be established for the HetNets. Every player in the game will select either the femtocell or macrocell as its targeting access network according to its utilities. Existence of pure strategy NE is proven for arbitrarily utility function. In this case, the following network scenarios are considered: (a) large-scale fading including both path loss and shadowing, and (b) co-channel deployment between macrocell and femtocell.

A. Network Scenarios

The concept of CR is utilized to model the behaviors of spectrum-sharing and interference control between the femtocell and macrocell. As mentioned above, the UEs that connect to the mBS are defined as PUEs; while those connecting to fBS are defined as SUEs. This definition is feasible since the main purpose of licensed spectrum is to allow the UEs to access the macrocell; while the fBSs are considered auxiliary equipments to increase the probability of spectrum reuse. If a channel is utilized by a PUE, the SUE can only transmit data in the channel with interference constraint in order to guarantee the QoS requirements of PUE.

Fig. 1 illustrates the HetNet scenarios and the definitions of different types of UEs. Let R and R^C respectively be defined as a set of UEs whose reference signal receiving powers (RSRPs) from fBS are larger and smaller than that from mBS. By definition, all *subscribers* are considered in R in order to access their subscribing femtocell. The *nonsubscribers* can be classified according to whether they are in R or in R^C. Naturally, those *nonsubscribers* in R^C tend to select the macrocell as their target network, which are considered independent to our gaming problem. On the other hand, those *nonsubscribers* in R will have the choice to connect either to mBS or to fBS in order to pursue their maximum utilities. The set of *nonsubscribers* $\in R$ are denoted as the *players* in the game. To simplify the analysis, it is assumed that *subscribers* can only connect to the fBS. However, even *subscribers* are not players in this game, they are provided with the rights to affect the game, which will be explained in the next subsection. Notice that UE will execute cell selection or cell reselection procedure to find a suitable cell after power-on or link loss according to the LTE-A system [27]. Furthermore, let macro player and femto player be respectively defined as the player that connects to mBS and fBS. Based on CR concept, both *nonsubscribers* $\in R^C$ and macro players are considered as PUEs; while the *subscribers* and femto players are denoted as SUEs.

B. Existence of Pure Strategy NE

One of the major objectives in this paper is to observe the NE of a game, where the existence of NE should first be proven. There are two main types of NE defined in noncooperative game [28], i.e., the pure strategy NE and mixed strategy NE. Since the mixed strategies are considered impractical to describe the cell selection problem, the major concern in HetNet is to obtain the existence of pure strategy NE. To consider performance of all players in a more conservative manner, the utility functions of all players are assumed to be based on the player whose channel quality is the worst of all players, e.g., worst player (WP) in Fig. 1. Moreover, it is considered that the femto players have the same scheduling priority and preferences, and so do the macro players. The scheduling policies and preferences, i.e., capacity, power, cost, or security, cannot be determined since the total number of players connecting to the femtocell has yet to be decided in this game. Hence, the scheduling policies and preferences of the players are assumed to be identical within either the femtocell or macrocell. Note that it is implied that all players will possess the same utility function, and the utility function only depends on the number of players connecting to the femtocell. Based on [28], the following game can be defined to formulate cell selection problem.

Definition 1 (General Form of Cell Selection Game). *Consider the HetNet, a cell selection game is defined as a triplet*

$$\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle, \tag{1}$$

where $I = \{1, ..., N\}$ is a finite set of players, i.e., the set of nonsubscribers $\in R$, and N denotes the number of players. $(S_i)_{i\in I}$ represents the set of pure strategies, where S_i is the non-empty set of actions for player i. Let "0" and "1" be defined as the pure strategy of connecting to the mBS and fBS respectively for each player, i.e., $S_i = \{0,\ 1\}$. By defining $S = \prod_i S_i$ as the set of action profiles, $(u_i)_{i\in I}$ indicates the set of utility functions where $u_i : S \to \mathbb{R}$ is a function from the set of all action profiles S to real numbers.

Note that utility functions u_i of all players are identical as was explained in previous paragraph. Moreover, a tuple action profile is defined as (s_i, s_{-i}) where s_i and s_{-i} corresponds to the element in S_i and S_{-i} respectively. The set $S_{-i} = \prod_{j\neq i} S_j$ is denoted as the action profiles for all players except i. Note that the expression of action profile can be verbose owing to the element s_{-i}, e.g., $(s_i, s_{-i}) = (1, (1, 0, ...))$. Fortunately, every player will have the same utility function which only depends on its own strategy and the number of players except itself that connects to the fBS. Since the total number of players in cell selection game will be the major concern, the sum of all elements of s_{-i}, denoted as $\|s_{-i}\|_0$, will be considered instead of the individual element in s_{-i}. Note that $\|\mathbf{x}\|_0$ represents zero norm of vector $\mathbf{x}$, which is defined as the number of non-zero elements of $\mathbf{x}$. Therefore, the utility function for each player i can be stated as

$$u_i(s_i, s_{-i}) = \begin{cases} \tilde{u}_0(0, \|s_{-i}\|_0), & s_i = 0, \\ \tilde{u}_1(1, \|s_{-i}\|_0), & s_i = 1. \end{cases} \tag{2}$$

Note that $\tilde{u}_c$ represents the utility function of each player connecting to BS c, where $c = 0$ indicates mBS and $c = 1$ represents fBS. Both utility functions $\tilde{u}_0$ and $\tilde{u}_1$ only depend on the number of players connecting to the fBS. Note that $(s_i, \|s_{-i}\|_0)$ can contain different action profiles. For example, let $N = 5$ and $\|s_{-i}\|_0 = 2$, $(s_i, \|s_{-i}\|_0) = (1, 2)$ inherently represents various action profiles as $(1, (1, 1, 0, 0))$, $(1, (1, 0, 1, 0))$, $(1, (0, 1, 1, 0)), \ldots$, i.e., $u_i(1, (1, 1, 0, 0)) = u_i(1, (1, 0, 1, 0)) = u_i(1, (0, 1, 1, 0)) = \ldots = u_i(1, 2)$. Let $\|s\|_0 = s_i + \|s_{-i}\|_0 = \sum_i s_i$ be defined as the number of players that connect to the femtocell, (2)

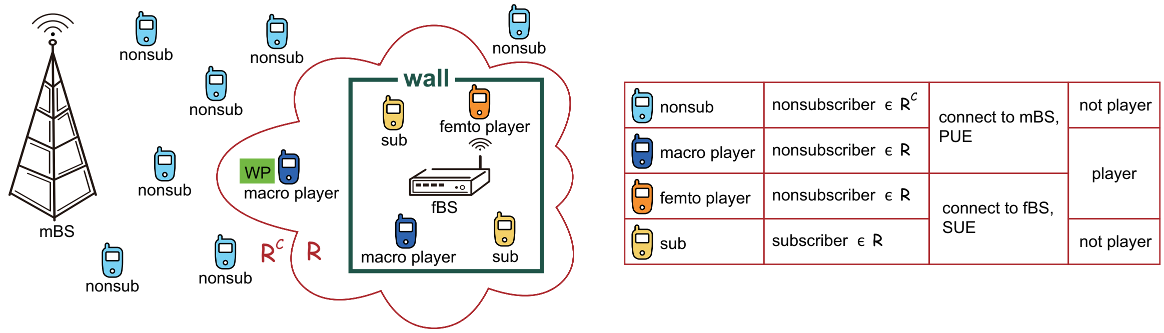

Fig. 1. HetNet scenario and the definitions of different types of UEs.

can further be simplified as

$$u_i(s) = \begin{cases} \tilde{u}_0(\|s\|_0), & s_i = 0, \\ \tilde{u}_1(\|s\|_0), & s_i = 1. \end{cases} \tag{3}$$

In order to prove the existence of a pure strategy NE of cell selection game, the potential game and its associated pure strategy NE as defined in [29] are stated as follows.

Definition 2 (Potential Game). *A function $\Phi : S \rightarrow \mathbb{R}$ is called a potential function for the game Γ if $\forall i, \forall s_{-i} \in S_{-i}$,*

$$u_i(x, s_{-i}) - u_i(y, s_{-i}) = \Phi(x, s_{-i}) - \Phi(y, s_{-i}), \forall\ x, y \in S_i. \tag{4}$$

If a potential function Φ exists, the game Γ is called a potential game.

Property 1. *The set $s^* \in S$ is a pure strategy Nash equilibrium (NE) of a potential game if and only if*

$$\Phi(s_i^*, s_{-i}^*) \geq \Phi(s_i, s_{-i}^*) \quad \forall i, \forall s_i \in S_i. \tag{5}$$

Note that potential function Φ is a global function which can be employed to express the incentive of all players to change their strategies. With this function, descriptions of players' interaction can be simplified. Based on the definition of potential game, the following theorem will illustrate the existence of a pure strategy NE for cell selection game *I*.

