Auction-Stackelberg Game Framework for Access Permission in Femtocell Networks with Multiple Network Operators

Sanshan Sun[1,2], Gang Feng[1], *Senior Member*, *IEEE*, Shuang Qin[1], Yao Sun[1], Zhaorong Zhou[2]

[1] National Key Laboratory of Science and Technology on Communications,
University of Electronic Science and Technology of China, Chengdu 611731, China
[2] School of Physics and Electronic Engineering,
Sichuan Normal University, Chengdu 610101, China

Abstract—**With the explosive growth of indoor data traffic in forthcoming fifth generation cellular networks (5G), it is imperative for mobile network operators to improve network coverage and capacity. Femtocells are widely recognized as a promising technology to address these demands. As Femtocells are sold or loaned by a mobile network operator (MNO) to its residential or enterprise customers, MNOs usually employ refunding scheme to compensate the femtocell holders (FHs) providing indoor access to other subscribers by configuring the femtocell to operate in open or hybrid access mode. Due to the selfishness nature, competition between network operators as well as femtocell holders makes it challenging for operators to select appropriate FHs for trading access resources. This inspires us to develop an effective refunding framework, with aim to improve overall network resource utilization, through promoting FHs to make reasonable access permission for well-matched macro users. In this paper, we develop a two-stage auction-Stackelberg game (ASGF) framework for access permission in femtocell networks, where MNO and mobile virtual network operator (MVNO) lease access resources from multiple FHs. We first design an auction mechanism to determine the winner femtocell that fulfils the access request of macro users. We next formulate the access permission problem between the winner femtocell and operators as a Stackelberg game, and theoretically prove the existence of unique equilibrium. As a higher system payoff can be gained by improving individual players' payoff in the game, each player can choose the best response to others' action by implementing access permission, while avoiding solving a complicated optimization problem. Numerical results validate the effectiveness of our proposed ASGF based refunding framework and the overall network efficiency can be improved significantly.**

Index Terms—**Femtocell, Mobile Network Operator, Mobile Virtual Network Operator, Access Permission, Auction, Stackelberg Game.**

I. INTRODUCTION

The explosive mobile traffic poses an enormous challenge to the next generation mobile communication system (5G) in recent years [1]. It is also challenging for mobile cellular networks to provide efficient high-speed indoor data transmissions due to precious radio resources and poor coverage in some typical technical scenarios of 5G [2], which may lead to poor user quality of experience (QoE) and affect the income of mobile network operators (MNOs). Recently, small cell technology including microcell, picocell and femtocell, has been explored as a cost-efficient solution to improve indoor coverage and data rate. On the other hand, mobile virtual network operators (MVNOs) have been emerging to enhance network resource utilization by wholesaling spare resource of MNOs to provide wireless access service. Being short of network infrastructure, MVNOs should prefer employing small cells to acquire network resources rather than only wholesaling [3][4].

Compared with other small cells, femtocell is more preferable to MNOs and MVNOs because of the low power consumption and easy-configuration [5]. Femtocell holders (FHs), who can be individual users or network operators, may place femtocell anywhere and configure the operation mode arbitrarily. Femtocell has three operation modes including open access, closed access and hybrid access [6]. In order to exclusively utilize femtocell, FHs usually prefer closed mode. Hence, it is necessary for MNOs and MVNOs who want to exploit the access resource of femtocells, to make economic strategy to motivate FHs to adopt hybrid mode.

Existing research work has proved that auction mechanism and game theory are efficient tools to address the competition-oriented femtocell access permission problem. The authors of [7] consider the trade of access time between femtocells and mobile user equipments (MUEs), and propose a Vickrey-Clarke-Groves (VCG) auction based incentive framework for single macro user and multiple macro users separately to access femtocells. However, in real markets, MUEs usually prefer authorizing their served network operators rather than themselves to make trades with femtocells. This is also helpful to simplify the bipartite matching problem in multiple MUEs access through operators implementing auction as the number of operators is much less than that of MUEs. The authors of [8] develop a reverse auction framework to motivate access
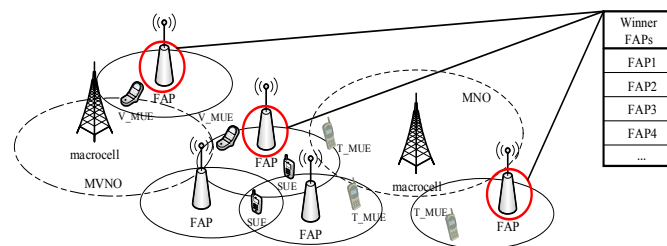
permission trading of femtocells in network operator's perspective. In order to avoid much time-consuming problem in VCG auction, the authors further propose a suboptimal mechanism by allowing range outcome in auction. However, the truthfulness of this modified auction is not proved strictly, and the participating agent is able to cheat. Hence, the authors of [9] propose a utility-aware refunding framework to solve access trading between wireless service provider (WSP) and FHs in hybrid access femtocell network based on time division multiple address (TDMA) system. They formulate the problem as a Stackelberg game, and prove the existence of unique Nash Equilibrium by analyzing the optimal strategies of both WSP and FHs. However, there are some defects in their work. First, in access service market, there could be multiple network operators competing for access resources of femtocells. Thus addressing the scenario of multiple network operators is more meaningful. Second, the refunding policy of network operators can be distinct with each other by taking into account the objective CAPEX (capital expenditure) and OPEX (operating expenditure) in addition to user churn rate that is the only factor considered in [9]. The work in [10] [11] just analyzes the economic effect of deploying and sharing femtocells by network operators, and gives the cost expression.

In this paper, we are focused on the competition of access resources between multiple network operators, which intervenes FHs in making access permission. Specifically, we consider a pair of typical competitors, i.e. MNO and MVNO, in our system model. MNO and MVNO usually pay refunds to FHs in exchange for access resources, and the amount of refunds affects the availability of resources. Obviously, once MNO and MVNO fall into irrational competition, FHs probably admit excessive users who could be unqualified to be served, and thus system performance would be degraded. Under this circumstance, it is imperative to develop an effective mechanism to motivate every participant to make reasonable decision in the access permission game. This is essential to retain network operation stability while improving network resource utilization. Due to the nature of the access permission problem in femtocell network, double-auction mechanism is an effective tool for solving it. Unfortunately, double auctions are notoriously hard to design and implement in our considered scenario [12]. Furthermore, the high computational complexity also makes double-auction mechanism difficult to apply [13].

In order to address the high computational complexity in double-auction design for the access permission, we propose a two-stage auction-Stackelberg game (ASGF) framework. We first use reverse auction model to select the winner femtocells that are able to provide reliable access service. Then, we formulate the access permission problem between single winner femtocell holder (FH) and operators as a Stackelberg game, in which MNO and MVNO are leaders, and the winner FH is the follower. We prove the existence and uniqueness of equilibrium of formulated Stackelberg game. When the equilibrium is reached, the access resources are appropriately allocated as every participant is satisfied with the allocation scheme to maximize their own utility. Meanwhile, due to the uniqueness

of equilibrium, every participant is qualified to select unique appropriate strategy from the set of strategies, and is unwilling to change the strategy unless others change, leading to stable access resource utilization and thus overall network efficiency.

In the first stage of the framework, we use greedy algorithm to determine the winner with polynomial time complexity, which guarantees the truthfulness of auction as well. In the second stage of the framework, due to the existence and uniqueness of equilibrium of Stackelberg game, every participant can reach their unique appropriate strategy in two steps. We suggest a practical algorithm to implement the ASGF framework based access permission, in which every participant collects some system parameters, such as Signal to Interference plus Noise Ratio (SINR) and equivalent revenue on unit data rate from users, to determine their strategies through solving the equilibrium. We conduct simulation experiments to evaluate the proposed ASGF framework. Numerical results show that every participant can maximize their own utility, and the overall network efficiency is improved significantly as well.

The rest of this paper is organized as follows. In Section II, we describe system model. In Section III, we give the definition of refunding strategy function (RSF) and price-coefficient, and formulate the access permission problem. In Section IV, we employ iterative two-stage auction-Stackelberg game framework for access permission in femtocell networks and prove the existence of unique Nash Equilibrium for the Stackelberg game. We present the implementation of our proposed two-stage auction-Stackelberg game based access permission scheme in Section V. Section VI presents the numerical results and discussions. We review the related work in Section VII and finally conclude the paper in Section VIII.

