An Incentive Mechanism Design View for Hybrid Access in Small Cell Networks: Keeping a Secret Is Not Smart

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***Abstract*—In this paper, we investigate the hybrid access control policy in two-tier small cell networks from the perspective of incentive mechanism design, considering macro-cell base station's (MBS) private information. Then, we formulate this problem as a Stackelberg game. To be specific, the MBS and small cell base stations (SBSs) are modeled as leader and followers, respectively. A subsidy mechanism is adopted by MBS when the SBS can provide acceptable service level for macro user equipment. Moreover, we consider the impacts of MBS's private information on the Stackelberg equilibrium (SE) of the proposed game, and we present the equilibrium analysis and relationship under different available information circumstances. To obtain relatively satisfactory outcome for both MBS and SBS, we discuss the design of bargaining scheme based on the SE. Theoretical analysis and simulation results show that it is better for MBS to broadcast the private information to get more payoff from the perspective of incentive mechanism design.**

***Index Terms*—Bargaining, hybrid access, private information, smallcell, Stackelberg game.**

I. Introduction

SMALL cells have recently emerged as an efficient solution for the next generation communication system, also known as 5G, to boost network throughput and enhance mobile users' quality of experience (QoE) [1]–[3]. Different from traditional macro-cell base station (MBS), small cell base station (SBS) is a low power short-range wireless access point, overlaying the MBS. Thus, SBS can provide higher frequency reuse in spatial domain [4].

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Generally, there are mainly three access control mechanisms for small cells: open access, closed access, and hybrid access [5]. In open access mode, SBS permits any nearby mobile users to communicate with it; however, that may result in SBS's throughput degradation. On the other hand, closed access mode is a completely opposite manner compared to open access and SBS only serves the licensed small cell user equipments (SUEs) with quality of service (QoS) guarantee. On the contrary, the co-channel macro user equipments (MUEs) may be the victim users and suffer severe cross-tier interference from nearby SBSs. Hybrid access mode is a tradeoff between open access and closed access, which allows SBS to provide service for partial licensed MUEs. Hybrid access mode can significantly improve the victim MUEs' performance and reduce the cross-tier interference. However, in reality, some typically exclusive small cells, such as femtocells, are deployed by enterprises or users in plug-and-play manner and connect to core networks through broadband backhaul (i.e., digital subscriber line). Exclusive SBSs have no incentive to open partial spectrum resource for MUE due to loss of the associated SUEs' benefits. From the perspective of SUE's profits, SUEs are more favorable to the closed access mode for privacy protection and performance enhancement rather than the hybrid manner. Consequently, the practical challenge to implement the hybrid access for SBSs is the sophisticated and attractive design of the incentive mechanism to compensate SBSs.

Game theory provides a powerful framework to analyze the interactions amongst selfish and rational players, and it has been widely applied for resource allocation in wireless communication systems[6]–[9]. Stackelberg game, also known as leader–follower game, is widely applied to model the hierarchical interaction among players with different priorities. Thus, it is naturally applied to model the hierarchical competition in two-tier small cell networks [10]–[13] and antijamming communications [14], [15]. However, most of the existing studies based on game theory assume that the players involved in game have perfect and complete information. Due to the dynamic wireless environment and players' limited ability to acquire information, the full information assumption is not reasonable. In reality, the uncertainty in information will be present including users' type, physical presence, packet traffic, system parameters, and physical channel [16]. On the other hand, there exists information asymmetry among players in some specific scenarios, i.e., partial players involved in game have some private information; therefore, they own information advantage and are unwilling to broadcast their private information to others [17].

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In this paper, considering MBS's private information, we investigate the hybrid access control in two-tier small cell networks from the perspective of incentive mechanism design. The main contributions of this paper can be summarized as follows.

1) We formulate the hybrid access control problem in small cell networks as a *Stackelberg game:* MBS and SBSs are leader and followers in the proposed game, respectively. To encourage SBS opening partial resource for nearby MUE, MBS provides subsidy to compensate SBS's loss. Meanwhile, MBS can decide whether to adopt the subsidy policy based on the current system configuration, i.e., if the SBS cannot provide acceptable service experience for MUE, MBS serves MUE by itself.
2) Considering the impacts of MBS's private information, we analyze the equilibrium of the one-MBS and one-SBS game for two different scenarios based on the MBS's utility information availability for SBS: *partial MBS's utility information scenario* (PIS) and *complete MBS's utility information scenario* (CIS). We prove the existence and uniqueness of Stackelberg Equilibrium (SE) in PIS. Moreover, we reveal the equilibrium relationships between CIS and PIS.
3) We extend our proposed game to one-MBS and multi-SBS scenario and show that the game can be transferred to one-MBS and one-SBS game with introducing an extra information, relating to the biggest competitor among SBSs for the potential winner SBS.

The rest of the paper is organized as follows. In Section II, we review the related work. Section III introduces the system model and problem formulation. Section IV presents a hierarchical joint user scheduling and power control game, then the implement process and some discussions are presented in Section V. Extensive simulations are performed and the convergence and effectiveness of proposed hierarchical game are demonstrated in Section VI. Finally, the conclusions are drawn in Section VII.

II. Related Work

In this section, some related studies are presented. There exist some efforts on the resource allocation and interference management in small cell networks. Centralized schemes, mostly based on the convex optimization techniques, have the advantage of finding the global optimal solution to maximize the network performance [18]–[21]. Nevertheless, these schemes generally face rapidly increasing computational complexity with the increase in the network scale. Furthermore, they need largely and timely information exchange. Due to the randomness of SBS's activity and lack of mutual coordination, it is desirable to design distributed schemes. Game theory provides a theoretic framework to analyze interactions among conflicting players and predict the stable outcome such as the solution concept equilibrium. For the game-based incentive mechanism of hybrid access control, in [22], Chen *et al.* proposed a utility-aware refunding framework for hybrid access femtocell networks. A refunding mechanism is adopted by a wireless service provider to compensate the femtocells that implement hybrid access and spare transmission time to MUE. In [23], Shen *et al.* studied the user-centric energy aware compensation framework to motivate the hybrid access in the uplink transmission of the femtocell network. In [24], Hamouda *et al.* presented a price-based hybrid access mechanism, in which macro-eNodeB imposes a price on the HeNBs' required frequency band and lower the price if HeNBs are capable of serving some victim macro-users. Li *et al.* [25] proposed an incentive framework within which the MBS provides profit to femtocells by pricing accessed MUEs' transmission rates guaranteed by femtocells.

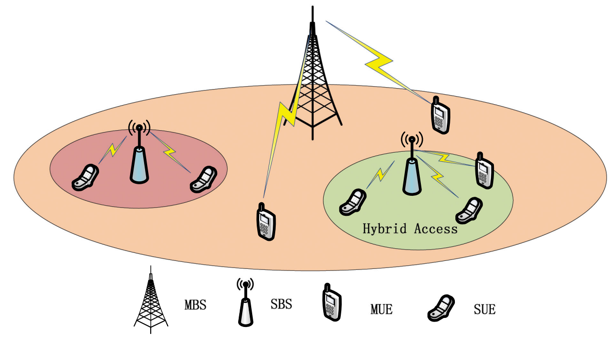

Fig. 1. System model.

However, the aforementioned game-based works concerning the hybrid access control, generally follow the two common assumptions.

1) *Involved Players Have the Perfect and Complete Information:* But, in practical networks, there may exist information uncertainty and information asymmetry. So far, only limited literature focus on hierarchical power control in small cell networks such as [12] and[13] that considered the information uncertainty introduced by the time varying physical channel.
2) *Incentive Mechanism Is Designed for the Given Victim Macro Mobile Users:* These works do not tell us when the MBS needs to adopt the incentive mechanism.

Different from these existing studies related to the hybrid access control policy, in this paper, we consider a more general model to analyze the hybrid access control in small cell networks and MBS can determine whether to adopt the incentive mechanism based on the system configuration such as current load, MUE's location, etc.

III. System Model and Problem Formulation

As shown in Fig. 1, we consider the downlink transmission of a two-tier small cell network, involving one central MBS and several SBSs.[1] Each SBS serves a certain number of wireless devices and operates in hybrid access manner, i.e., SBS permits partial licensed MUEs communicate with it. A user's throughput is determined by the physical layer data rate, the load on the associated network, and the network side resource allocation policy. For networks' side resource allocation policy, we assume that the proportional fairness and soft-QoS based service differentiation are adopted in networks. These schemes are widely used in cellular networks including LTE-A. In this context, the average throughput of a user m given the accessed SBS i is derived by [26]

$$\theta_{i,m} = \frac{w_{i,m} R_{i,m}}{W_i}, m \in \mathbf{UE}_i \tag{1}$$

where $R_{i,m}$ is the physical layer data rate, $w_{i,m}$ denotes user m's weight, and W_i is the total user weight of SBS i, indicating

[1] Our model is suitable for both co-channel and independent channel deployment scenarios.