Theorem 1. *Cell selection game I $\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle$ is a potential game and has a pure strategy Nash equilibrium (NE).*

Proof: Based on Definition 1 for cell selection game *I* $\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle$, the potential function of this game can be selected as the combination of its utility functions defined in (3), i.e.,

$$\Phi(s) = \tilde{\Phi}(\|s\|_0) = \sum_{n=1}^{\|s\|_0} \tilde{u}_1(n) + \sum_{n=\|s\|_0}^{N-1} \tilde{u}_0(n). \tag{6}$$

It is observed from (3) that there are only two choices for each player, i.e., $u_i(s) = \tilde{u}_0(\|s\|_0)$ for $s_i = 0$ and $u_i(s) = \tilde{u}_1(\|s\|_0)$ for $s_i = 1$. Furthermore, since we are only interested in the total number of players, the relationship for potential game in (4) can be rewritten by substituting (6) as

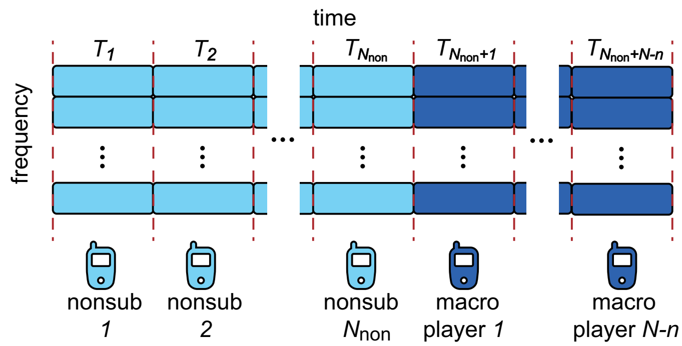

Fig. 2. Round robin scheduling in macrocell for cell selection game *I*.

$$\begin{aligned}
&\Phi(1, s_{-i}) - \Phi(0, s_{-i}) = \tilde{\Phi}(1 + \|s_{-i}\|_0) - \tilde{\Phi}(0 + \|s_{-i}\|_0) \\
&= \sum_{n=1}^{1+\|s_{-i}\|_0} \tilde{u}_1(n) + \sum_{n=1+\|s_{-i}\|_0}^{N-1} \tilde{u}_0(n) \\
&- \left[\sum_{n=1}^{\|s_{-i}\|_0} \tilde{u}_1(n) + \sum_{n=\|s_{-i}\|_0}^{N-1} \tilde{u}_0(n) \right] \\
&= \tilde{u}_1(1 + \|s_{-i}\|_0) - \tilde{u}_0(0 + \|s_{-i}\|_0) \\
&= u_i(1, s_{-i}) - u_i(0, s_{-i}).
\end{aligned} \tag{7}$$

It is observed from (7) that the defined cell selection game *I* belongs to the class of potential games, which indicates the existence of a pure strategy NE according to Property 1. This completes the proof. □

C. Utility Functions for Cell Selection Game I

Previous subsection proves the existence of pure strategy NE for general utility functions $\tilde{u}_0$ and $\tilde{u}_1$ under the specified assumptions. In this subsection, practical utility functions that focus on channel capacity and charging policy will be demonstrated. Considering round robin scheduling for downlink scenario, the time dimension is divided into equal-length slots for the usages of PUEs. Fig. 2 shows a specific time period of round robin scheduling in macrocell with N_{non} *nonsubscribers* $\in R^C$ and n players connecting to fBS, i.e., with $N-n$ players connecting to mBS. Therefore, there are total $N_{\text{non}} + N - n$ PUEs connecting to mBS. For each UE, RSRPs from serving cell and neighboring cell are measured by this UE and will be reported back to its serving cell. For example, under the situation that the UE connects to the mBS, the UE should also report the neighbor fBS' channel quality to the mBS. Therefore, mBS will be aware of all the channel qualities of PUEs. Let $Rsrp_{k,c}^{\text{PUE}}$ be denoted as the value of RSRP of kth PUE received from BS c (BS $c=0$ indicates mBS; while BS $c=1$ represents fBS), which can be written as

$$Rsrp_{k,c}^{\text{PUE}} = P_{\text{MAX},c} \cdot L_{k,c}^{\text{PUE}}. \tag{8}$$

The parameter $P_{\text{MAX},c}$ represents the maximum transmission power of BS c, and $L_{k,c}^{\text{PUE}}$ indicates the large-scale channel gain (including path loss, shadowing, penetration loss) between BS c and kth PUE. It is noted that the first N_{non} PUEs are *nonsubscribers* $\in R^C$; while the remaining PUEs are macro players. Let T_k be defined as the time slot utilized by mBS to serve kth PUE as shown in Fig. 2. It is considered that fBS can schedule SUEs during the time slot T_k if the interference from fBS to kth PUE is not significant. Note that this concept is similar as almost blank subframe (ABS) defined in the LTE-A systems [30]. In the ABSs, fBS is not allowed to transmit any message except for important ones, e.g., reference signals. Hence, macro players can be scheduled in the ABSs in order to obtain better link qualities. Let p_k be denoted as allowable power of fBS for data transmission during the time slot T_k. In order to reduce communication overhead between mBS and fBS, it is considered that fBS only has two power levels as follows:

$$p_k = \begin{cases} P_{\text{MAX},1}, & Rsrp_{k,0}^{\text{PUE}}[\text{dBm}] \geqslant Rsrp_{k,1}^{\text{PUE}}[\text{dBm}] + \beta, \\ 0, & Rsrp_{k,0}^{\text{PUE}}[\text{dBm}] < Rsrp_{k,1}^{\text{PUE}}[\text{dBm}] + \beta, \end{cases} \tag{9}$$

where the parameter β is a threshold to determine the interference level. Obviously, larger β can significantly reduce interference to PUEs. However, it will also reduce the available resource of fBS. Note that BS always transmits reference signals such that UE can measure RSRP and evaluate channel qualities. As mentioned in previous subsection, the performance of WP is utilized for the utility functions of all players. Considering that fBS allocates all its resource for WP, the cell capacity of fBS $C_{\text{fBS}}^{\text{WP}}$ given that n players connecting to fBS can be formulated as

$$C_{\text{fBS}}^{\text{WP}}(n) = \frac{W}{N_{\text{non}} + N - n} \cdot \sum_{k=1}^{N_{\text{non}}+N-n} \log_2\left(1 + \frac{p_k \cdot L_{\text{WP},1}}{\sigma_{\text{N}}^2 + P_{\text{MAX},0} \cdot L_{\text{WP},0}}\right). \tag{10}$$

The parameters W, $L_{\text{WP},c}$, and σ_{N}^2 respectively represent system bandwidth, large-scale channel gain between BS c and WP, and additive white Gaussian noise (AWGN) power over the system bandwidth. Moreover, in most situations, the fBS is not allowed to transmit any power during the slots from $T_{N_{\text{non}}+1}$ to $T_{N_{\text{non}}+N-n}$ since these slots are utilized by macro players. The fBS will produce strong interference to macro players if fBS transmits during those time slots owing to the reason that $Rsrp_{k,0}^{\text{PUE}} < Rsrp_{k,1}^{\text{PUE}} + \beta$ usually holds for $N_{\text{non}} + 1 \leqslant k \leqslant N_{\text{non}} + N - n$. Let $U = \sum_{k=1}^{N_{\text{non}}} \mathbf{1}(Rsrp_{k,0}^{\text{PUE}} < Rsrp_{k,1}^{\text{PUE}} + \beta)$, where $\mathbf{1}(\cdot)$ stands for indicator function, i.e., $\mathbf{1}(\text{True}) = 1$ and $\mathbf{1}(\text{False}) = 0$. Therefore, (10) can be rewritten as

$$C_{\text{fBS}}^{\text{WP}}(n) = \frac{(N_{\text{non}} - U) \cdot W}{N_{\text{non}} + N - n} \cdot \log_2\left(1 + \frac{P_{\text{MAX},1} \cdot L_{\text{WP},1}}{\sigma_{\text{N}}^2 + P_{\text{MAX},0} \cdot L_{\text{WP},0}}\right). \tag{11}$$