II. SYSTEM MODEL

In this paper, we consider a femtocell network, where MNO and MVNO employ refunding policy to compensate the FHs to provide indoor access service for their users. We present the network model and refunding model respectively in this section.

A. Network model

In the femtocell network shown in Fig.1(a), there are some femto access points (FAPs) that are configured to operate in hybrid access mode by the femtocell holders (FHs). The FHs authorize subscribed user equipments (SUEs) to access FAPs.

(a) Femtocell network and winner FAPs selection

(b) Access permission of single winner FAP

Fig. 1 Illustration of femtocell network and access scenario

Without loss of generality, we assume that the access resources of each FAP are divided into resource blocks that can be allocated to users for access as shown in Fig.1(b). For single FAP, let us denote by p the number of served SUEs, and by β_i the allocated fraction of total resources to the ith SUE. The aggregated fractions of access resources for served SUEs can be expressed as $\sum_{i=1}^{p} \beta_i = \Phi_p$. In order to attain higher SINR, macrocell UEs of MNO (T-MUEs) and macrocell UE of MVNO (V-MUEs) may move into a femtocell. MNO and MVNO are willing to pay refunds for access resources of FAP to their users. If having spare resources, FH may control FAP to admit additional T-MUEs and V-MUEs. The aggregated fractions of access resources for served T-MUEs and served V-MUEs can also be expressed as $\sum_{i=1}^{m} \gamma_i = \Phi_m$ and $\sum_{i=1}^{n} \delta_i = \Phi_n$ respectively, where m and n denote the number of T-MUEs and V-MUEs respectively, and γ_i and δ_i represent the allocated fraction of total resource blocks to ith T-MUE and ith V-MUE respectively. As all the access resources are allocated to the admitted users, we have $\Phi_p + \Phi_m + \Phi_n = 1$.

Furthermore, we assume that femtocells access the same frequency band as the macrocell, and different femtocell may reuse the same spectrum. The interference of femtocell can be introduced by macrocell and neighboring femtocells. We use $I_{tot}(X)$ to denote the total interference power introduced by neighboring femtocells, and $I_M(D)$ to denote the interference power introduced by macrocell which share the same spectrum with femtocells. We consider $I_{tot}(X)$ is a function of the number of neighboring femto cells X, and $I_M(D)$ is a function of the distance between studied femtocell and macrocell. Hence the SINR of a UE is given by

$$\eta_i = \left(\frac{P}{N + I_{tot}(X) + I_M(D)} \right) S d_i^{-r} |h|^2 \qquad (1)$$

where P is the transmit power of FAP, N is the Gaussian noise, S is the log-normal shadowing component, d_i is the

distance between ith UE and FAP, r is the path fading exponent, $|h|$ is the Rayleigh-distributed fading magnitude satisfying $E\left(|h|^2\right) = 1$.

Without loss of generality, we normalize the channel bandwidth, and then the capacity of the ith UE is given by

$$C_i = \log_2(1 + \eta_i), \qquad (2)$$

We assume that each type of served UE such as SUE, T-MUE and V-MUE, require specific targeted SINR when they access FAP. Hence, we define a threshold of SINR as the basic service quality. Denote by η_F, η_M and η_V the SINR threshold for SUEs, T-MUEs, and V-MUEs respectively. Therefore, the total data rate of each type of UEs, which is denoted by τ, can be given respectively by:

$$\tau_{FH} = \Phi_p \log_2(1 + \eta_F), \qquad (3)$$

$$\tau_{MNO} = \Phi_m \log_2(1 + \eta_M), \qquad (4)$$

$$\tau_{MVNO} = \Phi_n \log_2(1 + \eta_V). \qquad (5)$$

B. Refunding model

With strong wish to improve indoor transmission data rate, network operators are naturally willing to trade the money directly for spare resources of femtocell as long as the higher indoor rate brings more income. An FH is likely to get extra revenues from operators to compensate the investment on equipment in case of bringing no apparent performance degradation to the communication service for the subscribers. Obviously, it is a win-win situation for operators and FHs to adopt the trade that is indeed a refunding scheme. In the refunding, operators first consider the benefits from the trade. If the income from indoor UEs is larger than the refunds compensated to the FH, operators start to refund, vice versa. We define the utility function of operators as:

$$U_{MNO} = \omega_M \Phi_m \log_2(1 + \eta_M) - R_{MNO}, \qquad (6)$$

$$U_{MVNO} = \omega_V \Phi_n \log_2(1 + \eta_V) - R_{MVNO}, \qquad (7)$$

where ω_M denotes the equivalent revenue the MNO receives on unit data rate from the T-MUEs admitted by FAP; ω_V denotes the equivalent revenue the MVNO receives on unit data rate from the V-MUEs admitted by FAP; R_{MNO} denotes the refunds that the MNO pays to FH; R_{MVNO} denotes the refunds that the MVNO pays to FH.

Similarly, we define the utility function of FH as:

$$U_{FH} = \omega_F \Phi_p \log_2(1 + \eta_F) + R_{MNO} + R_{MVNO}, \qquad (8)$$

which includes three parts: the first part represents the income from innate FAP service, where ω_F denotes the equivalent revenue the FH receives on unit data rate from SUEs. The rest two parts represent the refunds gained from MNO and MVNO respectively.

III. PROBLEM FORMULATION

In this section, we first define a refunding strategy function (RSF) to describe the relationship between refunding amount and corresponding attained resources. We also propose the price-coefficient to reflect the strategy space for network operators, followed by the formulation of access permission problem.

A. Problem description

Due to selfishness nature, both MNO and MVNO may pursue utility maximization by paying refunds in exchange for indoor access resources. Meanwhile, they are supposed to offer appropriate amount of refunds in a rational way when knowing no information about opponent's strategy. A reasonable approach of designing refunding strategy is to take into account some relevant factors. For instance, when an operator determines the amount of refunds to an FH, he may investigate whether the femtocell is worthy of accessing, how many data rates it can provide, and how much profits it can make from admitted users. Similarly, the FH faces the following dilemma. On the other hand, he may also worry about the negative influence on the network performance if sharing resources only to the one who offers higher refunds, as he cannot ensure that the communicate service will not be degraded if end users are admitted only according to their refunds. For example, when some users acquire access resources, the channel capacity and data rate of femtocell may be substantially decreased. This certainly leads to dissatisfaction of authorized users of the femtocell. Therefore, femtocell access permission is indeed the access resource allocation, in which FHs allocate appropriate access resources to requesting users according to channel conditions and the amount of refunds provided by MNO and MVNO. In order to maximize own utility, every participant should employ reasonable strategy.

B. Refunding strategy function and price-coefficient

In general, when network operators pay refunds to FHs for user access, they always make decision while complying with some laws on technology and market. For instance, at the beginning of refunding, operators are positive to trade access resources by using large amount of refunds if they have sufficient capital. However, with the growth of the number of admitted users, FAP may provide poor indoor access for new requesting users. This may lead to decrease on the benefits if operators continue employing high refunds. In this case, it could be more reasonable for the operators to mount femtocell by themselves instead of leasing resources form the FH. Hence, operators may decrease the refunding amount when the FAP have permitted certain number of UEs. Based on this observation, we propose a refunding strategy function (RSF) of operators as:

$$R = B \log_\alpha (x+1) , \qquad (9)$$

where B represents the refund base satisfying $B = Income - Investment$, in which $Income$ denotes the earnings of the operator from total business such as ADSL,

cellular and other services; $Investment$ denotes the fundamental expenditure of the operators for infrastructure or operation. Obviously, B is an indicator to reflect the capital quantity of the operator. x represents the fraction of access resources allocated to an operator. α denotes the price-coefficient, which indicates the refunding strategy of operators. The RSF actually reflects the trend of refunding amount versus the number of admitted UEs in network operator's perspective. Considering the value of this function is non-negative and increasing, we have $B \geq 0$, $\alpha > 1$, and $0 < x < 1$.