the load of the network. Let $\mathbf{UE}_i$ represent the SBS *i*'s user set. Let 0 denote the index of MBS. Similarly, MUE *m*'s throughput associated to the MBS is

$$\theta_{0,m} = \frac{w_{0,m} R_{0,m}}{W_0}, m \in \mathbf{UE}_0. \quad (2)$$

In this paper, we mainly focus on a specific MUE's handover so that the MUE's index *m* can be omitted for concise notation.[2] Let h be the binary handover decision of the target MUE. Specifically, $h = 0$ means that the MUE is associated with MBS, otherwise $h = 1$ implies that MUE is served by nearby SBS. Accordingly, the MBS's utility is designed as the following piecewise function:

$$U_0 = \begin{cases} U_0^{h_0} = \lambda_0 \theta_0, & h = 0 \\ U_0^{h_1} = \lambda_0 \theta_0^i - \beta_0 \alpha_i, & h = 1 \end{cases} \quad (3)$$

and

$$\begin{cases} \theta_0 = \frac{w_0 R_0}{W_0};\ \theta_0^i = \frac{w_{i,0} R_{i,0}}{W_i^0} \\ \alpha_i = \frac{w_{i,0}}{w_{i,0} + W_i} = \frac{w_{i,0}}{w_{i,0} + \sum_{j \in \mathbf{UE}_i} w_{i,j}} \in [0, 1) \end{cases}$$

where λ_0 denotes the utility transfer parameter. θ_0 and θ_0^i are scheduled MUE's average throughput in MBS and SBS *i*, respectively. $w_{i,0}$ is the allocated weight for MUE served by SBS and $W_i^0 = w_{i,0} + W_i = w_{i,0} + \sum_{j \in \mathbf{UE}_i} w_{i,j}$ denotes the total user weight of SBS after adding MUE into its licensed user set. MBS adopts an incentive mechanism to encourage SBS accessing MUE when MBS cannot provide satisfactory QoS for MUE. β_0 is the maximum subsidy for SBS and α_i denotes the fraction of the allotted weight for MUE in the total user weight, indicating the SBS's open resource degree for MUE. Note that $U_0^{h_0} = \lambda_0 \theta_0$ is only related to the parameters of MBS; therefore, we view it as the MBS's *private information* unless MBS is willing to broadcast to SBSs. On the other hand, $U_0^{h_1} = \lambda_0 \theta_0^i - \beta_0 \alpha_i$ is always regarded as the *public information* to SBSs.

We consider that MBS has access preference characterized by a non-negative parameter κ, which is MBS's private information. If the following inequality holds:

$$U_0^{h_1}(\alpha_i, \beta_0) \geq (1 + \kappa) U_0^{h_0}, \kappa > 0 \quad (4)$$

where $(1 + \kappa)$ is the minimum acceptable payoff-gain that can attract MBS to accept the SBS's assistance, then, MBS handovers MUE to SBS which means $h = 1$. Otherwise, $h = 0$. On the other hand, the SBS's utility is designed as

$$U_i = \beta_0 \alpha_i - \lambda_i \alpha_i \Gamma_i - C_i(\alpha_i)$$
$$\text{s.t. } 0 \leq \alpha_i \leq \alpha_i^{\mathrm{TH}} \quad (5)$$

where α_i^{TH} is the maximum open resource ratio for MUE to guarantee the minimum requirement of SBS's served users.[3] $\Gamma_i = \sum_{j \in \mathbf{UE}_i} \theta_{i,j}$ is the sum throughput of SUEs in SBS *i*. Note that U_i consists of three parts: $-\lambda_i \alpha_i \Gamma_i$ and $\beta_0 \alpha_i$ denote the SUEs' throughput loss and obtained subsidy from MBS, respectively; the third part $C_i(\alpha_i)$ is applied to model the SBS's cost of open resource for MUE, which is widely used such as [24], i.e., due to the increase of open resource ratio α_i, SBS needs to provide corresponding compensation to SUEs for their QoS decrease. Generally, the $C_i(\alpha_i)$ is a non-decreasing function of α_i. We apply $C_i(\alpha_i) = \gamma_i \alpha_i^2$ to model the cost for simplicity, where γ_i is the cost parameter and reflects the relatively heterogeneous importance of the served SUEs, i.e., the delay-sensitive SUEs need to set a relatively large γ_i to guarantee the QoS requirement. Other types of $C_i(\alpha_i)$ are also available based on the practical system model, while the insights behind are similar.[4]

Define the MBS's combination strategy as $\Theta = (\beta_0, h)$. Recalling the MBS's minimum acceptable level constraint, it is equivalent to the following constraints:

$$\begin{cases} U_0(\Theta, \alpha_i) \geq (1 + \kappa) U_0^{h_0}, & h = 1 \\ U_0(\Theta, \alpha_i) = U_0^{h_0}, & h = 0. \end{cases} \quad (6)$$

From the MBS's side, the optimization problem of MBS is to determine the optimal combination strategy Θ as follows:

$$(\mathbf{OP1}):\ \Theta^* = \underset{\Theta}{\operatorname{argmax}}\, U_0$$
$$\text{s.t. } \beta_0 \geq 0, h = \{0, 1\}, \text{Constraints in (6)}. \quad (7)$$

Note that there is no interaction between SBS and MBS when MBS's handover strategy is $h = 1$, that is to say, MBS provides no subsidy to SBS, thus we set $\beta_0^* = 0$ in this scenario. From the SBS's side, SBS *i* aims to maximize its utility via optimizing the following optimization problem:

$$(\mathbf{OP2}):\quad \alpha_i^* = \underset{\alpha_i}{\operatorname{argmax}}\, U_i$$
$$\text{s.t. } 0 \leq \alpha_i \leq \alpha_i^{\mathrm{TH}}. \quad (8)$$

In this paper, we formulate the MUE handover problem as a Stackelberg game, considering private information. MBS is modeled as the leader with private information and moves first, then, SBSs move sequently based on the observation of leader's actions. It is suitable to apply the Stackelberg game to model the hierarchical interaction between MBS and SBSs [10], [12], [13]. Our game model is more general to formulate the hybrid access control in two-tier small cell networks. MBS can determine whether to provide hybrid-access refunding to SBS. If SBS cannot bring more payoff to MBS in hybrid access mode than that MUE is served by MBS, there is no need to handover MUE to SBS and no subsidy provided by MBS. In the following, we further consider the impact of MBS's private information on the incentive mechanism. The abbreviations used in this paper are provided in the Table I and the key variables are listed in Table II.

IV. Analysis of the Proposed Stackelberg Game

In this section, for analysis simplicity, we first focus on the hybrid access control game considering the interactions between

[2]Generally, due to the random distribution of MUEs' location and the difference in their service priorities, we assume that each MUE's handover decision made by MBS can be decoupled, thus, we only focus on the hybrid access control for a specific MUE.

[3]The α_i^{TH} is up to the degree of SBS's current traffic load. Specially, the α_i^{TH} can be set as 1, that means all associated SUEs are inactive or out of the small cell's coverage.

[4]The cost model $C_i(\alpha_i)$ is determined by practical system configuration related to the SUEs' traffic type, QoS requirement, service priority, etc. As mentioned before, $C_i(\alpha_i)$ is a non-decreasing function of α_i generally. Henceforth, given the cost model $C_i(\alpha_i)$, the equilibrium analysis (if the equilibrium exists) can be implemented as the following process shown in Section IV.

TABLE I
ABBREVIATIONS USED IN THIS PAPER

Abbreviations	Explanation	Abbreviations	Explanation
MBS	Macro cell base station	SE	Stackelberg equilibrium
SBS	Small cell Base station	CIS-B	Implement bargaining scheme in CIS
MUE	Macro user equipment	PIS-B	Implement bargaining scheme in PIS
SUE	Small cell user equipment	CIS-WB	Implement non-cooperative game without bargaining scheme in CIS
PIS	Partial MBS's utility information available scenario	PIS-WB	Implement non-cooperative game without bargaining scheme in PIS
CIS	Complete MBS's utility information available scenario	QoE	Quality of experience

TABLE II
KEY VARIABLES USED IN THIS PAPER

Variables	Explanation
θ_0	MUE's average throughput in MBS
θ_0^i	MUE's average throughput in SBS
α_i	SBS's open resource degree for MUE
α_i^{TH}	Maximum open resource ratio of SBS for MUE
β_0	MBS's maximum subsidy for SBS
κ	MBS's payoff preference parameter
Γ_i	SBS's current load
C_i	SBS's cost of open resource for MUE
$\lambda_0(\lambda_i)$	MBS's (SBS's) utility transfer parameter
γ_i	Cost parameter of SBS
$R_{i,0}$	MUE's physical layer data rate obtained from SBS *i*
R_0	MUE's physical layer data rate obtained from MBS
α_i^{S}	SBS *i*'s minimum open resource ratio in hybrid access
α_i^{W}	SBS *i*'s maximum open resource ratio to obtain profit

one MBS and one SBS, i.e., sparsely deployed scenario as shown in [10], in the process of the decision. Then, we will show later that our game model can be easily extended to multi-SBS densely deployed scenario.

To begin with, we give the definition of SE in our proposed game as follows.

Definition 1 (SE): A strategy profile (Θ^*, α_i^*) is termed as SE if Θ^* maximizes the MBS's (leader's) utility and α_i^* is the SBS *i*'s best response in lower subgame. Mathematically, for any strategy profile (Θ, α_i), the following conditions are satisfied:

$$\begin{aligned} U_0(\Theta^*, \alpha_i^*) &\geq U_0(\Theta, \alpha_i^*) \\ U_i(\Theta^*, \alpha_i^*) &\geq U_i(\Theta^*, \alpha_i) \end{aligned}$$

and any available strategy profile (Θ, α_i) must satisfy the constraints in (6).