Since *subscribers* should possess higher priority to access the fBS, it is not fair for those players connecting to the femtocell to be designed with the same scheduling priority as *subscribers*. Therefore, a system admission control parameter, called closed rate α, is defined in this paper. It indicates that all *subscribers* can firstly be allocated with the ratio α of total resource for the femtocell, and all the SUEs will share the remaining $(1-\alpha)$ of resource. Hence, given that n players connecting to the fBS, each *subscribers* can share $\left(\frac{\alpha}{N_{\text{sub}}} + \frac{1-\alpha}{N_{\text{sub}}+n}\right)$ of resource. If $\alpha = 1$, $\left(\frac{1}{N_{\text{sub}}}\right)$ of resource represents that the femtocell is completely closed since total resource are allocated to the *subscribers*. On the other hand, if $\alpha = 0$, $\left(\frac{1}{N_{\text{sub}}+n}\right)$ of resource indicates that the femtocell is completely open. Note that the BS is assumed to always receive the connection requests from UEs if those UEs choose the BS as their serving station. However, the fBS can still control the total number of its serving UEs via the value of closed rate α. Moreover, each femto player can be allocated with $\left(\frac{1-\alpha}{N_{\text{sub}}+n}\right)$ of resource. Finally, let θ be defined as the price that operator can charge on each player who connects to fBS. The utility function $u_i(s)$ for each player i can be formulated as

$$u_i(s) = \begin{cases} \tilde{u}_0(\|s\|_0) = \dfrac{W}{N_{\text{non}} + N - \|s\|_0} \cdot \log_2\left(1 + \frac{P_{\text{MAX},0} \cdot L_{\text{WP},0}}{\sigma_{\text{N}}^2}\right), & s_i = 0, \\ \tilde{u}_1(\|s\|_0) = \dfrac{1-\alpha}{N_{\text{sub}} + \|s\|_0} \cdot C_{\text{fBS}}^{\text{WP}}(\|s\|_0) - \kappa \cdot \theta, & s_i = 1, \end{cases} \tag{12}$$

where $\kappa = 1$ Mbps is a constant such that $\frac{1-\alpha}{N_{\text{sub}}+\|s\|_0} \cdot C_{\text{fBS}}^{\text{WP}}(\|s\|_0)$ and $\kappa \cdot \theta$ possess the same unit. Furthermore, the operator can receive the amount of $\theta \cdot \|s\|_0$ as its revenue. All necessary parameters, e.g., α and $\|s\|_0$, will be added into the system information and periodically broadcast from fBS to UEs. Therefore, the UEs can observe the values of $\|s\|_0$ and α in order to calculate the utility functions. Moreover, best response, $B_i(s_{-i}) = \arg\max_{s_i} u_i(s_i, s_{-i})$, can be executed by each player i in turn to serve as a decentralized algorithm for achieving NE. In other words, according to the other players' strategies, each player can choose the best strategy to maximize its utility. Due to the property of potential game, cell selection game ensures to achieve an NE which can be obtained by best response mechanism. Note that the update process to NEs is asynchronous whereas the best response dynamics is still effective to achieve NEs. Those UEs can choose their best strategies according to the current value of $\|s\|_0$. Moreover, signaling overhead for cell selection is considered small since fast convergence rate to the NE can be achieved with the order of $(O(N))$. Due to the special structure of proposed utility function, it is obvious to observe that the convergence rate is $O(N)$ for the proposed cell selection game. The NEs are located at the local maximums of potential function, i.e., possible NEs are located at $\|s\|_0 = 0$, $\|s\|_0 = 1$, ..., and $\|s\|_0 = N$. Therefore, NEs can be observed if the local minimums of $\tilde{\Phi}(n), 0 \leq n \leq N$ are acquired, which naturally results in the convergence rate to be $O(N)$ for proposed cell selection game.

III. Construction of Cell Selection Game *II*

In previous section, it is considered that each player will possess the same utility function for cell selection game *I*. With this behavior, the existence of pure strategy NE can be proven for arbitrary utility function. In this section, cell selection game *II* will be established by considering that each player will have distinct utility function. With this specific property, the utility functions needs to be determined first in order to verify if there exist a corresponding strategy NE.

A. Network Scenarios and Utility Functions for Cell Selection Game *II*

In cell selection game *II*, independent channel deployment between macrocell and femtocell is considered. This corresponds to the network scenario that the fBS is located close to the mBS such that fBS cannot reuse the frequency spectrum with the overlay macrocell. This scenario is considered common in practice since the fBSs can be arbitrarily installed by the users in the network. The operator cannot guarantee that the locations of fBSs are located far away from the mBS. Moreover, for the utility function, different from cell selection game *I* that only considers large-scale fading, the channel model adopted in game *II* includes large-scale fading and small-scale fading where both slow fading and frequency selective fading are considered. The reason to additionally consider small-scale fading in this game is that the fBS is located close to mBS where short-distance effects should be included. On the other hand, since generic situation is considered in game *I* with same utility function for each player, sufficient long distance is assumed between the mBS and fBS such that only the dominating large-scale fading is included. It is assumed that a player will connect to a targeting network during a period of time which is much larger than the coherent time. Furthermore, the values of path loss and shadowing fading are considered fixed; while those of slow fading and frequency selective fading are random variables in cell selection game *II*. Note that slow fading means that the channels are almost time-invariant during the time period of packet transmission. However, it is still time-variant during the connection period to either the mBS or fBS since the coherent time is much shorter compared to connection time. In addition, the distribution of channel gain in each subchannel during every coherent time is assumed to be independent and identically distributed (i.i.d.) for a specific player. Considering slow fading effect, UEs can hardly transmit data if deep fade happens, i.e., very small channel gain, which will result in temporary failure of communication. Hence, for the utility function, the ϵ-outage capacity is employed for cell selection game *II*, which is defined as the largest capacity such that the outage probability is less than ϵ as shown in Fig. 3. For more details about ϵ-outage capacity, please refer to chapter 5 of

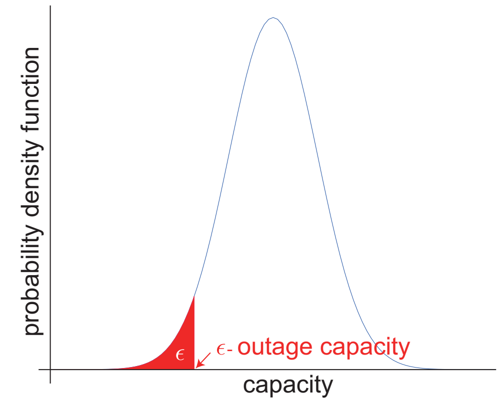

Fig. 3. ϵ-outage capacity

[31]. In order to derive the ϵ-outage capacity, it is necessary to formulate the distributions of capacity first. However, it is difficult to obtain accurate distributions of capacity for UEs since the number of samples of the distribution is not sufficient. Fortunately, the distribution of capacity in each coherent time can be approximated as Gaussian distribution if the number of subchannels is large enough.

Considering the scenario that the total available spectrum bandwidth W is divided into J subchannels with equal size. Since each player can measure RSRP for each subchannel, the capacity of ith player provided by BS c in subchannel j for all coherent times can be formulated as

$$\mathbf{C}_{i,c}^{j} = \frac{W}{J} \cdot \log_2\left(1 + \frac{P_{\mathrm{MAX},c} \cdot L_{i,c} \cdot |\mathbf{H}_{i,c}^{j}|^2}{\sigma_{\mathrm{N}}^2}\right). \qquad (13)$$

The parameters $L_{i,c}$ and $|\mathbf{H}_{i,c}^{j}|^2$ respectively represent the large-scale channel gain and small-scale channel gain in subchannel j for the link between the ith player and BS c. Note that $|\mathbf{H}_{i,c}^{j}|^2$ is considered i.i.d. for all j given specific i and c such that $\mathbf{C}_{i,c}^{j}$ can be simplified as $\mathbf{C}_{i,c}$. Since each player i can measure RSRP from BS c for subchannel j, J samples $(C_{i,c}^{j}, 1 \leqslant j \leqslant J)$ can be obtained to estimate the values of mean $\hat{m}_{i,c}$ and variance $\hat{\sigma}_{i,c}^2$ for $\mathbf{C}_{i,c}$ by $\hat{m}_{i,c} = \frac{1}{J}\sum_{j=1}^{J} C_{i,c}^{j}$ and $\hat{\sigma}_{i,c}^2 = \frac{1}{J-1}\sum_{j=1}^{J}(C_{i,c}^{j} - \hat{m}_{i,c})^2$. It is noted that $\hat{m}_{i,c}$ and $\hat{\sigma}_{i,c}^2$ are calculated during certain period of coherent time, but they can also be utilized to respectively represent estimated mean and variance for the future coherent time. Given that n players connect to the fBS, the number of UEs that connects to the fBS is $N_{\mathrm{sub}} + n$; while the number of UEs that connect to the mBS is $N_{\mathrm{non}} + N - n$. For fairness concern, the number of subchannels assigned to fBS is considered as $\frac{(N_{\mathrm{sub}}+n)\cdot J}{N_{\mathrm{non}}+N_{\mathrm{sub}}+N}$. It is intuitively that $\frac{(N_{\mathrm{sub}}+n)\cdot J}{N_{\mathrm{non}}+N_{\mathrm{sub}}+N}$ will not be an integer under most situations. Let ω_n and ρ_n be respectively denoted as integer and decimal parts of $\frac{(N_{\mathrm{sub}}+n)\cdot J}{N_{\mathrm{non}}+N_{\mathrm{sub}}+N}$ as follows

$$\omega_n = \left\lfloor \frac{(N_{\mathrm{sub}} + n) \cdot J}{N_{\mathrm{non}} + N_{\mathrm{sub}} + N} \right\rfloor, \qquad (14)$$

$$\rho_n = \frac{(N_{\mathrm{sub}} + n) \cdot J}{N_{\mathrm{non}} + N_{\mathrm{sub}} + N} - \left\lfloor \frac{(N_{\mathrm{sub}} + n) \cdot J}{N_{\mathrm{non}} + N_{\mathrm{sub}} + N} \right\rfloor. \qquad (15)$$