However, in our system model, competition for access resources exists between MNO and MVNO. Although the refund base and allocated access resource can be the same, MNO and MVNO are still capable of adopting different strategy dynamically by changing the amount of refunds. For instance, as being lack in infrastructure and customer base, MVNO could be more aggressive than MNO to hunt for the same amount of resources, and thus the refunds provided by MVNO could be larger. Yet, coming with the growth of attained resources, MVNO is hard to support the high refunds with financial deficiency. Thus the MVNO has to adjust the strategy and pays less refunds. Based on these considerations, we design price-coefficient as refunding strategy form of operators. The network operators change the value of price-coefficient in RSF to determine certain refunding amount. Therefore, we have the refunding amount of MNO and MVNO respectively as

$$R_{MNO} = B_M \log_{\alpha_M} (\Phi_m + 1), \qquad (10)$$

$$R_{MVNO} = B_V \log_{\alpha_V} (\Phi_n + 1), \qquad (11)$$

where B_M and B_V denote the refund base of MNO and MVNO respectively; α_M and α_V denote the price-coefficient of MNO and MVNO respectively.

C. Utility maximization

As mentioned before, both MNO and MVNO are willing to pay refunds to the FH on the basis of obtaining benefits from indoor data rate improvement. From the financial perspective, the utility of network operators consists of two parts: one is the income contributed by providing indoor data service to the admitted UEs in FAP, and the other is the expense as funds paid to FH. For the selfishness and rationality, operators are delighted to maximize their own utility, which depends on some factors, such as the equivalent revenue on unit data rate, the fraction of resources allocated by FH, the price-coefficient. Therefore, we formulate the utility maximization problem for MNO and MVNO respectively as follows:

$$\max_{\alpha_M} U_{MNO} = \max_{\alpha_M} \left[\omega_M \Phi_m \log_2 (1+\eta_M) - B_M \log_{\alpha_M} (\Phi_m + 1) \right] \qquad (12)$$

$$\max_{\alpha_V} U_{MVNO} = \max_{\alpha_V} \left[\omega_V \Phi_n \log_2 (1+\eta_V) - B_V \log_{\alpha_V} (\Phi_n + 1) \right] \qquad (13)$$

It is clear that α_M and α_V are critical to maximize the utility, as α_M and α_V determine the refunding amount directly and affect the allocated resource fraction as well. Other factors, including equivalent revenue on one unit data rate, refund base, and SINR threshold, may be considered constant for a time period of interest. Furthermore, when operators determine the refunding amount, the allocated fractions Φ_m and Φ_n are generally known. So we define α_M and α_V as variable for the utility maximization problems (12) and (13).

On the other hand, the FH receives the refunds and tries to make an optimal allocation of access resources. The FH partitions the access resources of FAP into three parts with ratios of Φ_p, Φ_m and Φ_n, respectively. As $\Phi_p + \Phi_m + \Phi_n = 1$, Φ_p can be represented as $1 - \Phi_m - \Phi_n$. So, in order to improve his utility, the FH may assign appropriate value for Φ_m and Φ_n to allocate the spare access resources to MNO and MVNO according to the refunding amount. Thus we can formulate the problem of FH utility maximization as follows:

$$\max_{\Phi_m, \Phi_n} = \max_{\Phi_m, \Phi_n} \left[(1 - \Phi_m - \Phi_n) \omega_F \log_2 (1 + \eta_F) \right. \\ \left. + B_M \log_{\alpha_M} (\Phi_m + 1) + B_V \log_{\alpha_V} (\Phi_n + 1) \right], \quad (14)$$

where Φ_m and Φ_n are variables for the utility maximization problem of FH.

IV. TWO-STAGE AUCTION-STACKELBERG GAME FRAMEWORK

In this section, we propose an iterative two-stage auction-Stackelberg game framework (ASGF) for access permission in femtocell networks. In the first stage, we employ auction mechanism to select appropriate FAPs which are capable of sharing spare access resources. In the second stage, we formulate the access permission of single selected FAP as a Stackelberg game, in which MNO and MVNO are the leaders, and femtocell holder (FH) is the follower. The details are presented as follows.

A. Auction for selecting the winner FAP

In the first stage of ASGF framework, we make use of Vickrey-Clarke-Grove (VCG) mechanism based reverse auction to select appropriate FAPs to admit macro users. Considering the allocated access resources of FAPs can be multiple basic resource blocks, the auction is indeed a multi-unit reverse auction, in which FAPs are bidders, and MNO and MVNO are auctioneers. When FAPs participate in the auction, they usually intend to adopt rational bid for reasonable payoff, and they are not likely to adopt different bid respectively to MNO and MVNO. Thus, we assume the bids of FAPs to MNO and MVNO are the same.

Furthermore, let the number of FAPs in the femtocell network be denoted by I. The bid of the ith FAP contains three parts, i.e., the valuation of unit resource block v_i, the quantity of spare access resources of FAP q_i, and the coverage area of FAP c_i. Meanwhile, we assume that the coverage area of

femtocell network can be partitioned into K unit areas (or locations). If we use coordinate marks to denote different unit areas, the coverage can be represented by a vector, in which elements is corresponding coordinate mark. Naturally, the number of coordinate marks is K. If a FAP covers some locations (i.e. coordinate marks), the elements of the vector, are set to 1. Therefore, the coverage area of the ith FAP can be denoted by $c_i = \left\{ 0, 0, \cdots, \overbrace{1, \cdots}^{K} \right\}_i$. Finally, the bid of the ith FAP can be denoted by $bid_i = \{ v_i, q_i, \{0, 0, \cdots, 1, \cdots\}_i \}$. Every FAP would submit their own bid to MNO and MVNO respectively to trade the spare access resources. Fig. 2 shows the reverse VCG auction for access resources between FAPs and two network operators.
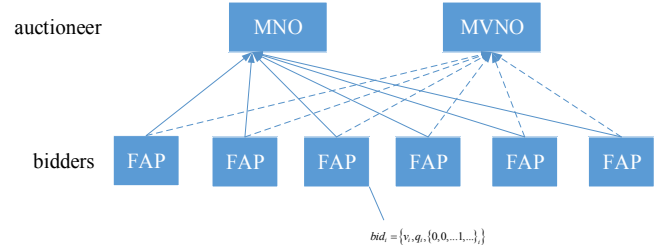
Fig. 2 Illustration of reverse VCG auction for access resources between FAPs and two network operators

a. VCG mechanism

In multi-unit reverse auction, VCG mechanism is efficient to guarantee the maximization of social welfare as well as the truthfulness of bid for valuation of goods [16]. Hence, the first part of the bid of FAPs (i.e., v_i) is equal to the true valuation of unit resource block. When MNO and MVNO have received the bids of FAPs, they can select appropriate FAPs as winners to minimize the expense that is used for satisfying the true valuation of unit resource block of FAPs. We can thus formulate this problem as follows,

$$A^* = \arg\min_A \sum_{i=1}^{I} \left(\sum_{k=1}^{K} q_{ik} \right) v_i , \text{ s.t. } c_i \cdot c_{MUE} > 0 , \sum_{k=1}^{K} q_{ik} \leq q_i \quad (15)$$

where A denotes the set of all feasible auction results; A^* denotes optimal auction results; c_{MUE} denotes the position distribution of MUE in the femtocell network; q_{ik} denotes the available amount of spare access resources of FAP in k coordinate. For consistency, we use the vector of the same dimension of c_i to represent c_{MUE}, in which the number of elements equals to K basic coordinate marks. Hence, the distribution of MUEs can be denoted by $c_{MUE} = \overbrace{(x_1, x_2, ..., x_k)}^{K}$, where x_k denotes the number of MUEs in k coordinate mark. The constraint of $c_i \cdot c_{MUE} > 0$ indicates that the winner FAP must covers at least one MUE.

According to the properties of VCG auction, we can calculate the price directly that network operators ought to pay for the ith winner FAP as

$$p_i^* = V(N \setminus i) - \sum_{j \neq i} q_j^* v_j , \qquad (16)$$

where $V(N \setminus i) = \min \sum_{j=1, j \neq i}^{J} q_j' v_j$ represents the new optimal auction result to minimize the expense for the bid of FAPs except the ith FAP. $\sum_{j \neq i} q_j^* v_j$ represents the rest expense of A^* optimal auction result except the ith FAP.

b. Winner determination algorithm (WDA)

In order to reduce the complexity of winner determination in the reverse auction, we assume that the FAP, which is unique in k coordinate as well as covers at least one MUE, can be selected as the winner directly by network operators. If many FAPs cover the same coordinate, we can employ greedy algorithm to determine the winner FAP in overlapped area. The Winner Determination Algorithm (WDA) is presented as follow.