Note that the SE is a common concept for the subgame perfect Nash equilibrium, which is a refinement of NEs for sequential move game. Generally, we can apply backward induction to find the NEs in the sub-games including the defined lower and upper games. In the following, we will present our equilibrium analysis for two different scenarios based on the MBS's utility information availability for SBS.

1) *Partial MBS's Utility Information Scenario:* In this scenario, we assume that SBS only has partial MBS's utility information. To be specific, SBS just has the knowledge of $U_0^{h_1}$ while it has no information related to $U_0^{h_0}$ and MBS's preference κ. That means, $U_0^{h_1}$ is the public information for SBS, whereas $U_0^{h_0}$ and κ are MBS's private information.
2) *Complete MBS's Utility Information Scenario:* If SBS can acquire the distribution of the $U_0^{h_0}$, our game model can be extended to a Bayesian game. In this scenario, we assume that SBS has complete information containing $U_0^{h_1}$, $U_0^{h_0}$, and κ. This implies that the MBS broadcasts its private information $U_0^{h_0}$ and κ to SBS.

A. Equilibrium Analysis in PIS

1) Solution of the Lower Game in PIS: Given the β_0 provided by MBS (i.e., assume $h = 1$), the optimization of SBS can be transferred as follows:

$$\begin{aligned} \min_{\alpha_i} \; & U_i = -\beta_0\alpha_i + \lambda_i\alpha_i\Gamma_i + C(\alpha_i) \\ \text{s.t.} \; & \alpha_i \leq \alpha_i^{\mathrm{TH}} \\ & -\alpha_i \leq 0. \end{aligned} \tag{9}$$

We now apply the following lemma to show the existence of the NE in the lower game[27].

Lemma 1 ([27]): A Nash equilibrium (NE) exists in the lower game if the following conditions are satisfied:

1) α_i is a nonempty, convex and compact subset of some Euclidean space.
2) U_i is continuous in α_i and quasi-concave in α_i.

We can verify that the proposed game meets these two conditions, thus, there exist at least one NE point in lower game. The optimization problem is a standard convex optimization and it can be solved by Lagrangian dual method. Henceforth, we can obtain the SBS's best response as follows:

$$\alpha_i^*(\beta_0) = \begin{cases} 0; & \beta_0 - \lambda_i\Gamma_i \leq 0 \\ \frac{\beta_0 - \lambda_i\Gamma_i}{2\gamma_i}; & 0 < \frac{\beta_0 - \lambda_i\Gamma_i}{2\gamma_i} \leq \alpha_i^{\mathrm{TH}} \\ \alpha_i^{\mathrm{TH}}; & \frac{\beta_0 - \lambda_i\Gamma_i}{2\gamma_i} > \alpha_i^{\mathrm{TH}} \end{cases}. \tag{10}$$

Remark 1:

1) The SBS denies to provide service for MUE if $\beta_0 \leq \lambda_i\Gamma_i$. A typical scenario is that SBS's current load is too heavy (Γ_i is a large value), in other words, SBS does not have enough resource allocated to MUE while maintaining SUEs' QoS at an acceptable level.
2) If the subsidy β_0 is larger than the threshold $\lambda_i\Gamma_i$, then α_i increases linearly with the increase of β_0 until α_i reaches the upper bound α_i^{TH}. On the other hand, note that the MBS's maximum subsidy β_0 will be no more than $2\gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i$ for selfish and rational MBS.

2) Solution of the Upper Game in PIS: To begin with, $U_0^{h_1}$ can be rewritten as follows:

$$U_0^{h_1} = \lambda_0\theta_0^i - \beta_0\alpha_i = \lambda_0\alpha_i R_{i,0} - \beta_0\alpha_i. \tag{11}$$

Given that $\alpha_i^* = \frac{\beta_0 - \lambda_i\Gamma_i}{2\gamma_i}, \lambda_i\Gamma_i < \beta_0 < 2\gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i$, we substitute it into the MBS's $U_0^{h_1}$ to solve the upper game. Then, we take the first-order and second-order derivatives with respect to β_0 as follows:

$$\frac{\partial U_0^{h_1}}{\partial \beta_0} = \frac{\lambda_0 R_{i,0}}{2\gamma_i} - \frac{2\beta_0}{2\gamma_i} + \frac{\lambda_i \Gamma_i}{2\gamma_i}$$
$$\frac{\partial U_0^{h_1}}{\partial \beta_0^2} = -\frac{2}{2\gamma_i} < 0.$$

Since the $U_0^{h_1}$ is a concave function of β_0, similar to analysis in lower game, we can verify the existence of NE in the upper game.

Let $\frac{\partial U_0^{h_1}}{\partial \beta_0} = 0$, then, we can get

$$\beta_0 = \frac{\lambda_0 R_{i,0} + \lambda_i \Gamma_i}{2}.$$

Note that β_0 should satisfy the constrain $\lambda_i \Gamma_i < \beta_0 < 2\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$.

Accordingly, we discuss the best responses of both MBS and SBS in the following three cases.

1) If $\lambda_0 R_{i,0} < \lambda_i \Gamma_i, \beta_0 - \lambda_i \Gamma_i \le 0$, MUE is denied by SBS, hence, MBS is forced to serve MUE.
2) If $\lambda_i \Gamma_i \le \lambda_0 R_{i,0} < 4\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i, 0 < \alpha_i^* = \frac{\lambda_0 R_{i,0} - \lambda_i \Gamma_i}{4\gamma_i} < \alpha_i^{\mathrm{TH}}$, then, $\beta_0^* = \frac{\lambda_0 R_{i,0} + \lambda_i \Gamma_i}{2}$.
3) If $\lambda_0 R_{i,0} \ge 4\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$, then $\beta_0^* = 2\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$.

Theorem 1: Given $\lambda_0 R_{i,0} > \lambda_i \Gamma_i$, only if the following condition is satisfied, SBS permits to serve MUE in PIS

$$R_0 \le \frac{W_0 \alpha_i^* (\lambda_0 R_{i,0} - \beta_0^*)}{(1+\kappa)\lambda_0 w_0}. \tag{12}$$

That implies $[(\beta_0^*, 1), \alpha_i^*]$ is the SE.

Proof: The proof is straightforward and intuitive. Given $\lambda_0 R_{i,0} > \lambda_i \Gamma_i$, the SBS can always get more reward for providing service to MUE. From the MBS's side, only if SE can bring larger payoff than $(1+\kappa)U_0^{h_0}$, MBS admits the outcome. That is to say, the following inequality must hold

$$U_0^{h_0}(\alpha_i^*, \beta_0^*) = \lambda_0 \alpha_i^* R_{i,0} - \beta_0^* \alpha_i^* \ge (1+\kappa) U_0^{h_0}, \kappa > 0. \tag{13}$$

Otherwise, MBS will not handover the MUE to SBS. Substituting $\theta_0 = \frac{w_0 R_0}{W_0}$ into (14), we can obtain $R_0 \le \frac{W_0 \alpha_i^* (\lambda_0 R_{i,0} - \beta_0^*)}{(1+\kappa)\lambda_0 w_0}$. This completes the proof. ■

Denoting the equilibrium outcome in PIS as Θ^*_{PIS} and $\alpha^*_{i,\mathrm{PIS}}$, we can get

$$\left[\Theta^*_{PIS}, \alpha^*_{i,PIS}\right] = \begin{cases} \left[\left(\frac{\lambda_0 R_{i,0} + \lambda_i \Gamma_i}{2}, 1\right), \frac{\lambda_0 R_{i,0} - \lambda_i \Gamma_i}{4\gamma_i}\right] \\ \text{R1 and (12) hold} \\ \left[\left(2\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i, 1\right), \alpha_i^{\mathrm{TH}}\right] \\ \text{R2 and (12) hold} \\ \left[(0,0), 0\right]; \text{Otherwise} \end{cases} \tag{14}$$

where R1 and R2 represent the constraints $\lambda_i \Gamma_i \le \lambda_0 R_{i,0} < 4\gamma \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$ and $\lambda_0 R_{i,0} \ge 4\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$, respectively. Note that if MBS provides no refund to SBS, rational SBSs will set the open resource ratio as $\alpha_i = 0$. Therefore, $[(0,0), 0]$ is the SE in this scenario. Given the system configuration, the SE is unique in PIS.

B. Equilibrium Analysis in CIS

1) Solution of the Lower Game in CIS: In this section, we will analyze the equilibrium in CIS. Since SBSs can obtain the complete MBS's utility information, SBSs need to take the MBS's payoff into consideration. If SBS's handover decision cannot bring profits more than $(1+\kappa)U_0^{h_0}$ for MBS, SBS can predict that MBS will serve MUE by itself, which means there is no chance to gain utility.

From the MBS's side, given $\beta_0 \ge \lambda_i \Gamma_i$, the minimum α_i^{S} for MBS must meet the following condition:

$$U_0^{h_1}(\alpha_i^{\mathrm{S}}, \beta_0) = (1+\kappa) U_0^{h_0}.$$

Therefore, we can get

$$\alpha_i^{\mathrm{S}} = \frac{(1+\kappa)\lambda_0 \theta_0}{\lambda_0 R_{i,0} - \beta_0}. \tag{15}$$

α_i^{S} is the minimum open resource ratio to guarantee that MBS can accept hybrid access.