Therefore, as shown in Fig. 4, ω_n subchannels and ρ_n of time in a subchannel will be assigned to the fBS; while the remaining resource will be occupied by the mBS. In addition, round robin scheduling is also employed for mBS for fairness concern. Available time in each subchannel is divided as $N_{\text{non}} + N - n$ parts with equal length, each *nonsubscriber* $\in R^C$ or macro player will occupy one part, i.e., $\frac{1}{N_{\text{non}}+N-n}$ of available time. Given that n players connect to the fBS, let $\tilde{\mathbf{C}}_{i,c}(n)$ be denoted as a random variable of ith player's capacity during a period of coherent time if the ith player decides to connect to BS c, $\tilde{\mathbf{C}}_{i,0}(n)$ can first be written as

$$\tilde{\mathbf{C}}_{i,0}(n) = \frac{1}{N_{\text{non}} + N - n} \cdot \left[(1-\rho_n) \cdot \mathbf{C}_{i,0}^{\omega_n+1} + \left(\sum_{j=\omega_n+2}^{J} \mathbf{C}_{i,0}^{j} \right) \right]. \quad (16)$$

Since $\mathbf{C}_{i,0}^j$ for $\forall j$ are i.i.d., $\sum_{j=\omega_n+2}^{J} \mathbf{C}_{i,0}^j$ can approach Gaussian distribution if $J-\omega_n-1$ is large enough. Moreover, $\sum_{j=\omega_n+2}^{J} \mathbf{C}_{i,0}^j$ is much larger compared to $(1-\rho_n)\cdot \mathbf{C}_{i,0}^{\omega_n+1}$. Therefore, $\tilde{\mathbf{C}}_{i,0}(n)$ can be approximated to follow Gaussian distribution. Besides, as mentioned previously, $\hat{m}_{i,c}$ and $\hat{\sigma}_{i,c}^2$ are respectively employed for estimated values of mean and variance of $\mathbf{C}_{i,c}^j$. The estimated values of mean and variance of $\tilde{\mathbf{C}}_{i,0}(n)$ will be

$$\begin{aligned}
\mathrm{E}[\tilde{\mathbf{C}}_{i,0}(n)] =& \frac{1}{N_{\text{non}} + N - n} \cdot \\
& \left[(1-\rho_n)\cdot \hat{m}_{i,0} + (J-\omega_n-1)\cdot \hat{m}_{i,0} \right] \\
=& \frac{\hat{m}_{i,0}\cdot J}{N_{\text{non}} + N_{\text{sub}} + N}, \\
\mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)] =& \frac{1}{(N_{\text{non}} + N - n)^2} \cdot \\
& \left[(1-\rho_n)^2 \cdot \hat{\sigma}_{i,0}^2 + (J-\omega_n-1)\cdot \hat{\sigma}_{i,0}^2 \right] \\
\simeq & \frac{\hat{\sigma}_{i,0}^2 \cdot J}{(N_{\text{non}} + N - n)\cdot (N_{\text{non}} + N_{\text{sub}} + N)}. \quad (17)
\end{aligned}$$

Note that the approximation in $\mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)]$ is to provide clear formulation. As mentioned above, the utility function is based on the ϵ-outage capacity, which denotes the largest capacity such that the outage probability is less than ϵ. Let $\tilde{C}_{i,0}^{\epsilon}(n)$ be denoted as ϵ-outage capacity of the ith player if it connects to the mBS. Based on $\tilde{\mathbf{C}}_{i,0}(n) \sim \mathcal{N}(\mathrm{E}[\tilde{\mathbf{C}}_{i,0}(n)], \mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)])$, the following equation will hold.

$$Q\left(\frac{\tilde{C}_{i,0}^{\epsilon}(n) - \mathrm{E}[\tilde{\mathbf{C}}_{i,0}(n)]}{\sqrt{\mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)]}} \right) = 1-\epsilon, \quad (18)$$

where $Q(x)$ represents the Q-function defined as $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{r^2}{2}} dr$. Therefore, $\tilde{C}_{i,0}^{\epsilon}(n)$ can be obtained as

$$\tilde{C}_{i,0}^{\epsilon}(n) = Q^{-1}(1-\epsilon)\cdot \sqrt{\mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)]} + \mathrm{E}[\tilde{\mathbf{C}}_{i,0}(n)]. \quad (19)$$

Next, similar to cell selection game *I*, all *subscribers* can firstly be allocated with the ratio α of total resource for the femtocell. All the UEs that connect to the femtocell will share the remaining $(1-\alpha)$ ratio of system resource. As shown in Fig. 4, given that n players connect to fBS, each *subscriber* can occupy $\frac{\alpha}{N_{\text{sub}}} + \frac{1-\alpha}{N_{\text{sub}}+n} = \frac{N_{\text{sub}}+n\cdot\alpha}{(N_{\text{sub}}+n)\cdot N_{\text{sub}}}$ of time in each subchannel; while each femto player can share $\frac{1-\alpha}{N_{\text{sub}}+n}$ of time in each subchannel. Therefore, $\tilde{\mathbf{C}}_{i,1}(n)$ can be formulated as

$$\tilde{\mathbf{C}}_{i,1}(n) = \frac{1-\alpha}{N_{\text{sub}} + n} \cdot \left[\rho_n \cdot \mathbf{C}_{i,1}^{\omega_n+1} + \left(\sum_{j=1}^{\omega_n} \mathbf{C}_{i,1}^{j} \right) \right]. \quad (20)$$

Moreover, $\mathrm{E}[\tilde{\mathbf{C}}_{i,1}(n)]$ and $\mathrm{Var}[\tilde{\mathbf{C}}_{i,1}(n)]$ can respectively be obtained similar to the derivations of (17) as

$$\begin{aligned}
\mathrm{E}[\tilde{\mathbf{C}}_{i,1}(n)] &= (1-\alpha)\cdot \frac{\hat{m}_{i,1}\cdot J}{N_{\text{non}} + N_{\text{sub}} + N}, \\
\mathrm{Var}[\tilde{\mathbf{C}}_{i,1}(n)] &\simeq \frac{(1-\alpha)^2 \cdot \hat{\sigma}_{i,1}^2 \cdot J}{(N_{\text{sub}} + n)\cdot (N_{\text{non}} + N_{\text{sub}} + N)}. \quad (21)
\end{aligned}$$

Hence, ϵ-outage capacity of the ith player connecting to the fBS $\tilde{C}_{i,1}^{\epsilon}(n)$ can be formulated as

$$\tilde{C}_{i,1}^{\epsilon}(n) = Q^{-1}(1-\epsilon)\cdot \sqrt{\mathrm{Var}[\tilde{\mathbf{C}}_{i,1}(n)]} + \mathrm{E}[\tilde{\mathbf{C}}_{i,1}(n)]. \quad (22)$$

Finally, by incorporating (19) and (22), the utility function of the ith player can be written as

$$u_i(s) = \begin{cases} \tilde{C}_{i,0}^{\epsilon}(\|s\|_0), & s_i = 0, \\ \tilde{C}_{i,1}^{\epsilon}(\|s\|_0) - \kappa\cdot\theta, & s_i = 1. \end{cases} \quad (23)$$

Note that θ is the price that operator can take charge from each player who connects to the fBS, and $\kappa = 1$ Mbps is a constant such that $\tilde{C}_{i,1}^{\epsilon}(\|s\|_0))$ and $\kappa\cdot\theta$ have the same unit.

B. Existence of Pure Strategy NE

The general form of cell selection game as stated in Definition 1 will still be feasible for cell selection game *II*. However, since the characteristics of utility functions in cell selection game *II* are different from that in game *I*, the existences of pure strategy NEs should be re-proven. In order to prove the existence of pure strategy NE for cell selection game *II*, another important type of games called supermodular game [32], [33] is defined as follows.