TABLE 1. WDA

L : the set of FAPs sorted by v_i in ascending order;

  for $i \in L$

    if $c_i \cdot c_{MUE} < 0$ then

    $L' = L \setminus \{i\}$;

  end for

  $\boldsymbol{H} = \sum_{L'} c_i$;

  if $H_k = 1$ then

  $i^* = i$ who covers the k coordinate

  $L'' = L' \setminus \{i\}$;

  while $x_k > 0$ for each k and $L'' \neq 0$ do

  $j = next(L'')$;

    for all $k \in K$ do

      if $x_k > 0$ then

      $e_{jk} = \min\{x_k, q_{jk}\}$;

      $x_k = x_k - e_{jk}$;

      $i^* = j$;

      Update(q_{i*k})

    end if

    end for

  end while

In WDA, MNO and MVNO sorts all the FAPs in ascending order of their value of unit resource block v_i . Then they exclude the FAPs which cover no MUE, and determine the FAP that has no overlapped coverage with other FAPs as winner. At last, MNO and MVNO iteratively check the bid of FAPs in overlapped coverage to select their own respective winners by satisfying the access request of MUEs as well as minimizing the expense for the auction.

Some FAPs can be selected as the winner by MNO and MVNO simultaneously, or by one of them only. Hence, the selected winner FAP can perform the access permission in the second stage for one network operator only, or both MNO and MVNO. The difference lies at the number of leaders in the Stackelberg game. In the next subsection, we are focused on the

analysis of the Stackelberg game with two leaders for access permission. We do not analyze the case with one leader due to page limit, as the details of the analyses can be referred to [9].

B. Stackelberg game for access permission of winner FAP

We formulate the access permission of winner FAP as a Stackelberg game, in which MNO and MVNO are leaders, and FH is follower. Obviously, the game consists of two phases: the first one is the refunds compensation of MNO and MVNO, and the second one is the access resource allocation of the FH.

Back induction method is classical to solve Stackelberg game. In the following, we first derive the optimal strategy of follower based on utility maximization. Next, we use the result in leaders' utilities for maximization. We then prove the existence of the Nash Equilibrium.

a. Best response of FH

The utility of FH is a function of two optimization variables Φ_m and Φ_n , which represent the strategy of FH in the game, denoted by $\{\Phi_m, \Phi_n\}$. When receiving the information of price-coefficients α_M and α_V from MNO and MVNO, the FH makes the best response $\{\Phi_m^*, \Phi_n^*\}$ to allocate access resources.

Proposition: Given price-coefficients α_M and α_V , the best response of the FH is given by

$$\{\Phi_m^*, \Phi_n^*\} = \left\{ \frac{B_M}{A_F \ln \alpha_M} - 1, \frac{B_V}{A_F \ln \alpha_V} - 1 \right\}, \quad \begin{cases} e^{\frac{B_M}{2A_F}} < \alpha_M < e^{\frac{B_M}{A_F}} \\ e^{\frac{B_V}{2A_F}} < \alpha_V < e^{\frac{B_V}{A_F}} \end{cases} .$$

(17)

Proof: For simplicity of notation, we define $A_F = \omega_F \log_2(1 + \eta_F)$, $A_M = \omega_M \log_2(1 + \eta_M)$, and $A_V = \omega_V \log_2(1 + \eta_V)$. Then, U_{FH} can be expressed as $(1 - \Phi_m - \Phi_n) A_F + B_M \log_{\alpha_M}(\Phi_m + 1) + B_V \log_{\alpha_V}(\Phi_n + 1)$.

The first order partial derivatives of U_{FH} with respect to Φ_m and Φ_n respectively are given by

$$\begin{cases} \dfrac{\partial U_{FH}}{\partial \Phi_m} = -A_F + \dfrac{B_M}{\ln \alpha_M} * \dfrac{1}{\Phi_m + 1} \\ \dfrac{\partial U_{FH}}{\partial \Phi_n} = -A_F + \dfrac{B_V}{\ln \alpha_V} * \dfrac{1}{\Phi_n + 1} \end{cases} .$$

(18)

The mixed and second order partial derivatives of U_{FH} with respect to Φ_m and Φ_n are respectively given by

$$\begin{cases} \dfrac{\partial^2 U_{FH}}{\partial \Phi_m \partial \Phi_n} = 0 \\ \dfrac{\partial^2 U_{FH}}{\partial^2 \Phi_m} = \dfrac{B_M}{\ln \alpha_M} * \dfrac{-1}{(\Phi_m + 1)^2} \\ \dfrac{\partial^2 U_{FH}}{\partial^2 \Phi_n} = \dfrac{B_V}{\ln \alpha_V} * \dfrac{-1}{(\Phi_n + 1)^2} \end{cases} .$$

(19)

As operators are willing to pay refunds for access resources only for the situation of having positive capital

quantity, we have $B_M > 0$, $B_V > 0$. Furthermore, we have $\ln \alpha_M > 0$ and $\ln \alpha_V > 0$ as $\alpha_M > 1$ and $\alpha_V > 1$. Obviously, $\partial^2 U_{FH}/\partial^2 \Phi_m < 0$ and $\partial^2 U_{FH}/\partial^2 \Phi_n < 0$. We know that if a function with two variables satisfies the condition that the difference between the square of mixed derivative and the product of two second order partial derivatives is negative while either second order partial derivative is negative, the unique maximum of this function exists. Hence the following conditions, which guarantee the existence of maximum utility, are satisfied:

$$\begin{cases} \left(\dfrac{\partial^2 U_{FH}}{\partial \Phi_m \partial \Phi_n} \right)^2 - \dfrac{\partial^2 U_{FH}}{\partial^2 \Phi_m} * \dfrac{\partial^2 U_{FH}}{\partial^2 \Phi_n} < 0 \\ \left| \dfrac{\partial^2 U_{FH}}{\partial^2 \Phi_m} \right| < 0 \end{cases} \quad (20)$$

Therefore, the maximization of U_{FH} is achieved by solving the following equations are derived by the first order partial derivatives being equal to 0:

$$\begin{cases} -A_F + \dfrac{B_M}{\ln \alpha_M} * \dfrac{1}{\Phi_m^* + 1} = 0 \\ -A_F + \dfrac{B_V}{\ln \alpha_V} * \dfrac{1}{\Phi_n^* + 1} = 0 \end{cases} \quad (21)$$

Finally, we obtain the solution as:

$$\{\Phi_m^*, \Phi_n^*\} = \left\{ \frac{B_M}{A_F \ln \alpha_M} - 1, \frac{B_V}{A_F \ln \alpha_V} - 1 \right\}. \quad (22)$$

As $0 < \Phi_m < 1$ and $0 < \Phi_n < 1$ according to their definitions, the solution has to satisfy the following conditions:

$$\begin{cases} 0 < \dfrac{B_M}{A_F \ln \alpha_M} - 1 < 1 \\ 0 < \dfrac{B_V}{A_F \ln \alpha_V} - 1 < 1 \end{cases} \quad (23)$$

Therefore, the constraints for obtaining the best response of the FH are given by

$$\begin{cases} e^{B_M/2A_F} < \alpha_M < e^{B_M/A_F} \\ e^{B_V/2A_F} < \alpha_V < e^{B_V/A_F} \end{cases} \quad (24)$$

Proof completes. Moreover, we can clearly see that the best response of FH is non-negative and monotonic with α_M and α_V.

b. Best response of MNO and MVNO

As leaders in the game, both MNO and MVNO will try to select their strategy to maximize their own utility while taking into account the best response of the FH. For given $\{\Phi_m^*, \Phi_n^*\}$, MNO and MVNO can make their best response α_M^* and α_V^* independently to determine their refunding amount. For the similarity of utility maximization for both MNO and MVNO, we present the solution procedure for MNO only in the following.