Remark 2:

1) If $\lambda_0 R_{i,0} - \beta_0 < 0$, then $\alpha_i^{\mathrm{S}} < 0$, implying that SBS cannot give service to MUE.
2) If $\lambda_0 R_{i,0} - \beta_0 > 0$, then $\alpha_i^{\mathrm{S}} > 0$, implying the MUE can be allocated a weight at least α_i^{S} if SBS permits the MUE's access.

From the SBS's side, the maximum open resource ratio α_i^{W} meets $U_i(\alpha_i = 0) = U_i(\alpha_i = \alpha_i^{\mathrm{W}})$.

Note that we temporarily remove the corresponding constraints for analysis convenient. Moreover, we can obtain

$$\alpha_i^{\mathrm{W}} = \frac{\beta_0 - \lambda_i \Gamma_i}{\gamma_i}. \tag{16}$$

Let $\alpha_i^{\mathrm{B}} = \frac{\beta_0 - \lambda_i \Gamma_i}{2\gamma_i}$, it is obvious that $\alpha_i^{\mathrm{B}} \le \alpha_i^{\mathrm{W}}$, then we analyze the best response of SBS from the relationship among $\alpha_i^{\mathrm{B}}, \alpha_i^{\mathrm{W}}$, and α_i^{S}, considering the constraints $\lambda_0 R_{i,0} > \beta_0 \ge \lambda_i \Gamma_i$. Note that $\alpha_i^{\mathrm{B}}, \alpha_i^{\mathrm{W}}$ are the functions of β_0.

2) Solution of the Upper Game in CIS: We will analyze the upper game in three cases, shown in Fig. 2, as follows:

1) *Case 1:* The curves of α_i^{S} and α_i^{W} have no intersection in the observation window (marked in Fig. 2).
First, we define the difference function as follows:

$$f_1(\beta_0) = \alpha_i^{\mathrm{S}} - \alpha_i^{\mathrm{W}} = \frac{\lambda_0 \theta_0 (1+\kappa)}{\lambda_0 R_{i,0} - \beta_0} - \frac{\beta_0 - \lambda_i \Gamma_i}{\gamma_i}.$$

Therefore, we can calculate the intersections of f_1 if $\Delta_1 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i \lambda_0 \theta_0 (1+\kappa) \ge 0$, then the two intersections can be obtained as follows:

$$\beta_0^{\mathrm{w}+} = \frac{(\lambda_i \Gamma_i + \lambda_0 R_{i,0}) + \sqrt{(\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i \lambda_0 \theta_0 (1+\kappa)}}{2}$$

$$\beta_0^{\mathrm{w}-} = \frac{(\lambda_i \Gamma_i + \lambda_0 R_{i,0}) - \sqrt{(\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i \lambda_0 \theta_0 (1+\kappa)}}{2}.$$

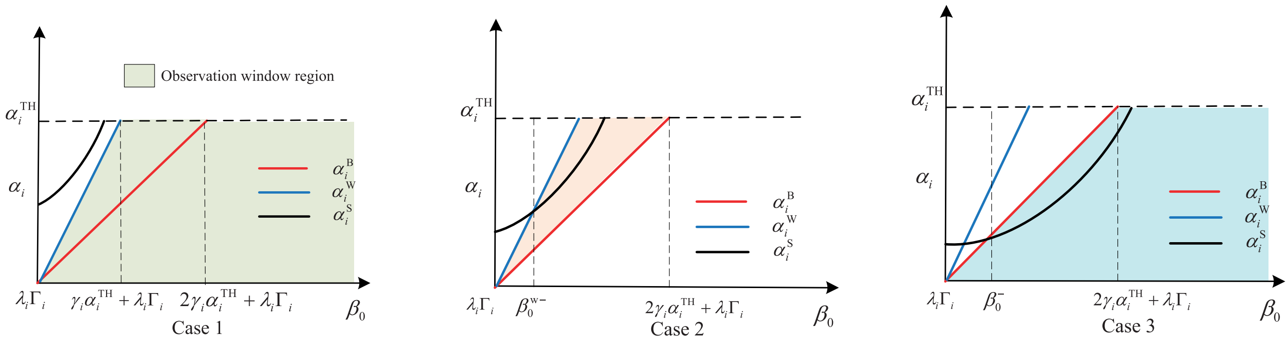

Fig. 2. Illustration of Case 1–Case 3.

Therefore, if there is no intersection, the following condition should be satisfied:

$$\Delta_1 = (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i\lambda_0\theta_0(1+\kappa) < 0$$

which is equivalent to the following:

$$(\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 < 4\gamma_i\lambda_0\theta_0(1+\kappa). \quad (17)$$

On the other hand, if the curves of α_i^{S} and α_i^{W} have intersections, while no one is located in the observation window, then, we can obtain

$$\begin{cases} \Delta_1 = (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i\lambda_0\theta_0(1+\kappa) \geq 0 \\ \beta_0^{\mathrm{w}-} > \gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i. \end{cases}$$

Assuming $\lambda_0 R_{i,0} - \lambda_i\Gamma_i \geq 2\gamma_i\alpha_i^{\mathrm{TH}}$, we can rewrite it as

$$\begin{cases} (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_1 \\ (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 \geq 4\gamma_i\lambda_0\theta_0(1+\kappa) \end{cases}$$

where $\Pi_1 = (\lambda_0 R_{i,0} - \lambda_i\Gamma_i - 2\gamma_i\alpha_i^{\mathrm{TH}})^2 + 4\gamma_i\lambda_0\theta_0(1+\kappa)$. Accordingly, we get

$$4\gamma_i\lambda_0\theta_0(1+\kappa) \leq (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_1. \quad (18)$$

On the other hand, if $\lambda_0 R_{i,0} - \lambda_i\Gamma_i < 2\gamma_i\alpha_i^{\mathrm{TH}}$, then $\beta_0^{\mathrm{w}-} > \gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i$ will not hold.

In case 1, the MBS chooses to reject SBS's assistance in both CIS and PIS. Since SBS cannot share the required resource for MUE even SBS takes his best efforts, i.e., taking the strategy α_i^{W}. However, the MUE's minimum demand is always beyond α_i^{W}.

2) *Case 2:* The curves of α_i^{S} and α_i^{W} have intersection and α_i^{S} is always beyond α_i^{B} in the observation window. Similarly, we define the difference function as follows:

$$f_2(\beta_0) = \alpha_i^{\mathrm{S}} - \alpha_i^{\mathrm{B}} = \frac{\lambda_0\theta_0(1+\kappa)}{\lambda_0 R_{i,0} - \beta_0} - \frac{\beta_0 - \lambda_i\Gamma_i}{2\gamma_i}. \quad (19)$$

In the following, we can obtain the intersections of $f_2(\beta_0)$ as follows if $\Delta_2 = (\lambda_i\Gamma_i + \lambda_0 R_{i,0})^2 - 4(\lambda_0\lambda_i R_{i,0}\Gamma_i + 2\gamma_i\lambda_0\theta_0(1+\kappa)) \geq 0$:

$$\beta_0^+ = \frac{(\lambda_i\Gamma_i + \lambda_0 R_{i,0}) + \sqrt{(\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i\lambda_0\theta_0(1+\kappa)}}{2}$$

$$\beta_0^- = \frac{(\lambda_i\Gamma_i + \lambda_0 R_{i,0}) - \sqrt{(\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i\lambda_0\theta_0(1+\kappa)}}{2}. \quad (20)$$

Then, we discuss two scenarios as follows:

S1: α_i^{S} and α_i^{B} have intersections, while the intersections are out of the observation window.

S2: α_i^{S} and α_i^{B} have no intersections, implying the curve of α_i^{S} is always beyond the curve of α_i^{B}.

For *S1*, we can list the conditions as follows:

$$\begin{cases} \Delta_1 = (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i\lambda_0\theta_0(1+\kappa) > 0 \\ \beta_0^{\mathrm{w}-} < \gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i \\ \Delta_2 = (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i\lambda_0\theta_0(1+\kappa) \geq 0 \\ \beta_0^- > 2\gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i. \end{cases} \quad (21)$$

The existence of $\beta_0^- > 2\gamma_i\alpha_i^{\mathrm{TH}} + \lambda_i\Gamma_i$ requires $\lambda_0 R_{i,0} - \lambda_i\Gamma_i \geq 4\gamma_i\alpha_i^{\mathrm{TH}}$.