Definition 3 (Supermodular Game). *According to Definition 1, the strategic form of cell selection game $\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle$ is a supermodular game if the following conditions are satisfied for all i:*

1. *The set S of feasible joint strategies is a sublattice of $\mathbb{R}^{\Sigma_{i=1}^N m_i}$, where m_i is the dimension of s_i;*
2. *u_i is supermodular in s_i on S_i, $\forall i, \forall s_{-i} \in S_{-i}$;*
3. *u_i has increasing differences in (s_i, s_{-i}).*

Note that a function $f(x)$ is supermodular on a sublattice X if

$$f(x) + f(x') \leq f(x \vee x') + f(x \wedge x'), \forall x, x' \in X, \quad (24)$$

where the notations "$\vee$" and "$\wedge$" are respectively defined as "join" (least upper bound) and "meet" (greatest lower bound), e.g., $(1\vee 0) = (0\vee 1) = 1$ and $(1\wedge 0) = (0\vee 1) = 0$. Note again that the sets S_i and $S_{-i} = \prod_{j\neq i} S_j$ are respectively denoted as the action profiles of ith player and the action profiles of all players except the ith player. Moreover, the function u_i has

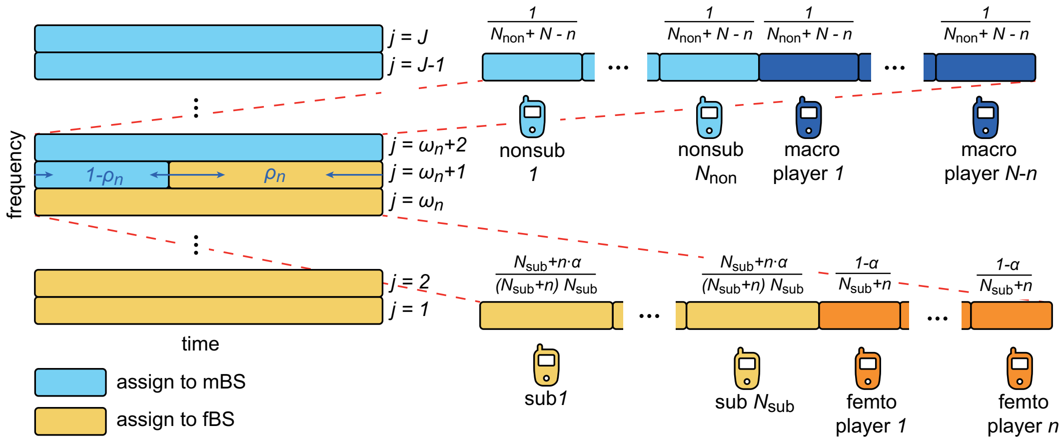

Fig. 4. Subchannel assignment and scheduling scheme for cell selection game *II*.

increasing differences[1] in (s_i, s_{-i}) can be denoted as

$$u_i(s_i, s_{-i}) - u_i(s'_i, s_{-i}) \geq u_i(s_i, s'_{-i}) - u_i(s'_i, s'_{-i})$$
$$\text{if } s_i \geq s'_i, s_{-i} \geq s'_{-i}, \forall i, \forall s_i, s'_i \in S_i, \forall s_{-i}, s'_{-i} \in S_{-i}. \quad (25)$$

Property 2. *If $\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle$ is a supermodular game, the set of strategies that survive iterated strict dominance, i.e., iterated elimination of strictly dominated strategies (IESDS), has the greatest NE $\overline{s}$ and the least NE $\underline{s}$.*

In Property 2, strictly dominated strategies represent the strategies that are never selected by a player regardless of the other players decisions, and IESDS is a process in which strictly dominated strategies from a game can be iteratively deleted. Moreover, the utility function for cell selection game *II* possesses the following property.

Property 3. *$\tilde{C}^{\epsilon}_{i,0}(n)$ in (19) and $\tilde{C}^{\epsilon}_{i,1}(n)$ in (22) are respectively monotonically non-increasing and non-decreasing with respect to n when $\epsilon \leq 0.5$.*

Clearly, both $\mathrm{E}[\tilde{\mathbf{C}}_{i,0}(n)]$ and $\mathrm{E}[\tilde{\mathbf{C}}_{i,1}(n)]$ are constant with respect to the parameter n. Moreover, $\mathrm{Var}[\tilde{\mathbf{C}}_{i,0}(n)]$ and $\mathrm{Var}[\tilde{\mathbf{C}}_{i,1}(n)]$ are monotonically non-decreasing and non-increasing with respect to n. Therefore, $\tilde{C}^{\epsilon}_{i,0}(n)$ in (19) and $\tilde{C}^{\epsilon}_{i,1}(n)$ in (22) are respectively monotonically non-increasing and non-decreasing with respect to n when $\epsilon \leq 0.5$. Based on the description above for supermodular game, the existences of pure strategy NEs for cell selection game *II* can be proven as follows.

Theorem 2. *The cell selection game II $\langle I, (S_i)_{i\in I}, (u_i)_{i\in I}\rangle$ is a supermodular game and has the greatest and the least pure strategy NEs $\overline{s}$ and $\underline{s}$ respectively if $\epsilon \leq 0.5$ for $u_i(s)$.*

Proof: The existence of pure strategy NE for cell selection game *II* can be proved based on the required three conditions of supermodular game as stated in Definition 3 as follows.

1. The feasible set of S_i is independent from S_{-i}, $\forall i$. Hence, the first condition of Definition 3 can be simplified as to check if the individual S_i is a sublattice of $\mathbb{R}$. Since $S_i = \{0, 1\}$, it is intuitive that $a \vee b \in S_i$ and $a \wedge b \in S_i$ $\forall a, b \in S_i$. Therefore, S_i is a sublattice of $\mathbb{R}$.
2. Intuitively, the following relationship can be be acquired:
$$u_i(s_i \vee s'_i, s_{-i}) + u_i(s_i \wedge s'_i, s_{-i})$$
$$= u_i(s_i, s_{-i}) + u_i(s'_i, s_{-i}), \forall i, \forall s_i, s'_i \in S_i, \forall s_{-i} \in S_{-i}. \quad (26)$$
Therefore, u_i is supermodular in s_i on S_i.
3. Based on Property 3, $\tilde{C}^{\epsilon}_{i,0}(\|s\|_0)$ and $\tilde{C}^{\epsilon}_{i,1}(\|s\|_0)$ are respectively non-increasing and non-decreasing with respect to $\|s\|_0$ when $\epsilon \leq 0.5$ for all i. If $s_{-i} \geq s'_{-i}$, $\forall s_{-i}, s'_{-i} \in S_{-i}$, it can be found that $1 + \|s_{-i}\|_0 \geq 1 + \|s'_{-i}\|_0$. Therefore, $\tilde{C}^{\epsilon}_{i,1}(1 + \|s_{-i}\|_0) - \theta \geq \tilde{C}^{\epsilon}_{i,1}(1 + \|s'_{-i}\|_0) - \theta$ such that $u_i(1, s_{-i}) \geq u_i(1, s'_{-i})$. Furthermore, since $\|s_{-i}\|_0 \geq \|s'_{-i}\|_0$, it can be acquired that $\tilde{C}^{\epsilon}_{i,0}(\|s_{-i}\|_0) \leq \tilde{C}^{\epsilon}_{i,0}(\|s'_{-i}\|_0)$ such that $u_i(0, s_{-i}) \leq u_i(0, s'_{-i})$. According to the above results, the following relationship can be obtained as
$$u_i(1, s_{-i}) - u_i(0, s_{-i}) \geq u_i(1, s'_{-i}) - u_i(0, s'_{-i}). \quad (27)$$

After all these three conditions are satisfied, The proof of cell selection game *II* to be a supermodular game can be completed. Note that ϵ is chosen as a small value for realistic cases. □

In addition, the NEs of cell selection game *II* can be obtained by iterating best response mapping [33], which indicates that the players in this iterated round choose their best strategies according to the results from previous iterated round. Moreover, similar as game *I*, by broadcasting all necessary parameters from fBS, e.g., α and $\|s\|_0$, the utility function can therefore be calculated by each player. the best response mapping can also be performed by each player i to serve as a decentralized algorithm for achieving NE.

IV. Performance Evaluation

The effectiveness of proposed cell selection games *I* and *II* will be evaluated in this section based on the defined utility functions. Consider a HetNet as shown in Fig. 1, there exists one mBS with radius of transmission range equal to 866 m and one fBS that is located at the center of room of 30 m × 30 m. The default system parameters and configurations are

[1]For some $x, y \in S_{-i}$, "$x \geq y$" if and only if $x_j \geq y_j, \forall j, x = \{x_1, \ldots, x_j, \ldots, x_{N-1}\}, y = \{y_1, \ldots, x_j, \ldots, y_{N-1}\}$.