Proposition: Given $\{\Phi_m^*, \Phi_n^*\}$, the best response of MNO is given by

$$\alpha_M^* = e^{\frac{B_M}{A_F * e^{(A_M/A_F - 1)}}}, \quad \frac{B_M}{A_F \ln \alpha_M} < e^{[-1/(2 + \ln \alpha_M) - A_M/A_F + 1]}. \quad (25)$$

Proof: Substituting the best response of FH into the utility function of MNO yields

$$\begin{aligned} U_{MNO} &= A_M \left(\frac{B_M}{A_F \ln \alpha_M} - 1 \right) - B_M \log_{\alpha_M} \left(\frac{B_M}{A_F \ln \alpha_M} - 1 + 1 \right) \\ &= \frac{A_M B_M}{A_F \ln \alpha_M} - B_M * \frac{\ln (B_M / A_F \ln \alpha_M)}{\ln \alpha_M} - A_M \end{aligned} \quad (26)$$

The first and second order derivatives of U_{MNO} are respectively given by

$$\frac{\partial U_{MNO}}{\partial \alpha_M} = \frac{B_M [A_F - A_M + A_F \ln (B_M / A_F \ln \alpha_M)]}{A_F \alpha_M (\ln \alpha_M)^2}. \quad (27)$$

$$\begin{aligned} \frac{\partial^2 U_{MNO}}{\partial^2 \alpha_M} = \frac{B_M}{A_F} \Bigg\{ &\frac{2[A_M - A_F + A_F \ln (B_M / A_F \ln \alpha_M)]}{(\ln \alpha_M)^3 (\alpha_M)^2} \\ &+ \frac{A_F}{(\ln \alpha_M)^3 (\alpha_M)^2} + \frac{A_M - A_F + A_F \ln (B_M / A_F \ln \alpha_M)}{(\ln \alpha_M)^2 (\alpha_M)^2} \Bigg\} \end{aligned} \quad (28)$$

In order to obtain the maximum utility of MNO, the second order derivative of U_{MNO} has to be negative. Since $\ln \alpha_M > 0$, $B_M > 0$, $A_F > 0$, we transform the proof of $\partial^2 U_{MNO}/\partial^2 \alpha_M < 0$ into the proof of inequality as

$$\left[A_M - A_F + A_F \ln \left(\frac{B_M}{A_F \ln \alpha_M} \right) \right] * (2 + \ln \alpha_M) + A_F < 0$$

$$\Rightarrow A_M - A_F + A_F \ln \left(\frac{B_M}{A_F \ln \alpha_M} \right) < \frac{-A_F}{2 + \ln \alpha_M}$$

$$\Rightarrow \ln \left(\frac{B_M}{A_F \ln \alpha_M} \right) < \frac{-1}{2 + \ln \alpha_M} - \frac{A_M}{A_F} + 1$$

$$\Rightarrow \frac{B_M}{A_F \ln \alpha_M} < e^{[-1/(2 + \ln \alpha_M) - A_M/A_F + 1]} \quad (29)$$

In fact, it is impossible to obtain analytical solution for α_M in (29). Fortunately, we can prove that the inequality in (29) stands easily in some value domain. For example, when $\alpha_M = e$, we can derive a new inequality as

$$\begin{aligned} &\ln (B_M / A_F) < 2/3 - A_M / A_F \\ &\Rightarrow 0 < B_M / A_F < e^{2/3 - A_M/A_F} \end{aligned} \quad (30)$$

Obviously, (30) is feasible in the value domain of B_M, A_M and A_F. Thus, $\partial^2 U_{MNO}/\partial^2 \alpha_M < 0$ is satisfied. Furthermore, letting $\partial U_{MNO}/\partial \alpha_M = 0$, we can obtain the solution as the best response of MNO as

$$\alpha_M^* = e^{\frac{B_M}{A_F * e^{(A_M/A_F - 1)}}}. \quad (31)$$

Proof completes.

Using the similar method, we can obtain the best response of

MVNO as $\alpha_V^* = e^{B_V/\left(A_F * e^{(A_V/A_F - 1)}\right)}$ on the condition $B_V / A_F \ln \alpha_V < e^{[-1/(2+\ln \alpha_V) - A_V/A_F + 1]}$.

We can see that α_M^* and α_V^* are positive as well as monotonic with some parameters such as B_M, A_M and A_F. It means that α_M^* and α_V^* are unique for particular parameters. Due to the monotonicity between $\{\Phi_m^*, \Phi_n^*\}$ and $\{\alpha_M^*, \alpha_V^*\}$, for given $\{\alpha_M^*, \alpha_V^*\}$, there would be a unique $\{\Phi_m^*, \Phi_n^*\}$. In other words, on the basis of positivity, monotonicity and scalability of respective best response [12], each player achieves its unique maximal own utility and is unwilling to change their strategies to decrease the utility. Therefore, the existence and the uniqueness of Nash Equilibrium are proved.

V. IMPLEMENTATION OF ACCESS PERMISSION

In this section, we describe the implementation of the refunding policy for access permission. We present the procedure for every participant to select appropriate strategy according to Stackelberg game analysis. Every participant can achieve his own utility maximization and reach Nash Equilibrium in two steps by the procedure.

A. Information collection

In order to select appropriate strategy, MNO and MVNO have to acquire the information about ω_F, ω_M, ω_V, η_F, η_M and η_V. Among these factors, ω_F, ω_M and ω_V can be readily obtained from historical data analysis as they can keep stable in a time period of interest. However, it is difficult for operators to obtain η_F, η_M and η_V, as they are varying in wireless networks and need to be measured. A feasible solution is that the FAP collects these parameter values periodically. FAP is able to measure the SINR of every UEs in the coverage and compute the average value as threshold for each kind of UEs (including SUEs, T-MUEs, and V-MUEs). Obviously, FAP then sends this information to MNO and MVNO to help them make decisions. Once a new access request arrives, the FAP would update the values and re-send the information. Internet backhaul link between FAP can facilitate this information collection.

As for FH, α_M and α_V are crucial factors to perform appropriate resource allocation. FH receives $\{\alpha_M$ and $\alpha_V\}$ from operators. Together with the previous measured η_F, the appropriate access permission can be determined. Moreover, B_M and B_V significantly affect the strategy selection of both FH and network operators. As they are relatively static, we can simply initialize the value when refunding mechanism begins.

B. Procedure of access permission

On basis of collected parameters values, the FH and network operators perform the following steps for access permission:
1) Initialize ω_F, ω_M, ω_V, B_M and B_V when the refunding

mechanism starts in hybrid access mode.
2) The FAP measures the SINR of every UE in its coverage area, and classify these SINRs according to the affiliation of UEs.
3) The FAP collects different kinds of SINRs and computes the average values as thresholds for every types of UEs: η_F, η_M and η_V. If the SINR of UEs is lower than the corresponding threshold of the same UE type, these UEs are rejected for access. The rest UEs are marked as permitted T-MUEs and V-MUEs.
4) The FAP sends η_M and η_V to MNO and MVNO respectively.
5) MNO and MVNO receive η_M and η_V, and compute α_M and α_V respectively. If $B_M / A_F \ln \alpha_M < e^{[-1/(2+\ln \alpha_M) - A_M/A_F + 1]}$ and $B_V / A_F \ln \alpha_V < e^{[-1/(2+\ln \alpha_V) - A_V/A_F + 1]}$ are satisfied, MNO and MVNO feedback α_M and α_V to FAP. Otherwise, MNO and MVNO return 0, which means that MNO and MVNO give up the access request.

The FAP receives α_M and α_V reported from MNO and MVNO, and examines whether $e^{B_M/2A_F} < \alpha_M < e^{B_M/A_F}$ and $e^{B_V/2A_F} < \alpha_V < e^{B_V/A_F}$ are satisfied first. If these conditions are satisfied, FAP computes Φ_m and Φ_n, and allocates the resources to permitted T-MUEs and V-MUEs.

VI. NUMERICAL RESULTS

In this section, we conduct simulation experiments to validate the effectiveness of our proposed scheme on access permission of hybrid femtocell networks.