Assuming $\lambda_0 R_{i,0} - \lambda_i\Gamma_i \geq 4\gamma_i\alpha_i^{\mathrm{TH}}$, we can rewrite (21) as follows:

$$\begin{cases} (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 > 4\gamma_i\lambda_0\theta_0(1+\kappa) \\ (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 > \Pi_1 \\ (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 > 8\gamma_i\lambda_0\theta_0(1+\kappa) \\ (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_2 \end{cases} \quad (22)$$

where $\Pi_2 = (\lambda_0 R_{i,0} - \lambda_i\Gamma_i - 4\gamma_i\alpha_i^{\mathrm{TH}})^2 + 8\gamma_i\lambda_0\theta_0(1+\kappa)$. Therefore, we can obtain the following:

$$\max\left[8\gamma_i\lambda_0\theta_0(1+\kappa), \Pi_1\right] \leq (\lambda_i\Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_2. \quad (23)$$

Following the similar lines as *S1*, for *S2*, we can list the conditions as follows:

$$\begin{cases} \Delta_1 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i \lambda_0 \theta_0 (1+\kappa) > 0 \\ \Delta_2 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i \lambda_0 \theta_0 (1+\kappa) < 0 \\ \beta_0^{\mathrm{w}-} < \gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i. \end{cases} \tag{24}$$

Assuming $\lambda_0 R_{i,0} - \lambda_i \Gamma_i \geq 2\gamma_i \alpha_i^{\mathrm{TH}}$, we can rewrite (24) as

$$\begin{cases} (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 > 4\gamma_i \lambda_0 \theta_0 (1+\kappa) \\ (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < 8\gamma_i \lambda_0 \theta_0 (1+\kappa) \\ (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 > \Pi_1. \end{cases} \tag{25}$$

Therefore, we can obtain

$$\Pi_1 < (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < 8\gamma_i \lambda_0 \theta_0 (1+\kappa). \tag{26}$$

On the other hand, if $\lambda_0 R_{i,0} - \lambda_i \Gamma_i < 2\gamma_i \alpha_i^{\mathrm{TH}}$, then (24) can be expressed as

$$\begin{cases} \Delta_1 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 4\gamma_i \lambda_0 \theta_0 (1+\kappa) \geq 0 \\ \Delta_2 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i \lambda_0 \theta_0 (1+\kappa) < 0. \end{cases} \tag{27}$$

In what follows, we can get

$$4\gamma_i \lambda_0 \theta_0 (1+\kappa) \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < 8\gamma_i \lambda_0 \theta_0 (1+\kappa). \tag{28}$$

Theorem 2: In case 2, any $(\beta_0, 1)$ and $\alpha_i^{\mathrm{S}} = \frac{(1+\kappa)\lambda_0 \theta_0}{\lambda_0 R_{i,0} - \beta_0}$ constitute a feasible SE, where $\beta_0 \in (\beta_0^{\mathrm{w}-}, \min[\beta_0^{\mathrm{w}+}, \lambda_0 R_{i,0} - \frac{\lambda_0 \theta_0 (1+\kappa)}{\alpha_i^{\mathrm{TH}}}])$.

Proof: Note that MBS obtains equal rewards $\lambda_0 \theta_0 (1+\kappa)$ after selecting any strategy $\beta_0 \in (\beta_0^{\mathrm{w}-}, \min[\beta_0^{\mathrm{w}+}, \lambda_0 R_{i,0} - \frac{\lambda_0 \theta_0 (1+\kappa)}{\alpha_i^{\mathrm{TH}}}])$, and SBS's best response is $\alpha_i^{\mathrm{S}} = \frac{(1+\kappa)\lambda_0 \theta_0}{\lambda_0 R_{i,0} - \beta_0}$. This implies that there exists at least one SE in Case 2. Specifically, if $\min[\beta_0^{\mathrm{w}+}, \lambda_0 R_{i,0} - \frac{\lambda_0 \theta_0 (1+\kappa)}{\alpha_i^{\mathrm{TH}}}] > \beta_0^{\mathrm{w}-}$, that means there exists infinite SEs. ■

In case 2, if SBS takes the best response in PIS, then, MBS chooses to serve MUE by itself, that is to say, the $[(0,0), 0]$ is the unique SE in PIS.

3) *Case 3: The curves of α_i^{S} and α_i^{B} have intersections and at least one is located in the observation window.*

Case 3 means the following conditions hold:

$$\begin{cases} \Delta_2 = (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 - 8\gamma_i \lambda_0 \theta_0 (1+\kappa) \geq 0 \\ \beta_0^{-} \leq 2\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i. \end{cases} \tag{29}$$

Assuming $\lambda_0 R_{i,0} - \lambda_i \Gamma_i \geq 4\gamma_i \alpha_i^{\mathrm{TH}}$, then, (29) can be formulated as

$$\begin{cases} (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 \geq 8\gamma_i \lambda_0 \theta_0 (1+\kappa) \\ (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 \geq \Pi_2. \end{cases} \tag{30}$$

Accordingly, we can get

$$\max[8\gamma_i \lambda_0 \theta_0 (1+\kappa), \Pi_2] \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2. \tag{31}$$

If $\lambda_0 R_{i,0} - \lambda_i \Gamma_i < 4\gamma_i \alpha_i^{\mathrm{TH}}$, $\beta_0^{-} \leq 2\gamma_i \alpha_i^{\mathrm{TH}} + \lambda_i \Gamma_i$ always holds. Thus, (29) can be simplified as

$$(\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 \geq 8\gamma_i \lambda_0 \theta_0 (1+\kappa). \tag{32}$$

Theorem 3: The SE in case 3 of CIS is the same as the alternative in PIS.

Proof: In case 3, there exists at least one intersection between the curves of α_i^{S} and α_i^{B}. This implies that there exists at least one point in the curve of α_i^{B}, which brings MBS's profit to no less than $\lambda_0 \theta_0 (1+\kappa)$ and means that offloading MUE to SBS is a better choice for MBS.

Recall that any point in the curve of α_i^{S} brings equal utility $\lambda_0 \theta_0 (1+\kappa)$ to MBS. For any point in the part of the curve of α_i^{B}, which is beyond α_i^{S}, i.e., $\alpha_i^{\mathrm{B}}(\beta_0) > \alpha_i^{\mathrm{S}}(\beta_0)$, since $U_0^{h_1}(\alpha_i, \beta_0)$ is an increasing function with α_i for a given β_0, MBS can obtain more payoff than $\lambda_0 \theta_0 (1+\kappa)$. Therefore, the combination of the MBS's and SBS's best response is located in α_i^{B} in CIS for rational players. Meanwhile, we can easily verify the SE in CIS is the SE in PIS simultaneously. ■

In summary, given the configuration of both MBS and SBS, we can determine which case it belongs to.

For $(\lambda_i \Gamma_i - \lambda_0 R_{i,0}) < 2\gamma_i \alpha_i^{\mathrm{TH}}$, we can get

$$\begin{cases} (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_1 . C1 \\ \Upsilon_1 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_2 ; C2 \\ \Upsilon_2 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 ; C3 \end{cases} \tag{33}$$

where $\Upsilon_1 = 4\gamma_i \lambda_0 \theta_0 (1+\kappa)$ and $\Upsilon_2 = 8\gamma_i \lambda_0 \theta_0 (1+\kappa)$, *C1–C3* represent the corresponding case index for notational simplicity.

For $2\gamma_i \alpha_i^{\mathrm{TH}} \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0}) < 4\gamma_i \alpha_i^{\mathrm{TH}}$, we can obtain

$$\begin{cases} (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_1 . C1 \\ \Upsilon_1 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_1 ;\ C1 \\ \Pi_1 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_2 ,\ C2 \\ \Upsilon_2 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 ; C3. \end{cases} \tag{34}$$

For $4\gamma_i \alpha_i^{\mathrm{TH}} \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})$, we can get

$$\begin{cases} (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_1 . C1 \\ \Upsilon_1 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_1 ;\ C1 \\ \max[\Upsilon_2, \Pi_1] \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Pi_2 , C2 \\ \Pi_1 \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 < \Upsilon_2 , C2 \\ \max[\Upsilon_2, \Pi_2] \leq (\lambda_i \Gamma_i - \lambda_0 R_{i,0})^2 . C3. \end{cases} \tag{35}$$

Based on the analysis above, we can obtain the equilibrium relationship between CIS and PIS as follows:

$$[\Theta_{\mathrm{CIS}}^*, \alpha_{i,\mathrm{CIS}}^*] = \begin{cases} [\Theta_{\mathrm{PIS}}^*, \alpha_{i,\mathrm{PIS}}^*] ;\ C1 \text{ and } C3 \\ \left[(\beta_0, 1), \frac{(1+\kappa)\lambda_0 \theta_0}{\lambda_0 R_{i,0} - \beta_0}\right] ;\ \beta_0 \in \mathrm{BR}_{\beta_0} ;\ C2 \end{cases} \tag{36}$$

where $\mathrm{BR}_{\beta_0} = (\beta_0^{\mathrm{w}-}, \min[\beta_0^{\mathrm{w}+}, \lambda_0 R_{i,0} - \frac{\lambda_0 \theta_0 (1+\kappa)}{\alpha_i^{\mathrm{TH}}}])$.

In the decision process, MBS and SBSs need to exchange information periodically. To be specific, in CIS, SBS first reports its current load Γ_i, maximum open resource ratio α_i^{TH} to MBS, and MBS broadcasts its currently $U_0^{h_0}$ and κ to SBSs. Then, MBS decides whether to offload its MUE to SBS. Generally, the frequency of information exchange is adapted to the changing rate of the network traffic load.

