Stackelberg Game for Access Permission in Femtocell Network with Multiple Network Operators

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***Abstract*—Femtocells are widely recognized as a promising technology to meet the requirements of indoor coverage in forthcoming fifth generation cellular networks (5G). As femtocell holders (FHs) can be users themselves or mobile network operators, it makes challenges to holistic network resource utilization. In particular, due to the selfishness nature, FHs are usually unwilling to accommodate extra users without compensation. This inspires us to develop an effective refunding mechanism, with aim to allow competitive network operators to employ truthful refunding policy, and to encourage FHs to make appropriate access permission. In this paper, we first define a refunding strategy function and price-coefficient for the refunding policy. We then formulate the access permission as a Stackelberg game and theoretically prove the existence of unique Nash Equilibrium. Numerical results validate the effectiveness of our proposed mechanism and overall network efficiency is improved significantly as well.**

Keywords—Femtocell Holder, Mobile Network Operator, Access Permission, Refund, 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.

Compared with other small cells, femtocell is more preferable to MNOs and MVNOs because of the easy-configuration. Femtocell holders (FHs), who can be individual users or network operators, may place femtocell anywhere and configure the operation mode arbitrarily [3]. Femtocell has three operation modes including open access, closed access and hybrid access [4]. 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 encourage FHs to share femtocells for user access. The authors in [5] proposed a Vickrey-Clarke-Groves (VCG) auction based incentive framework for the trade of access time between femtocells and mobile user equipments (MUEs). However, in real markets, MUEs prefer to authorize their served network operators rather than themselves to make the deal with FHs. The authors in [6] developed a reverse auction framework to motivate access permission trading of femtocells in network operator's perspective. However, the truthfulness of this modified auction is not proved strictly, and the participating agent is able to cheat. Hence, the authors in [7] proposed a utility-aware refunding framework to solve access trading between single wireless service provider (WSP) and FHs in hybrid access femtocell network based on Stackelberg game analysis. However, the study on access permission in femtocell network with multiple network operators is more meaningful. Furthermore, 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) besides the user churn rate that is considered only in [7]. The work in [8] [9] just analyzed the economic effects of deploying and sharing femtocells by network operators, and gave the cost expression.

In this paper, we are focused on the competition with virtualized access resources between multiple network operators in hybrid femtocell network, which intervenes FHs in making access permission. Specifically, we consider a pair of typical competitors, i.e. MNO and MVNO, in our system model. Obviously, once MNO and MVNO fall into irrational competition, FHs probably admit excessive users who are not qualified to be served. Under this circumstance, it is imperative to develop an effective mechanism to motivate every participant to make reasonable decision in access permission game. This is essential to retain network operation stability and improve network resource utilization.

We first investigate refunding policy of MNO and MVNO, and define a refunding strategy function (RSF) to reflect the characteristics of refund compensation for sharing resources. Moreover, we define price-coefficient as the strategy form in RSF to specify strategy selection. Considering operators offer the amount of refunds before the access resource allocation of the FH, we formulate the femtocell access permission as a Stackelberg game. We prove the existence and uniqueness of Nash Equilibrium (NE) of the game. When equilibrium is achieved, the access resources are appropriately allocated as every participant is satisfied with allocation scheme to maximize their own utilities. Meanwhile, every participant is qualified to select unique appropriate strategy and unwilling to change, leading to stable access resource utilization and thus overall high network efficiency. Besides, we suggest a practical method to implement the game based access permission. We conduct simulation experiments to evaluate the proposed access permission scheme. Numerical results

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show that every participant can maximize their utilities when each other selects rational strategy, and overall network efficiency is improved significantly as well.

The rest of this paper is organized as follows. Section II describes system model. Section III gives the definition of RSF and price-coefficient, and formulates the access permission problem. In Section IV, we employ Stackelberg game to model the access permission and prove the existence of unique Nash Equilibrium. We present the implementation of our proposed Stackelberg game based access permission scheme in Section V. Section VI presents the numerical results and discussions. We finally conclude the paper in Section VII.

II. SYSTEM MODEL

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

A. Network Model

In the femtocell network shown in Fig. 1, there is a femto access point (FAP) that is configured to operate in hybrid access mode by the FH. The FH authorizes subscribed user equipments (SUEs) to access the FAP.