TABLE 1 : SYSTEM PARAMETERS

Parameter	Value	
	Game *I*	Game *II*
Number of subchannels (J)	25	
System bandwidth (W)	5 MHz	
Number of indoor *subscribers* (N_{sub})	6	
Number of indoor *nonsubscribers*	8	
Number of outdoor *nonsubscribers*	10	
Max power of mBS ($P_{\text{MAX},0}$)	33 dBm	
Max power of fBS ($P_{\text{MAX},1}$)	10 dBm	
Noise figure	9 dB	
Channel noise density	-174 dBm/Hz	
Path loss (mBS $\to$ outdoor UE)	$15.3 + 37.6 \cdot \log_{10}(r)$	
Path loss (mBS $\to$ indoor UE)	$15.3 + 37.6 \cdot \log_{10}(r)$	
Path loss (fBS $\to$ outdoor UE)	$15.3 + 37.6 \cdot \log_{10}(r)$	
Path loss (fBS $\to$ indoor UE)	$38.46 + 20.0 \cdot \log_{10}(r)$	
Shadowing standard deviation (mBS $\to$ outdoor UE)	8 dB	
Shadowing standard deviation (mBS $\to$ indoor UE)	8 dB	
Shadowing standard deviation (fBS $\to$ outdoor UE)	8 dB	
Shadowing standard deviation (fBS $\to$ indoor UE)	4 dB	
Wall penetration loss	20 dB	
Distance between mBS and fBS (D)	500 m	200 m
Interference threshold (β)	10 dB	Not applicable
Max outage probability (ϵ)	Not applicable	0.05

listed in Table 1. The distance between the mBS and fBS is denoted as D. In addition, the locations of indoor and outdoor UEs are respectively uniformly distributed within the room and the maximum transmission range of mBS. Large-scale channel model including the path loss, shadowing, and wall penetration loss is adopted from [34] for both cell selection games *I* and *II*. Moreover, *nonsubscriber* will first measure the RSRPs respectively from the mBS and fBS to determine whether it is a player of cell selection game. If RSRP from fBS is larger than that from mBS, the *nonsubscriber* is a player. The *nonsubscriber* is not a player if RSRP from fBS is smaller than that from mBS. Note that $100,000$ simulation runs are conducted for the following Figs. 6 to 13. After computing 95% confidence intervals for $100,000$ simulation runs, the confidence interval is short enough to be regard as almost a point. Therefore, we will neglect identifying the confidence interval in our simulation results in order to provide clear numerical results.

A. Performance Evaluation for Cell Selection Game I

In this subsection, performance evaluation without the consideration of small-scale fading is conducted for cell selection game *I*. If not further specified, the distance between mBS and fBS (D), and the price value (θ) are respectively set as 500 m and 0. The left subplot of Fig. 5 shows the utility functions $\tilde{u}_0$ and $\tilde{u}_1$ for each player versus the number of players $\|s\|_0$ connecting to the fBS under $\alpha = 0.7$ for example 1 (denoted as ex1) and $\alpha = 0.4$ for example 2 (denoted as ex2). Note that each example respectively represents one simulation run of the game in order to clearly describe a player's utilities $\tilde{u}_0$ and $\tilde{u}_1$ and the corresponding NEs. It can be observed that $\tilde{u}_1$ in both cases decrease first, then increase with the augmentation of $\|s\|_0$. The reason is that two major factors that will affect the value of $\tilde{u}_1$, as $\|s\|_0$ increases, are enlarged total capacity of femtocell and less amount of resource shared

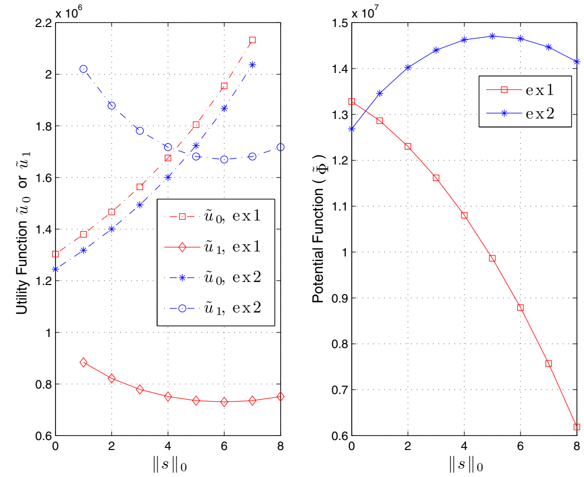

Fig. 5. Utility functions $\tilde{u}_0$ and $\tilde{u}_1$ (left subplot) for each player and their corresponding potential functions (right subplot) versus number of players connecting to the fBS $\|s\|_0$ under $\alpha = 0.7$ for ex1 and $\alpha = 0.4$ for ex2.

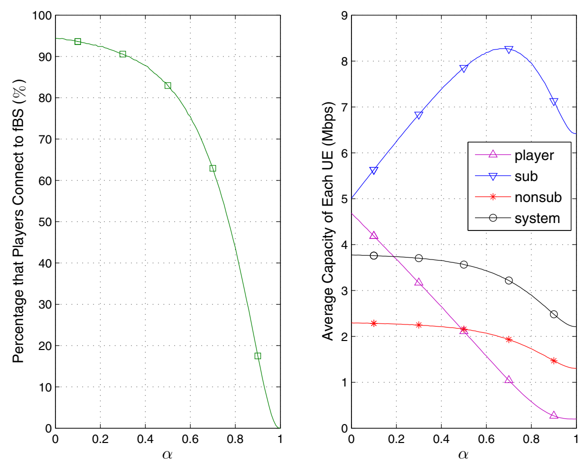

Fig. 6. Average percentage that players connect to the fBS at NE versus α (left subplot), and average capacity of each UE at NE versus α for player, *subscriber*, *nonsubscriber* $\in R^C$, and each UE in the system (right subplot).

for each femto player. The second factor dominates first factor under smaller $\|s\|_0$; while the opposite is true under the case of larger $\|s\|_0$. The right subplot of Fig. 5 illustrates the potential functions versus the number of players connecting to the fBS. The NEs of ex1 and ex2 are respectively located at $\|s\|_0 = 0$ and $\|s\|_0 = 5$ according to (5) in Property 1. It describes the characteristics of local maximum potential value that all players will not change their current strategies. Furthermore, compared to ex1 of $\alpha = 0.7$, the players in ex2 of $\alpha = 0.4$ will have more tendency connecting to the fBS. The reason is that its maximum potential value is located at a larger number of players $\|s\|_0 = 5$.

The left subplot of Fig. 6 demonstrates the average percentage that players connect to the fBS at NE decreases with the augmentation of α. The result is intuitive since lower α represents that there exists more femtocell resources for players to utilize, which will drive the players to connect to the fBS. On the other hand, players have the tendency to

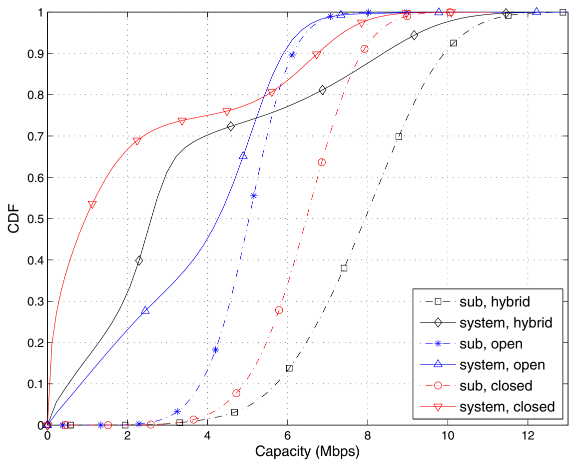

Fig. 7. CDF of capacity at NE for the *subscriber* and system in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

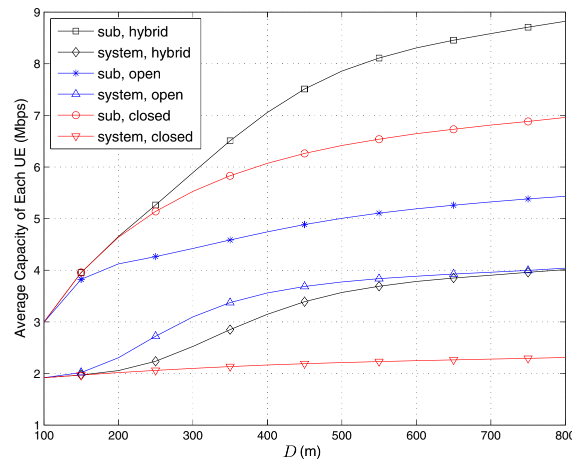

Fig. 8. Average capacity of *subscriber* and system UE at NE versus the distance between mBS and fBS (D) in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

connect to the mBS under the condition of larger α which can be explained in similar manners. The right subplot of Fig. 6 shows the average capacity of each UE at NE versus the closed rate α for different types of UEs, where the legends "player", "sub", "nonsub", "system" are respectively denoted as each player, *subscriber*, *nonsubscribers* $\in R^C$, and each UE in the HetNet system. It can be seen that the average capacity for each UE in the system, i.e., the "system" curve, decreases with increased value of α. This result reveals that better average system capacity can be achieved if the access policy can be adopted in a more open manner. Furthermore, the average capacity of *subscribers* has a peak value at $\alpha \simeq 0.7$, which indicates that there exists certain value of α such that the performance of *subscribers* in hybrid access mode is superior to that in both closed access mode ($\alpha = 1$) and open access mode ($\alpha = 0$). The reason for hybrid access mode to outperform closed access mode is that *subscribers* can acquire additional resource from those players connecting to the fBS in hybrid access mode. On the other hand, *subscribers* will not increase their capacity gain in closed access mode while there does not exist any player connecting to the fBS. Besides, the average capacities of players and *nonsubscribers* $\in R^C$ also decrease with the augmentation of α.