V. Multi-Small-Cell Scenario

In this section, we extend our game model to multi-small-cell scenario. The target MUE is located in the overlapping region of multiple SBSs, and we assume that it can only access one associated base station including MBS.[5]

Assume that there are N SBSs, which can provide service for MUE, and at most one SBS can win in the competition. Without loss of generality, we assume that SBS_1 is the final winner and SBS_2 is the biggest competitor among SBSs.[6]

A. PIS With Multiple SBSs

To begin with, we analyze the equilibrium in PIS. Given β_0 (i.e., assume $h=1$), we recall that SBS_2's maximum open resource ratio is $\alpha_2^{\mathrm{W}}=\frac{\beta_0-\lambda_2\Gamma_2}{\gamma_2}$ if $\alpha_2^{\mathrm{W}}\le\alpha_2^{\mathrm{TH}}$. We first assume that SBS_2 is completely altruistic and takes the strategy α_2^{W} for a given β_0. Accordingly, if MUE is served by SBS_2, then MBS's utility can be expressed as

$$U_{0,2}^{h_1}(\alpha_2^{\mathrm{W}})=\frac{\beta_0-\lambda_2\Gamma_2}{\gamma_2}\left(\lambda_0R_{2,0}-\beta_0\right). \tag{37}$$

Let $\frac{\partial U_{0,2}^{h_1}}{\partial\beta_0}=0$, we can obtain $\beta_0=\frac{\lambda_0R_{2,0}+\lambda_2\Gamma_2}{2}$. Considering the constraint $\alpha_2^{\mathrm{W}}\le\alpha_2^{\mathrm{TH}}$, we can easily get the upper bound of β_0 as $\beta_0^{\mathrm{U}}=\gamma_2\alpha_2^{\mathrm{TH}}+\lambda_2\Gamma_i$. Therefore, the optimal $\beta_0^{*(\mathrm{Altruistic})}$ in altruistic case is as follows:

$$\beta_0^{*(\mathrm{Altruistic})}=\begin{cases}\frac{\lambda_0R_{2,0}+\lambda_2\Gamma_2}{2}; \lambda_0R_{2,0}\le 2\gamma_2\alpha_2^{\mathrm{TH}}+\lambda_2\Gamma_2\\ \gamma_2\alpha_2^{\mathrm{TH}}+\lambda_2\Gamma_2; \lambda_0R_{2,0}>2\gamma_2\alpha_i^{\mathrm{TH}}+\lambda_2\Gamma_2.\end{cases} \tag{38}$$

The corresponding optimal MBS's utility is

$$U_{0,2}^{h_1(\mathrm{Altruistic})}=\begin{cases}\frac{1}{\gamma_2}\left(\frac{\lambda_0R_{2,0}-\lambda_2\Gamma_2}{2}\right)^2,\\ \quad\lambda_0R_{2,0}\le 2\gamma_2\alpha_2^{\mathrm{TH}}+\lambda_2\Gamma_2;\\ \left(\lambda_0R_{2,0}-\lambda_2\Gamma_2\right)\alpha_2^{\mathrm{TH}}-\gamma_2(\alpha_2^{\mathrm{TH}})^2,\\ \quad\lambda_0R_{2,0}>2\gamma_2\alpha_2^{\mathrm{TH}}+\lambda_2\Gamma_2.\end{cases} \tag{39}$$

Obviously, if the SBS_1 is the final winner, the following inequalities hold:

$$\begin{cases}U_{0,1}^{h_1(\mathrm{Altruistic})}>U_{0,2}^{h_1(\mathrm{Altruistic})}\\ U_{0,2}^{h_1(\mathrm{Altruistic})}\ge(1+\kappa)U_0^{h_0}.\end{cases} \tag{40}$$

Otherwise, no one can win in the game to obtain the opportunity to serve MUE.

Assuming $U_{0,2}^{h_1(\mathrm{Altruistic})}\ge(1+\kappa)U_0^{h_0}$, we can similarly analyze the equilibrium as previous CIS and just need to replace the $(1+\kappa)U_0^{h_0}$ and α_i^{S} by $U_{0,2}^{h_1(\mathrm{Altruistic})}$ and $\alpha_j^{\mathrm{PIS_{mul}}}$ in derivation process, respectively; where the $\alpha_1^{\mathrm{PIS_{mul}}}$ is shown as follows:

$$\alpha_1^{\mathrm{PIS_{mul}}}=\frac{U_{0,2}^{h_1(\mathrm{Altruistic})}}{\lambda_0R_{2,0}-\beta_0}. \tag{41}$$

Note that $\alpha_1^{\mathrm{PIS_{mul}}}$ is the minimum open resource ratio to win the game.

Therefore, one-MBS and multiple-SBS game transfers to one-MBS and one-SBS game with extra information $U_{0,2}^{h_1(\mathrm{Altruistic})}$. Due to the space limitation, we omit the detailed derivation process.

B. CIS With Multiple SBSs

In this scenario, we assume that each SBS has the knowledge of MBS's private information $U_0^{h_0}$ and κ, and the SBS_1 is the final winner. Accordingly, the following inequalities holds:

$$U_{0,1}^{h_1(\mathrm{Altruistic})}>\max\left[U_{0,2}^{h_1(\mathrm{Altruistic})},(1+\kappa)U_0^{h_0}\right]. \tag{42}$$

For a rational player, the SBS_1's minimum open resource ratio $\alpha_1^{\mathrm{CIS_{mul}}}$ to win the competition is as follows:

$$\alpha_1^{\mathrm{CIS_{mul}}}=\frac{\max\left[U_{0,2}^{h_1(\mathrm{Altruistic})},(1+\kappa)U_0^{h_0}\right]}{\lambda_0R_{2,0}-\beta_0}. \tag{43}$$

This implies that the SBS_1 jointly considers the biggest competitor SBS_2's strategy and MBS's minimum acceptable profit $(1+\kappa)U_0^{h_0}$. Similarly, the one-MBS and multiple-SBS game transfers to one-MBS and one-SBS game.

Remark 3:

1) In multiple SBSs competition scenario, the MBS can obtain more opportunities to improve profit comparing with the single SBS scenario in both PIS and CIS.
2) From the SBSs' side, the profit gain of the final winner in competition scenario is no more than the single SBS scenario in both PIS and CIS.

VI. Discussion and Improvements

From the above analysis, the SEs in CIS and PIS are identical in both case 1 and case 3. For the case 2, at first glance, it seems both MBS and SBS gain profits in CIS comparing with PIS. However, the gains are limited. Specifically, MBS gets the payoff, which is equal to $(1+\kappa)U_0^{h_0}$. For a small access preference κ, the MBS's reward is small. Whereas, the larger κ does not always bring higher reward for MBS. The reason is that SBS needs to make major tradeoff, to be specific, if SBS cannot support the MUE's minimum resource requirement related to κ, the MBS may lose a number of opportunities to offload MUE.

From the SBS's side, in case 2 of CIS, based on Theorem 2, MBS chooses any strategy β_0 from $\beta_0\in(\beta_0^{\mathrm{w}-},\min[\beta_0^{\mathrm{w}+},\lambda_0R_{i,0}-\frac{\lambda_0\theta_0(1+\kappa)}{\alpha_i^{\mathrm{TH}}}])$ brings equal payoff to MBS, whereas the reward of the SBS's best response $\alpha_i^{\mathrm{S}}=\frac{(1+\kappa)\lambda_0\theta_0}{\lambda_0R_{i,0}-\beta_0}$ is the function of β_0 as follows:

$$U_i(\beta_0)=\lambda_i\Gamma_i+\frac{\lambda_0\theta_0(1+\kappa)(1-\lambda_i\Gamma_i)\beta_0}{\lambda_0R_{i,0}-\beta_0}-\gamma_i\left(\frac{\lambda_0\theta_0(1+\kappa)}{\lambda_0R_{i,0}-\beta_0}\right)^2. \tag{44}$$

Obviously, there exists at least one optimal β_0^* for SBS to obtain the maximum profit in case 2. However, the final outcome of

[5] Note that we only consider a single connect scenario in this paper and we will consider the dual or multiple connect scenario in our future work.

[6] For N-SBSs scenario, we sort the $U_{0,i}^{h_1(\mathrm{Altruistic})}$, which will be introduced lately, in a decreasing order. Without loss of generality, assume $U_{0,1}^{h_1(\mathrm{Altruistic})}>U_{0,2}^{h_1(\mathrm{Altruistic})}>\cdots>U_{0,N}^{h_1(\mathrm{Altruistic})}$, thus, we can determine that the SBS_1 is the potential winner and the SBS _2 is its biggest competitor.

the game is determined by MBS's strategy. That is to say, the SBS's final profit is up to the MBS's attitude. For a unfriendly MBS, there is no hope for SBS to achieve significant profit gain, almost no gain, comparing to PIS.

How to obtain significant profit gain for both MBS and SBS in the CIS? The available way is via the negotiation or bargaining between MBS and SBS.

Next, we give a simple example to show that. To achieve win–win result, we can formulate the following optimization problem for both case 2 and case 3[7]:

$$\begin{aligned} \max_{\beta_0,\alpha_i} P = & \left[U_0^{h_1}(\alpha_i,\beta_0) - U_0^{h_1}(\Theta^*_{\text{CIS}},\alpha^*_{i,\text{CIS}})\right]^{\Psi_0} \\ & \times \left[U_i(\alpha_i,\beta_0) - U_i(\Theta^*_{\text{CIS}},\alpha^*_{i,\text{CIS}})\right]^{\Psi_i} \\ \text{s.t.} \quad & 0 < \alpha_i \le \alpha_i^{\text{TH}}; \\ & \beta_0 \ge 0 \end{aligned} \tag{45}$$

where Ψ_0 and Ψ_i denote the weight in the bargaining of MBS and SBS, respectively. This optimization problem (45) is similar to Nash bargaining (NB). $(U_0^{h_1}(\Theta^*_{\text{CIS}},\alpha^*_{i,\text{CIS}}), U_i(\Theta^*_{\text{CIS}},\alpha^*_{i,\text{CIS}}))$ can be expressed as combination of both MBS's and SBS's disagreement point. The solution of NB problem is termed as NB solution, which satisfies some nice properties such as *Pareto efficiency* and *fairness*. Thus, (45) can yield a relative fairness and satisfactory outcome. The detailed solution of the optimization problem (45) is out of the scope for this paper, so we do not discuss more and will just show some simulation results in the next section.