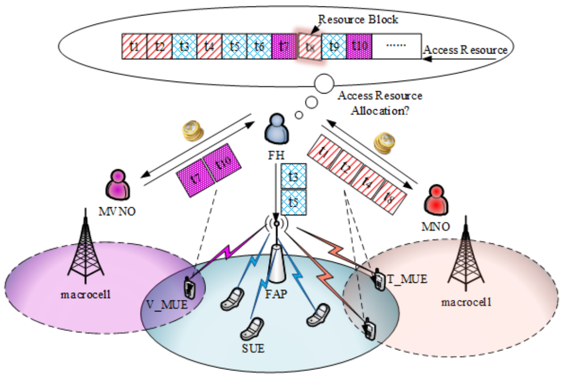


Fig. 1. Illustration of femtocell network shared by two network operators

Considering the multiple radio access technology (Multi-RAT) in next generation mobile communication system (5G) can be virtualized to pose a unified resources pool, we assume that the access resources of the FAP are divided into resource blocks rather than specific time-slots or frequency bands, to be allocated to users for access. Denote by p the number of served SUEs, and by β_i the fraction of access resources to ith SUE. Therefore, the total amount of access fractions for served SUEs can be represented as $\sum_{i=1}^{p}\beta_i = \Phi_p$. In order to attain higher SINR, macrocell user equipments of MNO (T-MUEs) and macrocell user equipments of MVNO (V-MUEs) may move into the femtocell. MNO and MVNO are willing to pay refunds for access resources of FAP to their users for data transmission. If having spare resource, FH may control FAP to allocate spare network resources to T-MUEs and V-MUEs. The total amount of access fractions for served T-MUEs and served V-MUEs can also be represented by $\sum_{i=1}^{m}\gamma_i = \Phi_m$ and $\sum_{i=1}^{n}\delta_i = \Phi_n$ respectively, where m and n denote the number of T-MUEs and V-MUEs respectively. γ_i and δ_i represent the fraction of access resources allocated to ith T-MUE and ith V-MUE respectively. As all the access resources are allocated to each participant, we have $\Phi_p + \Phi_m + \Phi_n = 1$.

Furthermore, we assume that macrocells and femtocells operate on different spectrum bands. The interference of femtocell is only introduced by neighboring femtocells who share the same spectrum. $I_{tot}(X)$ represents the total interference power, which is a function of the number of neighbors X . Hence the SINR of a UE is given by

$$\eta_i = \left(\frac{P}{N_0 + I_{tot}(X)}\right) S d_i^{-n} |h|^2 , \tag{1}$$

where P is the transmission power of FAP, N_0 is the Gaussian noise, S is the log-normal shadowing component, d_i is the distance between ith UE and FAP, n is the path fading exponent, $|h|$ is the Rayleigh-distributed fading magnitude, satisfying $E(|h|^2) = 1$.

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

$$C_i = \log_2(1+\eta_i) . \tag{2}$$

As FAP may provide a fixed SINR to different types of served user equipment such as SUE, T-MUE and V-MUE, we define threshold of SINR as basic service quality for them and compute their aggregated data rate respectively by multiplying allocated fractions and channel capacity as:

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

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

$$\tau_{MVNO} = \Phi_n \log_2(1+\eta_V) , \tag{5}$$

where η_F is the threshold of SUEs, η_M is the threshold of T-MUEs, η_V is the threshold of V-MUEs.

B. Refunding Model

With strong wish to improve indoor transmission data rate, network operators are willing to trade the money directly for spare resources of femtocell as long as higher indoor rate brings more income. An FH is likely to get extra earnings from operators to compensate the investment on equipment in case of bringing no serious degradation to the communication service for the subscribers. Obviously, it is a win-win situation for operators and FHs. 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 initiate access request, vice versa. We define the utility function of operators as:

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

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

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

On the other hand, we define the utility function of FH as:

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

(8) includes three parts: the first part is 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 are the refunds gained from MNO and MVNO respectively.