A. Scenarios and settings

The simulation scenario and system settings are as follows. There are some FAPs that have fixed coverage radius of 100 meters and transmission power of 33dBm. These FAPs constitute a femtocell network. The whole coverage of femtocell network can be partitioned into some areas, and these areas can be indicated by the related coordinate marks. We set the initial value of the number of FAPs is $I = 10$, and the initial value of the number of coordinate marks is K. Some active SUEs, T-MUEs and V-MUEs are randomly distributed around the FAP. The access demands of SUEs, T-MUEs and V-MUEs are random. As SUEs are usually served by FAP with higher priority and better service quality, we set the distance (related to SINR threshold) from SUEs to FAP to follow Normal distribution with mean 60 meters and variance 10. Similarly, the distance from T-MUEs or V-MUEs to FAP follows Gaussian distribution with mean 80 meters and variance 10. Considering the difference on capital quantity between MNO and MVNO, the refund base of MNO is set to $B_M = 15$, and the refund base of MVNO is set to $B_V = 10$. Accordingly, as each participant of the game may have different equivalent

revenue on unit data rate, we set $\omega_F = 3$, $\omega_M = 4$ and $\omega_V = 3.5$. These parameters of equivalent revenue and refund base may vary.

In addition, we define some more performance metrics:
1) *Utilization of FAPs (U_f):* the ratio of winner FAPs (i.e., the FAPs that provide access service for MUEs) to the total number of FAPs in the femtocell network;
2) *Throughput (T):* the sum of allocated access resources of permitted MUEs.
3) *Satisfaction for access demand (Sad):* the ratio of "*Throughput*" to the sum of access demand from all MUEs. It reflects the success rate of access request of MUE.
4) *Total valuation (Vt):* the sum of expenditure that permitted MUEs need to pay for the access service of FAPs. This indicator reflects the costs of permitted MUE occupying the access resource of femtocell network.
5) *Cost per access permission (Cp):* the ratio of "*total valuation*" to "*throughput*", which reflects the cost of unit access resource.

B. Numerical results

In the first simulation experiment, we investigate the social welfare of our proposed refunding policy, where the social welfare is defined as the sum of every participant's utility in the access permission. We compare the proposed refunding policy applied to three access modes for femtocells: open, closed, and hybrid modes. We set $\Phi_m = 0$ and $\Phi_n = 0$ for close access mode. Considering that the open access mode has random allocation scheme, we simulate a typical scenario in which SUEs are dominant and occupy 50% of total resources, the rest resources are allocated equally to MNO and MVNO, i.e. $\Phi_m = 0.25$ and $\Phi_n = 0.25$. In hybrid access, the FAP would select appropriate allocation scheme dynamically according to real time wireless environment and the announced price-coefficients from MNO and MVNO. Fig.3 shows the social welfare for three access modes. From Fig.3, we can see that the social welfare for hybrid access is the highest as the utility of every participant is improved compared with that for closed access and open access modes. Although selecting a typical value for open access mode, FH still prefers adopting hybrid access mode in other conditions because of less handover and signaling overhead.

In the second simulation experiments, we compare ASGF with TAIF. Fig.4 shows the performance comparison of ASGF and TAIF. We can see that ASGF outperforms TAIF in almost all performance metrics, except that ASGF has close V_t performance with TAIF. Specifically, ASGF approximately achieves 10% higher U_f and C_p, and 5-8% higher T and S_{ad} than TAIF. These results reveal that ASGF can enable more FAPs to provide access service for MUE, improve access capacity, and increase the success rate of access requests. On the other hand, the expenditure paid by MUEs for allocated access resource by using ASGF is almost the same as that by using TAIF.
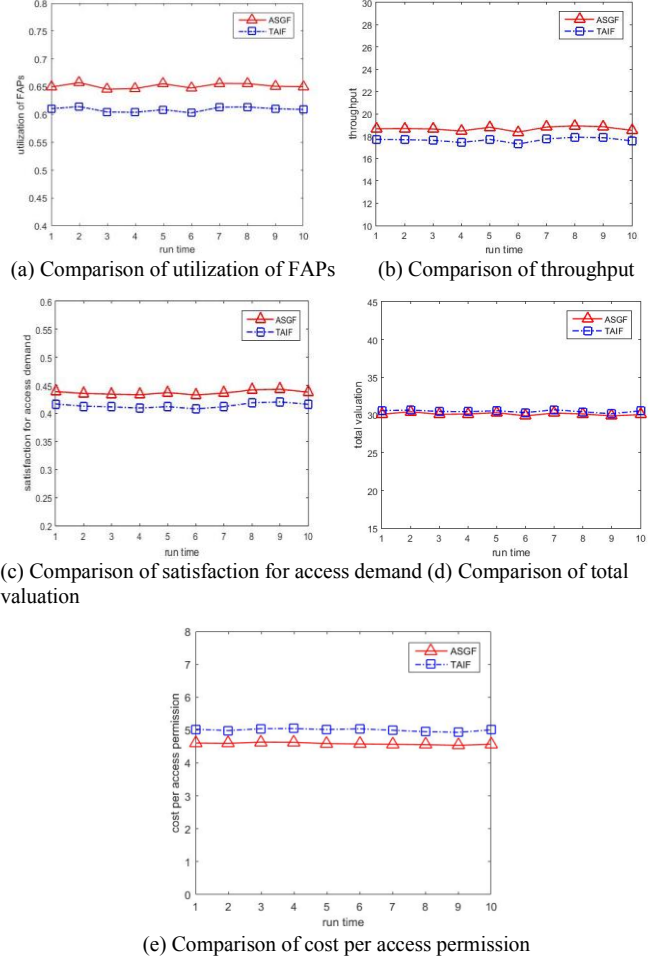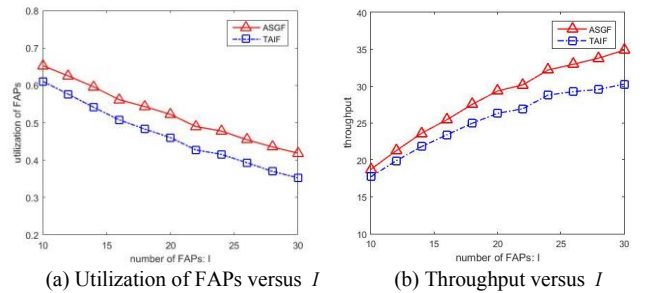
(a) Comparison of utilization of FAPs (b) Comparison of throughput

(c) Comparison of satisfaction for access demand (d) Comparison of total valuation

(e) Comparison of cost per access permission
Fig.4. Performance comparison between ASGF and TAIF

(a) Utilization of FAPs versus I (b) Throughput versus I

Fig.3. Comparison of social welfare

(c) Satisfaction for access demand versus I (d) Total valuation versus I

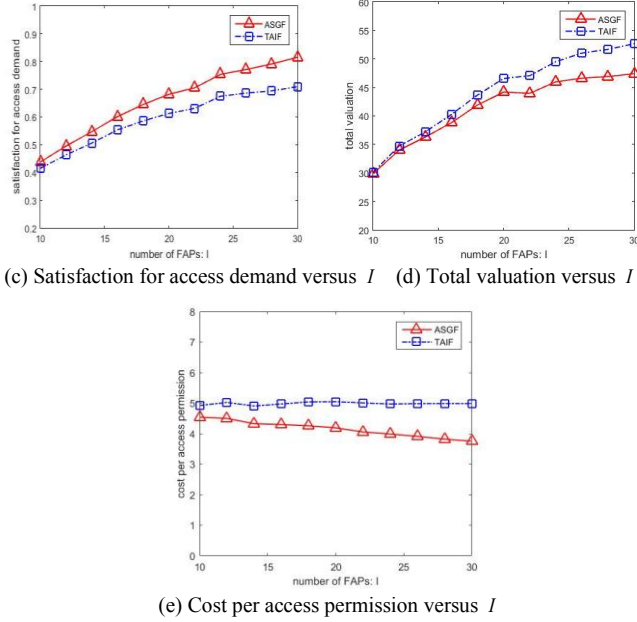(e) Cost per access permission versus I

Fig.5. Effectiveness of ASGF and TAIF versus I

In the third simulation experiments, we investigate the impact of the number of FAPs I on the performance of femtocell network. Intuitively, the number of FAPs has significant impact as it determines the density of femtocell. Fig.5 shows performance of ASGF and TAIF as a function of I. We can see that T, S_{ad} and V_t monotonically increase while U_f and C_p decrease with I. It indicates that deploying more FAPs enables MUEs to pay less expenditure and share more access capacity, while the system achieves higher success rate of access requests. However, deploying more FAPs may cause that some FAPs become idle if there are no sufficient access requests. Moreover, ASGF always outperforms TAIF in all metrics. In conclusion, the results reveal that increasing the density of FAPs in femtocell network can improve network performance, and the effect is more significant by utilizing ASGF.