VII. Numerical Results

In this section, the simulation parameters of the networks are set as in [26]. To be specific, the path losses from an MBS and an SBS to the user are $L = 128.1 + 37.6\log_{10} R$ and $L = 140.7 + 37.6\log_{10} R$, respectively, where R is the distance between the user and the corresponding BS in km. The standard deviation of lognormal shadowing is set as 10 dB. The transmitting powers of MBS and SBS are 46 dBm in 20 MHz carrier and 30 dBm in 10 MHz carrier, respectively. The parameters λ_0 and λ_i are set as 5×10^{-10} and 7×10^{-10}, respectively. The MBS's coverage radius r_0 is 300 m and SBS i's coverage radius r_i is 30 m. MBS's minimum profit gain is set as 1.1, i.e. $1 + \kappa$=1.1. Cost coefficient γ_i is 10^2 and the maximum resource open ratio $\alpha_i^{\text{TH}} = 0.2$. Let $\frac{w_0}{W_0} = \frac{1}{N_{\text{MUE}}} = 10^{-2}$, where N_{MUE} denotes the number of served MUEs, reflecting MBS's load. These parameters are fixed unless expressively stated. To begin with, we consider one MBS and one SBS scenario, i.e., a specific MUE is located on the line between MBS and SBS as shown in Fig. 3, where d_0 denotes the distance between MUE and MBS, d_i represents the distance between MUE and the nearby SBS, and $d_{0,i}$ denotes the distance between MBS and SBS i.

Under various parameter configurations, we perform extensive comparisons on the performance of the following schemes.

1) MBS and SBSs implement non-cooperative strategies without any bargaining scheme in PIS (PIS-WB).
2) MBS and SBSs implement non-cooperative strategies without any bargaining scheme in CIS (CIS-WB). Moreover, to show the different equilibrium outcome in case 2 as analyzed in previous section, we present the SBS's utility in worst case (CIS-WB-worst) and optimal case (CIS-WB-optimal).
3) MBS and SBSs implement cooperative strategies with bargaining scheme in CIS (CIS-B).
4) To investigate the performance of the proposed game in multiple SBSs competition scenario, we present the corresponding figures in CIS-WB with multiple SBSs (CIS-WB-Mul) and PIS-WB with multiple SBSs (PIS-WB-Mul), respectively.
5) SBS implements closed access, i.e., refusing the service requirement of MUE, which is regarded as a baseline scheme (marked "Closed access" in figures).
6) SBS implements open access and provides service to MUE in its coverage area. For analysis simplicity, SBS sets a fixed resource open ratio $\alpha_i = 0.05$ for MUE, which is regarded as a baseline scheme (marked "Open access" in figures). Note that in the open access mode, there is no subsidy from MBS, i.e., $\beta_0 = 0$.

[7]In case 1, there is no space to negotiation, because the MUE's minimum demand α_i^{S} is always beyond α_i^{W} for any available β_0.

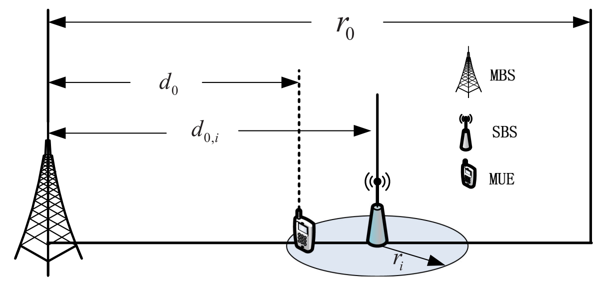

Fig. 3. Simulation setting illustration.

A. Impacts of SBS's Load on the Equilibrium

To show the impact of SBS's load Γ_i on the equilibrium, we vary Γ_i and fix $d_0 = 100$ m and $d_i = 20$ m. We present MBS's utility and SBS's utility in Fig. 4(a) and (b), respectively. Note that when the SBS's load is relatively small (<27 Mb/s), SBS has more available resource allotted to MUE. SBS's utility in both CIS-WB and PIS-WB are the same. With the increase in load, SBS's utility drops to zero in PIS-WB when the SBS's load is relatively heavy (27 Mb/s< $\Gamma_i <$ 44 Mb/s). Due to lack of MBS's utility information, SBS's optimal strategy cannot satisfy the MBS's minimum requirement; hence, MBS chooses to serve MUE by itself. On the other hand, for CIS-WB, there exists significant differences in SBS's utility, comparing the performance in CIS-WB-worst with the CIS-WB-optimal. As previous equilibrium analysis of the proposed game in case 2, the SBS's final outcome is determined by MBS's decision, that is to say, any SBS's utility value, which is located between the worst and optimal, is possible. To be specific, in the worst case, the SBS in CIS-WB has no utility gain comparing with the alternative in PIS-WB, although SBS has more information of MBS. From the perspective of MBS's utility, MBS only obtains minimum profit gain in CIS-WB when the game falls into case 2 region as shown in Fig. 4(b). By introducing bargaining scheme in CIS, MBS and SBS can obtain significant profit gain, comparing to PIS-WB. With the SBS's load tends to be more heavy ($\Gamma_i >$ 44 Mb/s), SBS has no spare resource for MUE for all schemes; hence, SBS maintains closed access manner. As shown in Fig. 4(a), in the pure closed access mode, SBS only serves its own registered users, so SBS's utility is 0. In the open access mode, SBS needs to assign partial wireless resource for MUE in its coverage with-

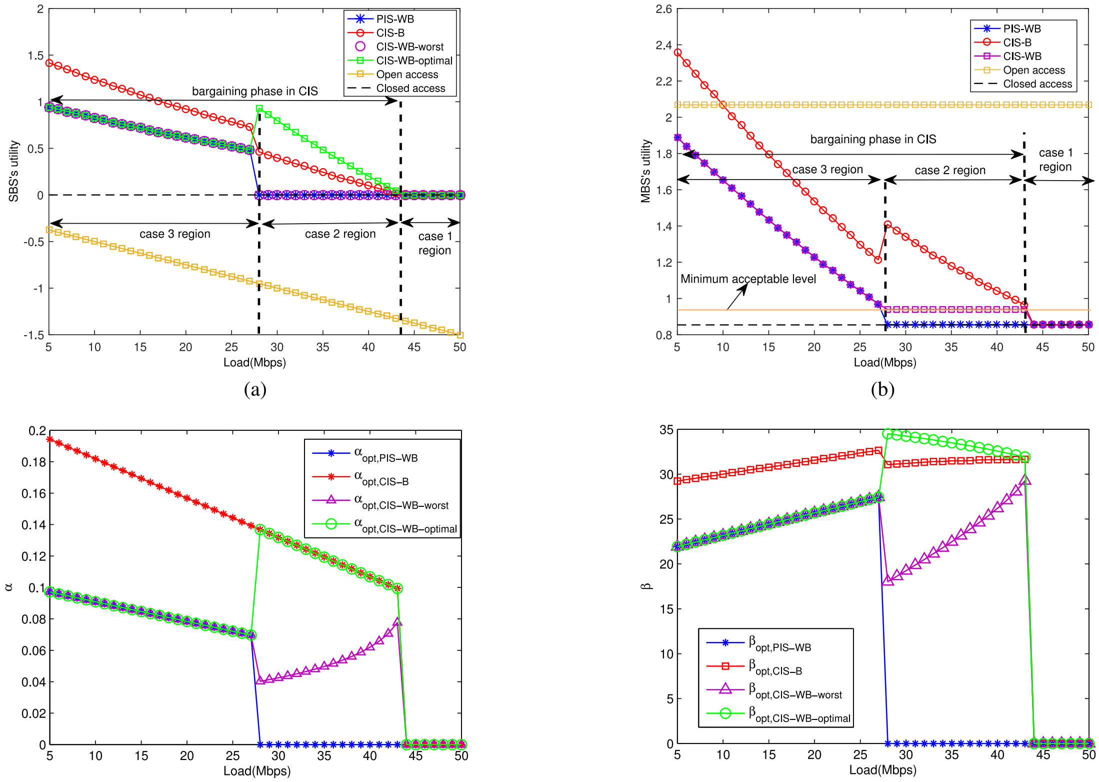

Fig. 4. The impacts of variation of SBS's load Γ_i. (a) SBS's utility in equilibrium. (b) MBS's utility in equilibrium. (c) Variation of SBS's optimal open resource ratio α in equilibrium. (d) Variation of MBS's optimal subsidy β in equilibrium.

out compensation. In current system configuration, as shown in Fig. 4(b), MBS can obtain a constant positive utility in open access mode because of SBS's fixed open resource ratio; however, SBS's utility is always negative as shown in Fig. 4(a). In practice, SBS lacks incentive to open partial spectrum resource for MUE with no benefit. Moreover, the variation of SBS's optimal open resource ratio α and MBS's optimal subsidy β in equilibrium state are shown in Fig. 4(c) and (d), respectively. In bargaining phase, the SBS owns the complete MBS's utility information and bargains with MBS to obtain better reward via providing larger α, which is higher than the α_i^{S}.