Fig. 7 shows the cumulative distribution function (CDF) of capacity at NE for both the *subscriber* and system in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. Note that only the *subscriber*'s and system UE's performances are displayed since one of the important purposes of this paper is to compare the performance tradeoff between the *subscriber* and system UE under different access policies. From the *subscriber*'s perspective, it can be seen that better performance can be obtained in hybrid access mode compared to the other two access strategies. Moreover, the entire system can lead to higher performance in open access mode relative to hybrid access mode for those UEs with relative worse performance; while the system performance in open access mode is inferior to that in hybrid access mode for those UEs with better performance. Therefore, by observing the gradually increasing trend of curve from open access mode as shown in Fig. 7, it can be intuitive concluded that higher fairness for resource sharing between the UEs can be achieved with the adoption of open access mode compared to hybrid access mode. Furthermore, considering the entire system, the performances for both the open and hybrid access modes are superior to that in closed access mode under most of cases.

Fig. 8 shows average capacity of *subscriber* and system UE at NE versus the distance D between mBS and fBS in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. It can be seen that average capacity of *subscriber* and system increase as D is augmented for all the three access modes. The major reason is that the femocell network is less interfered by the mBS under larger distance D. Moreover, hybrid access mode can achieve better balance of performance between *subscribers* and system UEs compared to open and closed access modes. The left subplot of Fig. 9 displays average capacity of *subscriber* and system UE at NE versus the price θ; while the right subplot shows average revenue that operator can charge versus the price θ in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. Note that average revenue that operator can receive is equal to $\theta \cdot \|s\|_0$. It can be seen from left subplot that the average capacity of both *subscriber* and system UE in closed access mode remain constant due to the reason that the players can only connect to mBS. Moreover, the performance in hybrid and open access modes will become closer to that in closed access mode as θ is augmented since higher charge will drive players to connect to mBS. With enlarged θ, average capacity of *subscriber* in open access mode increases owing to the reason that less players share the femtocell resource. Furthermore, it can be observed from right subplot that average revenues in open access mode is larger than that in hybrid access mode since more players tend to connect to the fBS in open access mode. In addition, both hybrid and open access modes have peak values respectively at $\theta \simeq 1$ and $\theta \simeq 2$, which represents that there exist a optimal price that operator can charge from players in order to maximize its revenue.

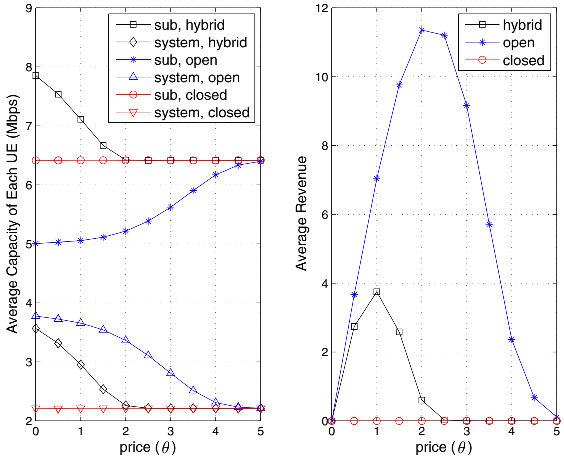

Fig. 9. Average capacity of *subscriber* and system UE at NE versus the price (θ) (left subplot), and average revenue that operator can charge versus the price (θ) (right subplot) in hybrid (with $\alpha = 0.5$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

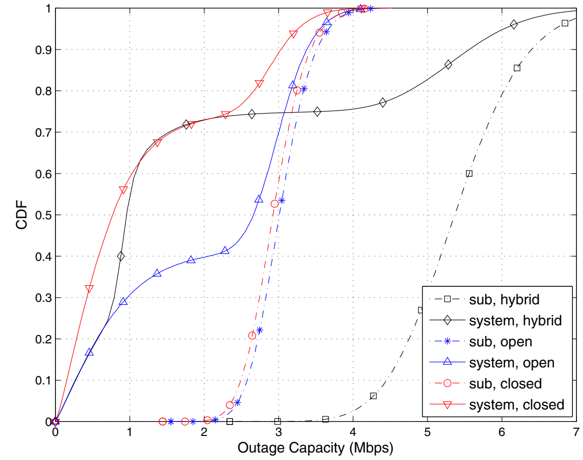

Fig. 11. CDF of outage capacity at NE for *subscriber* and system UE in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

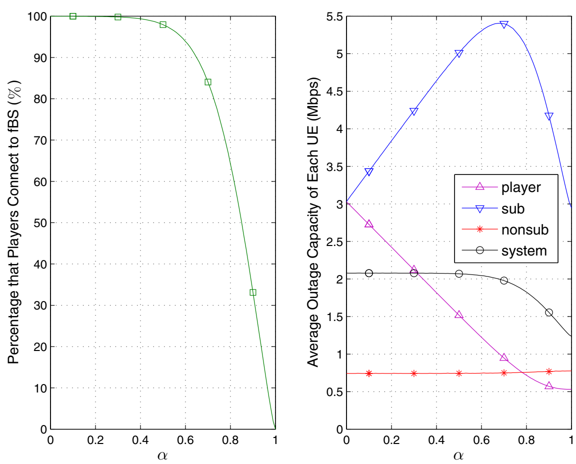

Fig. 10. Average percentage that players connect to the fBS at NE versus α (left subplot), and average outage capacity of each UE at NE versus α for player, *subscriber*, *nonsubscriber* $\in R^C$, and each UE in the HetNet system (right subplot).

B. Performance Evaluation for Cell Selection Game II

In this subsection, Rayleigh fading, i.e., $|\mathbf{H}_{i,c}^j|^2 \sim \text{Exp}(1)$, for each subchannel is additionally considered for small-scale fading. Besides, the NEs of cell selection game *II* can be obtained by iterating the best response mapping as in [33]. If not further specified, the distance between mBS and fBS (D) is chosen as 200m and the price value (θ) is set to be 0.

Fig. 10 displays the average percentage that players connect to the fBS at NE versus α, and average outage capacity of each UE at NE versus α for player, *subscriber*, *nonsubscriber* $\in R^C$, and each UE in the HetNet system. It can be observed that all the curves except for "non" have similar trend as their respective curves in Fig. 6. For instance, the performances of "player" and "system" decrease as parameter α is augmented; while a peak value occurs at $\alpha \simeq 0.7$ in the "sub" curve. On the other hand, enlarged α will drive the players to connect to the mBS, which result in *nonsubscribers* $\in R^C$ having more frequency diversity to achieve slightly higher outage capacity. In addition, it can be seen that the performances of *subscriber* at $\alpha = 0.0$ and $\alpha = 1.0$ are around the same. The reason is that none of the players are allowed to connect to the fBS in the closed access mode, *subscribers* cannot acquire additional system resource to utilize. On the other hand, for open access mode, *subscribers* will not be the beneficiary since extra channel resources are allocated for all players connecting to the fBS. Therefore, no matter either the open or closed access mode is employed, *subscriber's* available resources are observed to be identical. Although *subscriber's* available resources in the open and closed access mode are the same, more frequency diversity can be provided in open access mode compared to that in closed mode, which lead to *subscriber's* performance in open access mode slightly outperforms that in closed access mode. Moreover, it can be observed from the system UE's performance curve that open access mode is still superior to that in both hybrid and closed access modes.

Fig. 11 shows the CDF of outage capacity at NE for *subscriber* and system UE in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. Similar to the explanation as Fig. 7, the average outage capacity of *subscriber* in hybrid access mode still outperforms those in both closed and open access modes. Note that similar performance of *subscriber* is obtained from both the closed and open access modes, which is resulted from the design of parameter α as explained in previous paragraph. Furthermore, for system UE, the gradually increasing performance curve by the adoption of open access mode can provide better fairness than that from the hybrid access mode. It is also observed that the performance of both hybrid and open access modes are superior to that in the closed access mode.