(a) Utilization rate of FAPs versus I, K (b) Throughput versus I, K

(c) Satisfaction for access demand versus I, K (d) Total valuation versus I, K

(e) Cost performance versus I, K
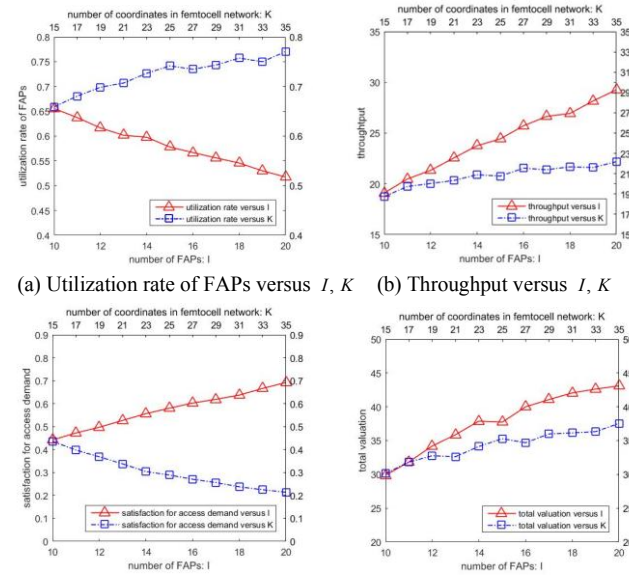
Fig.6. Impact of parameters (I, K) to network performance

In the next simulation experiments, we investigate the impact of the number of coordinate marks K on network performance of ASGF. The value of K can reflect the density of FAPs for certain number of FAPs. For example, we assume that there are 5 FAPs in a femtocell network, and the coverage of the femtocell network can be partitioned into 10 unit areas (i.e., K=10). The density of FAPs can be approximately considered as 5/10=50%. As both I and K can affect the density of FAPs, we fix one while varying the other. Fig.6 shows performance of ASGF as a function of I and K respectively. U_f, S_{ad} and C_p monotonically increase with K and decrease with I. Intuitively, for fixed I, increasing the value of K is equivalent to decreasing the density of FAPs, or decreasing the number of FAPs for fixed K. However, in Fig.6 (b) and Fig. 6 (d) , T and V_t increase with both K and I. the reason is that the "dilution" by fixing I and increasing K cannot truly decrease the capacity of access service. The increment on coverage makes some FAPs to become "hot" in certain areas. These hot FAPs would rather open more access resources if MUEs pay more refunds. Therefore, the allocated access resources of MUEs increase, resulting in the improvement on throughput, as shown in Fig.6 (d). However, this improvement is less significant than adding FAPs to the femtocell network, as the available access resources of hot FAPs is always limited. Thus the curve for varying K is below the curve for varying I.
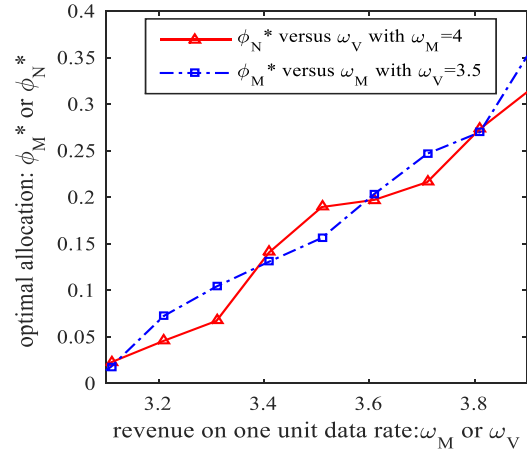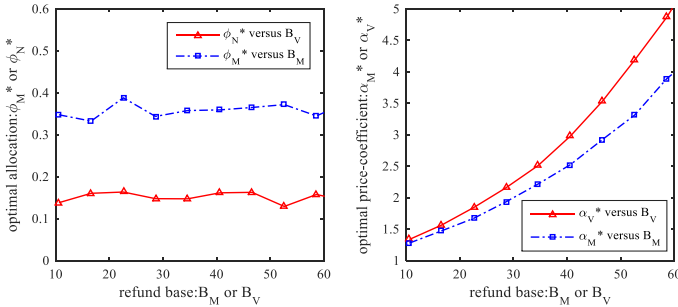

Fig.7. Allocated resource versus ω

Then, we investigate the change of the obtained resources of operators when the equivalent revenue on unit data rate of

operators varies. Fig. 4 shows both MNO and MVNO can attain more spare access resources if they increase the revenue on one unit data rate. From Fig.7, we can observe an interesting phenomenon. Both curves show that when an operator keeps his equivalent revenue unchanged, another operator may obtain more access resources than his opponent by increasing the equivalent revenue. We also find that once an operator selects the same strategy with his opponent, the dominant one may lose the advantage, because two curves in Fig.7 roughly overlap. Hence, the reasonable way for network operators to obtain more resources is providing differentiated services rather than merely increasing service price.

Finally, we investigate the influence of refund base on the best response of FH (allocated resources to MNO and MVNO respectively), and the best responses of MNO and MVNO (the best price-coefficients). Fig.8 shows that the allocated resources to operators are not determined by refund base, and the best price-coefficient can become larger when refund base of operators increase. From Fig.8 (a), we find that FH may not be sensitive to the refund base, as the amount of allocated resources of MNO and MVNO both keep relatively stable when operators increase their refund base. It indicates that the capital quantity of MNO and MVNO cannot affect FH to allocate access resources. From Fig.8 (b), we find that the best price-coefficients of both MNO and MVNO increase when operators increase their refund base. As the capital quantity of MNO is usually larger than that of MVNO, the best price-coefficient of MNO is smaller than that of MVNO. It indicates that MNO is indeed aggressive and may pay more refunds than MVNO for the same amount of resources.

(a) Allocated resources   (b) The best price-coefficient
Fig.8. Allocated resources and price-coefficient versus refund base

VII. RELATED WORK

When femtocell technology emerges, most attentions are paid on its influence to existing network. Four technical challenges are identified in [4], including interference coordination, cell association and biasing, mobility and soft handover, and self-organizing networks. Later, further studies [5]-[7] prove that access control mechanism can affects all above four technical challenges. Recent years witness the growing body of literatures on the access control of femtocell networks [12]-[15]. In [14], Lin Cui and Weijia Jia propose a heuristic algorithm for hybrid femtocells to solve mutual selection admission (MSA) problem. They consider that users prefer to access the femtocells that have the best signal quality for better service. Guruacharya et al. in [15] divide the transmitters of OFDMA femtocell network into two

complementary coalitions, depending on whether the transmitters connected to femto access points or not. Then, a coalition game is formulated, and some stable coalition structures are obtained as the solution of access control problem.

As femtocell holders (FHs) are dominant to configure and manage their femtocells, more studies start to investigate how individual actions affect the access control and network performance [16]-[19]. Yanjiao Chen et al. in [8] propose a utility-aware refunding framework to motivate FHs to adopt hybrid access mode. In the framework, Both FHs and MNO aim to maximize their utilities during spectrum allocation. The optimal strategies of them are analyzed by formulating a Stackelberg game. In [16], Yanjiao Chen et al. also propose a reverse auction framework for fair and efficient access permission transaction. The devised model allows wireless service providers accept partial demand fulfillment. Furthermore, the proposed greedy algorithm for winner and price determination reduce the computational complexity. Sha Hua et al. in [17] propose a Vickrey-Clarke-Grove (VCG) auction based incentive framework for hybrid access femtocells, and designed two scheme respectively for single user access and multiple user access. In [18], Xin Kang et al. assume that the macrocell protected itself by pricing the interference from femtocell users under spectrum-sharing deployment. Then, a Stackelberg game is formulated to analyze this problem, and uniform pricing and non-uniform pricing schemes is proposed for sparsely deployed scenario and densely deployed scenario. Pantisano et al. in [19] suggest a framework for macrocell-femtocell cooperation under closed access mode, in which each macrocell granted the cooperative relay femtocell a fraction of its super frame as return. The author of [19] make use of coalitional game to describe whether macrocell and femtocell are worthy cooperating while maximizing a utility function in terms of throughput and delay. It thus can be seen that game theory and some economic thinking have been efficient analytical tools to solve the problem of access control for femtocell network.