III. Problem Formulation of Refunding Policy

In this section, we define a refunding strategy function (RSF) to describe the relationship between refunding amount and attained resources. We also propose 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 more information about opponent's strategy. A reasonable approach of designing refunding strategy is to take into account 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 one hand, an FH is willing to obtain some refunds by sharing spare access resources to MNO and MVNO. 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 admitted users will not degrade his own communication service. Therefore, femtocell access permission is indeed the access resource allocation problem, 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 initiate access request by refunding, they always make decision 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 admitted users, FAP may provide poor indoor access for new requesting users. This may lead to decrease on the benefits if operators keep high refunds. Hence, operators may decrease the refunding amount when the FAP have permitted many UEs. Based on this observation, we propose refunding strategy function (RSF) of operators as:

$$R = B\log_{\alpha}(x+1)\ , \tag{9}$$

where B represents the refund base satisfying $B = I_{ncome} - I_{nvestment}$, in which I_{ncome} denotes the earnings of the operator from total business; $I_{nvestment}$ 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, the competition for access resources exists between MNO and MVNO. Even if having same refund base and allocated access resource, MNO and MVNO are still capable of adopting different strategy dynamically to change the amount of 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 generate different refunding amount. Therefore we have the refunding amount of MNO and MVNO respectively as

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

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

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. Therefore, we formulate the utility maximization problem for MNO and MVNO respectively as follows:

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

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

As some factors, including equivalent revenue on one unit data rate, refund base, and SINR threshold, may be considered constant for a time period of interest, we define α_M and α_V as optimization variable for the utility maximization problems (12) and (13) when the allocated fractions Φ_m and Φ_n are generally given.

On the other hand, the FH divides the access resources of FAP into three parts: Φ_p , Φ_m and Φ_n . As $\Phi_p + \Phi_m + \Phi_n = 1$, Φ_p can be represented as $1 - \Phi_m - \Phi_n$. So, 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:

$$\begin{aligned} \max_{\Phi_m,\Phi_n} U_{FH} = \max_{\Phi_m,\Phi_n}[&\omega_F(1-\Phi_m-\Phi_n)\log_2(1+\eta_F) \\ &+ B_M \log_{\alpha_M}(\Phi_m+1) + B_V \log_{\alpha_V}(\Phi_n+1)] \end{aligned}\ . \tag{14}$$

In (14), we define Φ_m and Φ_n as the optimization variables for the utility maximization problem of FH.

IV. Stackelberg Game Analysis

Since every participant in the access permission is selfish and rational to maximize their own utility, we formulate the access permission as a Stackelberg game, in which MNO and MVNO are leaders and the 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. We then utilize back induction method to prove the existence of the Nash Equilibrium for the Stackelberg game.

A. Best Response of FH

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

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

$$\{\Phi_m^*, \Phi_n^*\} = \left\{\frac{B_M}{A_F \ln\alpha_M} - 1, \frac{B_V}{A_F \ln\alpha_V} - 1\right\}, \quad \begin{cases} e^{\frac{B_M}{2A_F}} < \alpha_M < e^{\frac{B_M}{A_F}} \\ e^{\frac{B_V}{2A_F}} < \alpha_V < e^{\frac{B_V}{A_F}} \end{cases}. \quad (15)$$

Proof: For the simplicity of notation, we define $A_F = \omega_F \log_2(1+\eta_F)$, $A_M = \omega_M \log_2(1+\eta_M)$, $A_V = \omega_V \log_2(1+\eta_V)$.

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

$$\begin{cases} \frac{\partial U_{FH}}{\partial \Phi_m} = -A_F + \frac{B_M}{\ln \alpha_M} * \frac{1}{\Phi_m + 1} \\ \frac{\partial U_{FH}}{\partial \Phi_n} = -A_F + \frac{B_V}{\ln \alpha_V} * \frac{1}{\Phi_n + 1} \end{cases}. \quad (16)$$

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

$$\begin{cases} \frac{\partial^2 U_{FH}}{\partial \Phi_m \partial \Phi_n} = 0 \\ \frac{\partial^2 U_{FH}}{\partial^2 \Phi_m} = \frac{B_M}{\ln \alpha_M} * \frac{-1}{(\Phi_m + 1)^2} \\ \frac{\partial^2 U_{FH}}{\partial^2 \Phi_n} = \frac{B_V}{\ln \alpha_V} * \frac{-1}{(\Phi_n + 1)^2} \end{cases}. \quad (17)$$