Fig. 12 illustrates the average outage capacity of *subscriber* and system UE at NE versus the distance between mBS and fBS (D) in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. It can be observed that the average outage capacity of system UE in both hybrid and open access modes almost keep constant values for larger value of distance

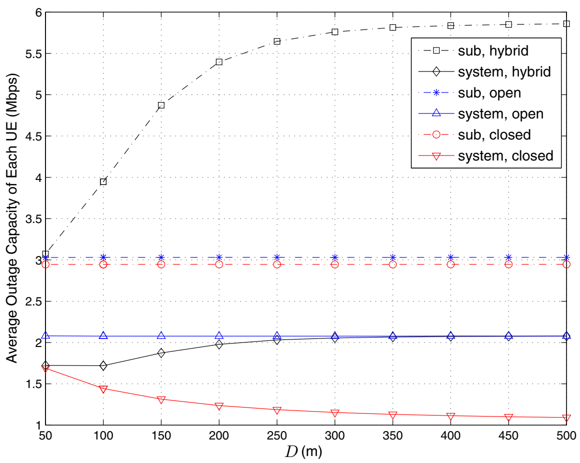

Fig. 12. Average outage capacity of *subscriber* and system UE at NE versus the distance between mBS and fBS (D) in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

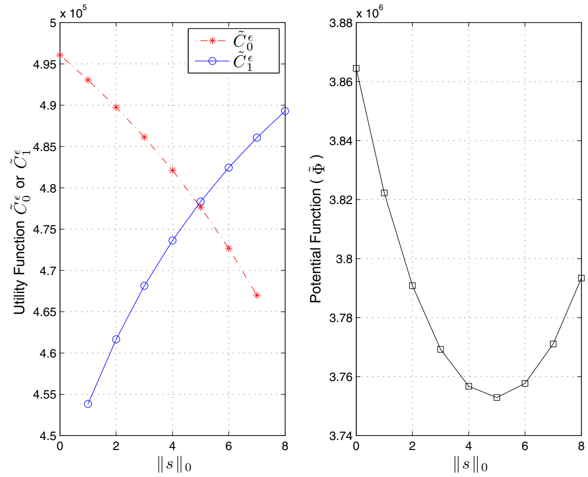

Fig. 14. Utility functions ($\tilde{C}_0^\epsilon$ and $\tilde{C}_1^\epsilon$) (left subplot) for all players and corresponding potential function (right subplot) versus number of players connecting to the fBS $\|s\|_0$.

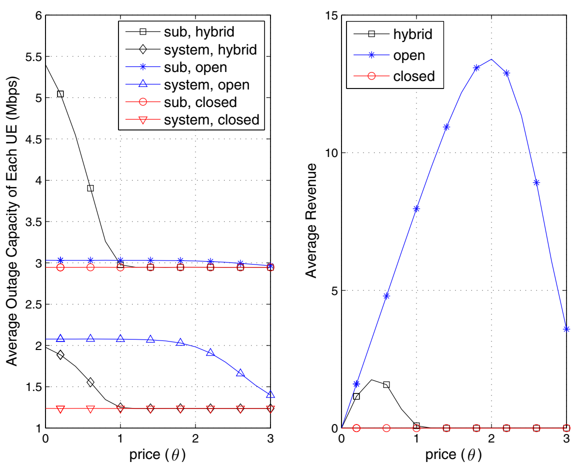

Fig. 13. Average outage capacity of *subscribers* and system UE at NE versus the price (θ) (left subplot), and average revenue that operator can charge versus the price (θ) (right subplot) in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes.

D. The reason for these performance curves not to increase as D is augmented is that the HetNet with independent-channel deployment is considered for cell selection game *II*, which does not benefit from the spectrum reuse of femtocell as that in cell selection game *I*. The outage capacity of system UE for closed access mode is decreased with the augmentation of D. The main reason is that all players decide to connect to the mBS, where the pathloss will be increased with the increment of distance D. Moreover, it can be seen that average outage capacities of *subscribers* in both open and closed access modes are around the same and almost keep constant as distance D is increased, which is resulted from the same reason of independent channel access.

The left subplot of Fig. 13 displays average outage capacity of *subscribers* and system UE at NE versus the price θ; while the right subplot illustrates average revenue that operator can charge versus the price θ in hybrid (with $\alpha = 0.7$), open ($\alpha = 0.0$), and closed ($\alpha = 1.0$) access modes. It can be observed that most curves have similar trend as their respective curves in Fig. 9. For example, the performance of hybrid and open access modes will become closer to closed access mode as θ is augmented, average revenues in open access mode is larger than that in hybrid access, and both hybrid and open access modes have peak values respectively at $\theta \simeq 0.4$ and $\theta \simeq 2$. In addition, the outage capacity of *subscriber* slightly decreases as θ is increased since the players tend to connect to mBS, which corresponds to the case that *subscribers* possess less channel diversities.

C. Special Case: NEs with different $\|s\|_0$ values for Cell Selection Games I and II

Whether the system converges to a better or a worse NE depends on the initial state. It is difficult to force UEs to achieve a better NE when the system is at the situation of a worse NE since UEs cannot communicate with each others. Therefore, we will observe the possibility to have the NEs with different $\|s\|_0$ values. In order to evaluate the occurring frequency of NEs with different $\|s\|_0$ values, one million simulation runs have been executed under $\alpha = 0.5$ and $\alpha = 0.7$ respectively for games *I* and *II*. Note again that it is possible to have multiple NEs in a game. For example, let $N = 5$ and NE occurs at $\|s\| = 2$, the locations of NEs become $(1, 1, 0, 0, 0)$, $(0, 1, 1, 0, 0)$, ..., and $(0, 0, 0, 1, 1)$. The occurrence of NEs with different $\|s\|_0$ values has not been observed for both games *I* and *II*. In other words, It can be seen from each simulation result that all NEs are with the same $\|s\|_0$ value. This result indicates that, in general situations, NEs are with the same $\|s\|_0$ value for the proposed games.

Nevertheless, for certain specific cases, these games may possess NEs with different $\|s\|_0$ values. Let's consider a special cell selection game *II* that all players are located at the same place, received wideband signal-to-noise ratio from mBS ($P_{\text{MAX},0} \cdot L_{i,0}/\sigma_{\text{N}}^2$) and from fBS ($P_{\text{MAX},1} \cdot L_{i,1}/\sigma_{\text{N}}^2$) are respectively 10 dB and 16 dB for player i. Obviously, this game is not only cell selection game *II*, but also game *I* since all players have the same utility function. Under the case of $\alpha = 0.4$, Fig. 14 illustrates the utility function defined by the outage capacity and the corresponding potential function. Note that $\tilde{C}^{\epsilon}_{i,0}$ and $\tilde{C}^{\epsilon}_{i,1}$ can be respectively simplified as $\tilde{C}^{\epsilon}_{0}$ and $\tilde{C}^{\epsilon}_{1}$ for Fig. 14 since all players have the identical utility function. It can be observed from the right plot of Fig. 14 that there exists two local maximum values at $\|s\|_0 = 0$ and 8, which respectively represent two NEs for the game. Moreover, since the game is also a supermodular game, the greatest NE at $\overline{s} = [1,1,1,1,1,1,1,1]$ ($\|s\|_0 = 8$) and the least NE at $\underline{s} = [0,0,0,0,0,0,0,0]$ ($\|s\|_0 = 0$) can still be obtained by iterating the best response mapping. Note that initial state will determine the final NE to be either $\|s\|_0 = 0$ or 8 from the perspective of potential function. For example, it is clear to observe from the right plot of Fig. 14 that the NE will be at $\|s\|_0 = 0$ if initial state is located within $0 \leq \|s\|_0 \leq 4$; while the NE will become $\|s\|_0 = 8$ if initial state is located within $6 \leq \|s\|_0 \leq 8$. On the other hand, the final NE may occur at either $\|s\|_0 = 0$ or $\|s\|_0 = 8$ if initial state is at $\|s\|_0 = 5$ since it is a local minimum within the range $0 \leq \|s\|_0 \leq 8$. This example shows that all NEs with the same $\|s\|_0$ cannot be guaranteed for both cell selection games *I* and *II*.

V. Conclusion

In this paper, two cell selection games are proposed for different network scenarios to describe the connection behaviors of *nonsubscribers* within the transmission range of femtocell base station. With the consideration of feasible utility functions for *nonsubscribers*, the existences of pure strategy Nash equilibria are respectively proven for the two cell selection games based on their distinct properties. Main numerical results of this paper can be summarized as follows:

- Hybrid access mode is superior to closed access mode no matter which perspective, *subscribers*, entire HetNet, or operator revenue, is considered.
- Open access mode can result in higher capacity for the entire HetNet and greater revenue for operator compared to both the hybrid and closed access modes.
- *Subscribers* can obtain higher capacity in the hybrid access mode compared to both the open and closed access modes.

Therefore, it is suggested to adopt hybrid access mode in order to provide higher flexibility for performance enhancement of all *subscribers*, entire system, and operator.

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