B. Impact of MUE's Location, MBS's, and SBS's Weights on the Equilibrium

In the following, we investigate the impact of MUE's location and weights of both MBS and SBS on the final equilibrium. To begin with, we fix the distance between SBS and the specific MUE as $d_i = 20$ m and SBS's load as $\Gamma_i = 30$ Mb/s, then, change the distance between MBS and MUE d_0. Meanwhile, to show the impact of MBS's and SBS's weight on the game, we fix the SBS's weight as $\Psi_i{=}1$ and vary the MBS's weight. In Fig. 5, we present the SBS's utility versus the distance d_0. It is noted that the SBS can obtain higher profit in CIS-B, comparing with the outcome in CIS-WB-worst. On the other hand, the SBS's utility decreases with the increase of MBS's weight, implying that the MBS's position in bargaining phase tends to be more important.

In Fig. 6, we show the performance of MBS's utility in equilibrium. MBS can only get minimum acceptable profit in CIS-WB when the distance between MBS and MUE is relatively small (<0.12 km), whereas in PIS-WB, only the corresponding distance is larger than 0.12 km as shown in Fig. 6, MBS accepts to offload MUE to nearby SBS.

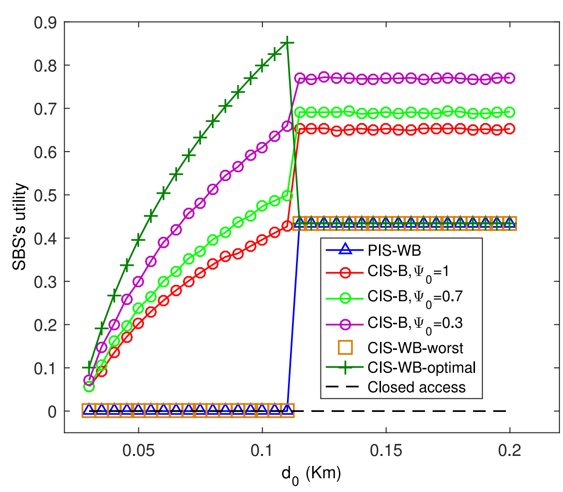

Fig. 5. SBS's utility versus the distance between MBS and MUE.

C. Multi-Small-Cell Case

In this section, we investigate the interactions among MBS and SBSs in densely deployment scenario and we assume that the target MUE is located in the overlapping region of several SBSs' coverage. For clear presentation, we consider that two small cells, SBS_1 and SBS_2, compete for providing service for a given MUE. Assume $\theta_0 = 1.22$ Mb/s and the distance

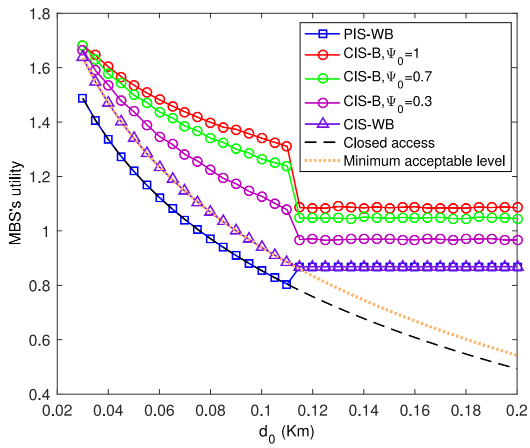

Fig. 6. MBS's utility versus the distance between MBS and MUE.

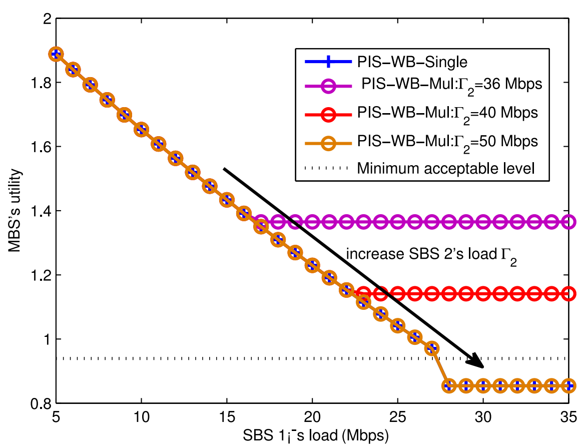

Fig. 7. MBS's utility versus the SBS 1's load in PIS.

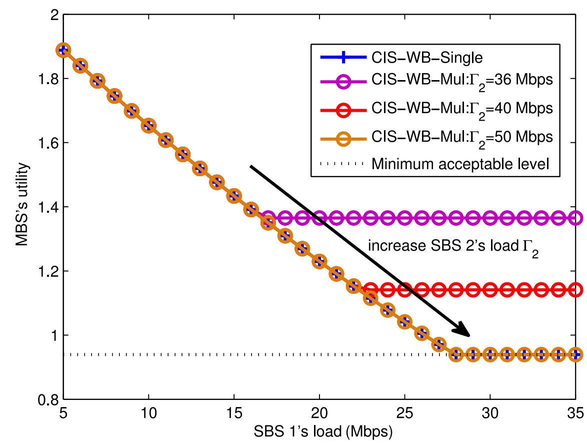

Fig. 8. MBS's utility versus the SBS 1's load in CIS.

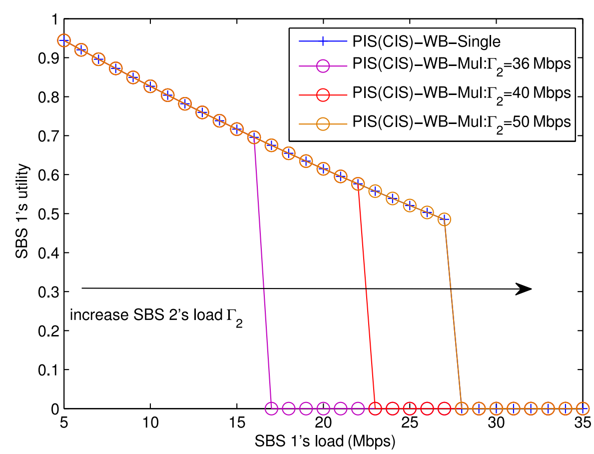

Fig. 9. SBS's utility versus the SBS 1's load in PIS/CIS.

between MUE to corresponding SBS_1 or SBS_2 are 20 m. We fix SBS_2's load and then vary SBS_1's load.

Fig. 7 shows the MBS's utility versus the SBS_1's load in PIS-WB. When the SBS_1's load is much lighter than SBS_2's, SBS_1 has no need to take SBS_2's threaten into consideration, that is to say, SBS_1's strategy in competition is not affected by SBS_2. Therefore, MBS's utilities are the same in both single and multiple SBSs scenario in SBS_1's lightly loaded region. With the increase of SBS_1's load, the SBS_2's competitiveness relatively increases for a given load. Henceforth, SBS_1 needs to consider the effects of the extra information $U_{0,2}^{h_1(Altruistic)}$, referring to (41). Interestingly, we can see that there exists the phenomenon of "performance floor," related to $U_{0,2}^{h_1(Altruistic)}$, to MBS's utility. The lighter SBS_2's load is, the higher the performance floor is. This implies that MBS has more opportunities to obtain higher utility in fierce competition among SBSs. On the other hand, if $U_{0,2}^{h_1(Altruistic)}$ is less than the MBS's minimum acceptable level, the performance floor will drop to $U_0^{h_0}$ in PIS-WB-Mul. However, since SBS 1 has the MBS's private information $U_0^{h_0}$ in CIS-WB-Mul, he will jointly consider $U_0^{h_0}$ and $U_{0,2}^{h_1(Altruistic)}$. Therefore, we can find the difference between Figs. 7 and 8 for the curves corresponding to $\Gamma_2 = 50$ Mb/s.

Fig. 9 shows the SBS_1's utility versus the SBS_1's load in PIS/CIS. For clear presentation, we only give SBS's utility in worst case for the scenario of CIS-WB-Mul. There are two interesting observations as follows.

1) SBS_1's performance is not improved even though it owns more information. It is noted that the SBS_1's utilities in PIS-WB-Mul and CIS-WB-Mul are equal.
2) The SBS_1's profit space is shrinking with the increase of the SBS_2's competitiveness.

VIII. Conclusion

In this paper, we focused on the hybrid access control in two-tier small cell networks from the perspective of incentive mechanism design, considering private information. Then, we formulated this problem as a Stackelberg game. To be specific, MBS and SBSs are modeled as leader and followers, respectively. A subsidy mechanism is adopted by MBS. Moreover, we presented the equilibrium analysis and revealed the equilibrium relationship under different available information circumstances. We extended our model to dense small cell deployment scenario and discussed how to exploit equilibrium outcome to achieve more satisfactory win–win results via bargaining. Theoretical analysis and simulation results showed that it is better for MBS to broadcast the involved private information to get more payoff.

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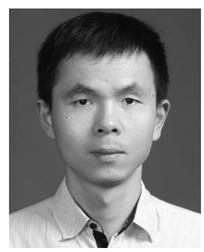

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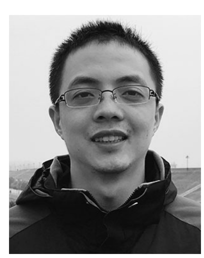

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