In addition, other studies are focused on the relationship between femtocell and mobile virtual network operators (MVNOs), and give some suggestions on efficient spectrum utilization of femtocell network in the perspective of MVNOs [20]-[22]. These works inspire us to consider the competition between MNOs and MVNOs on access control of femtocell network.

VIII. CONCLUSION

In this paper, we have investigated the competition between MNO and MVNO in the access permission of hybrid femtocell network. We have proposed a two-stage auction-Stackelberg game (ASGF) framework, which motivates network operators and FHs to share the spare access resources of FAPs by refunding policy, and guarantees operators and FHs make reasonable decisions as well. In the refunding policy, we have designed refunding strategy function to describe the relationship between the refunding amount and attained

resource, and defined price-coefficient to reflect the refunding strategy diversity of MNO and MVNO. In the first stage of ASGF framework, VCG based reverse auction determined the winner FAPs that can be qualified to make access permission for macro users. In the second stage of proposed framework, with the help of Stackelberg game analysis, we concluded that MNO, MVNO and FH can maximize their utility by reaching a unique Nash Equilibrium in the access permission. A feasible procedure of access permission has been proposed to guide every participant to make appropriate strategy by collecting necessary information about system. Simulation results have illustrated that proposed ASGF framework improves the social welfare of network, and every participant achieves the win-win situation by appropriate resource allocation.

REFERENCES

[1] Cisco, "Cisco visual networking index: global mobile data traffic forecast update, 20102015," *Whitepaper*, Feb. 2011.

[2] A. Osseiran, F. Boccardi, and V. Braun, et al, "Scenarios for 5G mobile and wireless communications: the vision of the METIS project," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26-35, 2014.

[3] M. Balon, B. Liau, "Mobile Virtual Network Operator-Architecture Evolution and Economic Stakes," *Telecommunications Network Strategy and Planning Symposium (NETWORKS),* 2012 XVth International, pp.1-6, 2012.

[4] M. Debbah, L. Echabbi, and C. Hamlaoui, "Market Share Analysis between MNO and MVNO under Brand Appeal Based Segmentation," *Network Games, Control and Optimization (NetGCoop)*, 2012 6th International Conference on, pp. 9-16, 2012.

[5] J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. C. Reed, "Femtocells: past, present, and future," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 497–508, 2012.

[6] G. de la Roche, A. Valcarce, D. Lopez-Perez, and J. Zhang, "Access control mechanisms for femtocells," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 1–7, 2010.

[7] S. Hua, X. Zhuo, and S. S. Panwar, "A truthful auction based incentive framework for femtocell access," in *Proc. 2013 IEEE WCNC*, pp. 2271–2276, 2013.

[8] Y. Chen, J. Zhang, Q. Zhang, and J. Jia, "A reverse auction framework for access permission transaction to promote hybrid access in femtocell network," in *Proc. 2012 IEEE INFOCOM*, pp. 2761–2765, 2012.

[9] Y. Chen, J. Zhang, and Q. Zhang, "Utility-aware refunding framework for hybrid access femtocell network," *IEEE Trans. Wirel. Commun.*, vol. 11, no. 5, pp. 1688–1697, 2012.

[10] S. Yun, Y. Yi, D. Cho, and J. Mo, "The economic effects of sharing femtocells," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 595–606, 2012.

[11] H. Claussen, L. T. W. Ho, and L. G. Samuel, "Financial analysis of a pico-cellular home network deployment," in *Proc. 2007 ICC*, pp. 5604–5609, 2007.

[12] G. Iosifidis, L. Gao, J. Huang, and L. Tassiulas, "A Double-Auction Mechanism for Mobile Data-Offloading Markets," *IEEE/ACM Trans. Netw.*, vol. 23, no. 5, pp. 1634–1647, 2015.

[13] R.B. Mynerson and M.A. Satterthwaite, "Efficient Mechanism for Bilateral Trading," *J. Econ. Theory*, vol. 29, no. 2, pp.265–281, 1983.

[14] L. Cui and W. Jia, "A novel mutual-preference-based admission control mechanism for hybrid femtocells system," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4555–4564, 2013.

[15] S. Guruacharya, D. Niyato, and D. I. Kim, "Access control via coalitional power game," in *Proc. 2012 IEEE WCNC*, pp. 2824–2828, 2012.

[16] Y. Chen, J. Zhang, Q. Zhang, and J. Jia, "A reverse auction framework for access permission transaction to promote hybrid access in femtocell network," in *Proc. 2012 IEEE INFOCOM*, Mini-Conf, pp. 2761–2765, 2012.

[17] S. Hua, X. Zhuo, and S. S. Panwar, "A truthful auction based incentive framework for femtocell access," in *Proc. 2013 IEEE WCNC*, pp. 2271–2276, 2013.

[18] X. Kang, R. Zhang, and M. Motani, "Price-based resource allocation for spectrum-sharing femtocell networks: A Stackelberg game approach," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 538–549, 2012.

[19] F. Pantisano, M. Bennis, and W. Saad, "Spectrum Leasing as an Incentive Towards Uplink Macrocell and Femtocell Cooperation," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 3, pp. 617–630, 2012.

[20] W. Hong, Z. Tsai, "On the Femtocell-based MVNO Model: A Game Theoretic Approach for Optimal Power Setting," *Veh. Technol. Conf. 2010-Spring*, 2010 IEEE 71st, pp. 1–5, 2010.

[21] L. Duan, J. Huang, and B. Shou, "Cognitive Mobile Virtual Network Operator: Investment and Pricing with Supply Uncertainty," in *Proc. 2012 IEEE INFOCOM*, pp.1–9, 2010.

[22] S. Pattanavichai, N. Jongsawat, and W. Premchaiswadi, "A pricing model and sensitivity analysis for MVNO investment decision making in 3G UMTS networks," *Ind. Electron. & Appl. (ISIEA), 2010 IEEE Symp.On*, pp. 22–27, 2010.

[23] Z. Han, D. Niyato, W. Saad, T. Basar and A. Hjorungnes, Game Theory in Wireless and Communication Networks, 2012.

Sanshan Sun received the B.S. degree in Electrical Engineering and Automation from Sichuan Normal University in 2006 and the M.S. degree in Communication and Information Systems from Chongqing University of Posts and Telecommunications in 2009, respectively. He is currently a Ph.D. candidate in National Key Laboratory of Science and Technology on Communications in University of Electronic Science and Technology of China (UESTC). His research interests include resource management and game theory.

Gang Feng (M'01, SM'06) received his BEng and MEng degrees in Electronic Engineering from the University of Electronic Science and Technology of China (UESTC), in 1986 and1989, respectively, and the Ph.D. degrees in Information Engineering from The Chinese University of Hong Kong in1998. He joined the School of Electric and Electronic Engineering, Nanyang Technological University in December 2000 as an assistant professor and was promoted as an associate professor in October 2005. At present he is a professor with the National Laboratory of Communications, University of Electronic Science and Technology of China. Dr. Feng has extensive research experience and has published widely in computer networking and wireless networking research. His research interests include resource management in wireless networks, next generation cellular networks, etc. Dr. Feng is a senior member of IEEE.
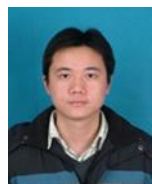
Shuang Qin received the B.S. degree in Electronic Information Science and Technology, and the Ph.D. degree in Communication and Information System from University of Electronic Science and Technology of China (UESTC), in 2006 and 2012, respectively. He is currently an associate professor with National Key Laboratory of Science and Technology on Communications in UESTC. His research interests include cooperative communication in wireless networks, data transmission in opportunistic networks and green communication in heterogeneous networks.

Yao Sun received the B.S. degree in Mathematical Sciences from the University of Electronic Science and Technology of China (UESTC). He is currently working towards his Ph.D. degree at National Key Laboratory of Science and Technology on Communications, UESTC. His research and study interests are in cell association and resource allocation in wireless networks.

Zhaorong Zhou received his BS degree in Information Engineering from Zhejiang University, Hangzhou, China, in 1998 and his PhD degree in Communication and Information Systems from the University of Electronic Science and Technology of China, Chengdu, China, in 2009, respectively. Now, he is an associate professor at the School of Physics and Electronic Engineering, Sichuan Normal University of China, Chengdu, China. His current research interests include wireless communication technique and radio resource management.