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 $\alpha_V > 1$. Hence the following conditions, which guarantee the existence of maximum utility, are satisfied:

$$\begin{cases} \left(\frac{\partial^2 U_{FH}}{\partial \Phi_m \partial \Phi_n}\right)^2 - \frac{\partial^2 U_{FH}}{\partial^2 \Phi_m} * \frac{\partial^2 U_{FH}}{\partial^2 \Phi_n} < 0 \\ \frac{\partial^2 U_{FH}}{\partial^2 \Phi_m} < 0 \end{cases}. \quad (18)$$

Therefore, the maximization of U_{FH} is achieved by solving the following equations:

$$\begin{cases} -A_F + \frac{B_M}{\ln \alpha_M} * \frac{1}{\Phi_m^* + 1} = 0 \\ -A_F + \frac{B_V}{\ln \alpha_V} * \frac{1}{\Phi_n^* + 1} = 0 \end{cases}. \quad (19)$$

Finally, we obtain the solution as:

$$\{\Phi_m^*, \Phi_n^*\} = \left\{\frac{B_M}{A_F \ln\alpha_M} - 1, \frac{B_V}{A_F \ln\alpha_V} - 1\right\}. \quad (20)$$

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

$$\begin{cases} 0 < \frac{B_M}{A_F \ln\alpha_M} - 1 < 1 \\ 0 < \frac{B_V}{A_F \ln\alpha_V} - 1 < 1 \end{cases}. \quad (21)$$

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

$$\begin{cases} e^{B_M/2A_F} < \alpha_M < e^{B_M/A_F} \\ e^{B_V/2A_F} < \alpha_V < e^{B_V/A_F} \end{cases}. \quad (22)$$

Proof completes.

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 generate 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

$$\alpha_M^* = e^{\frac{B_M}{A_F * e^{(A_M/A_F - 1)}}}, \quad \frac{B_M}{A_F \ln \alpha_M} < e^{[-1/(2+\ln\alpha_M) - A_M/A_F + 1]}. \quad (23)$$

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

$$\begin{aligned} U_{MNO} &= A_M\left(\frac{B_M}{A_F \ln\alpha_M} - 1\right) - B_M \log_{\alpha_M}\left(\frac{B_M}{A_F \ln\alpha_M} - 1 + 1\right) \\ &= \frac{A_M B_M}{A_F \ln\alpha_M} - B_M * \frac{\ln(B_M / A_F \ln\alpha_M)}{\ln\alpha_M} - A_M \end{aligned}. \quad (24)$$

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

$$\frac{\partial U_{MNO}}{\partial \alpha_M} = \frac{B_M\left[A_F - A_M + A_F \ln(B_M / A_F \ln\alpha_M)\right]}{A_F \alpha_M (\ln\alpha_M)^2}. \quad (25)$$

$$\begin{aligned} \frac{\partial^2 U_{MNO}}{\partial^2 \alpha_M} = \frac{B_M}{A_F}\Bigg\{ &\frac{2\left[A_M - A_F + A_F \ln(B_M/A_F \ln\alpha_M)\right]}{(\ln\alpha_M)^3(\alpha_M)^2} \\ &+ \frac{A_F}{(\ln\alpha_M)^3(\alpha_M)^2} + \frac{A_M - A_F + A_F \ln(B_M/A_F\ln\alpha_M)}{(\ln\alpha_M)^2(\alpha_M)^2}\Bigg\} \end{aligned}. \quad (26)$$

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 $\partial U_{MNO} / \partial^2 \alpha_M < 0$ into the proof of inequality as follows:

$$\begin{aligned} &\left[A_M - A_F + A_F \ln\left(\frac{B_M}{A_F \ln\alpha_M}\right)\right] * (2 + \ln\alpha_M) + A_F < 0 \\ &\Rightarrow A_M - A_F + A_F \ln\left(\frac{B_M}{A_F \ln\alpha_M}\right) < \frac{-A_F}{2 + \ln\alpha_M} \\ &\Rightarrow \ln\left(\frac{B_M}{A_F \ln\alpha_M}\right) < \frac{-1}{2 + \ln\alpha_M} - \frac{A_M}{A_F} + 1 \\ &\Rightarrow \frac{B_M}{A_F \ln\alpha_M} < e^{\left[-1/(2+\ln\alpha_M) - A_M/A_F + 1\right]} \end{aligned}. \quad (27)$$

In fact, it is impossible to obtain analytical solution for α_M in (27). Fortunately, we can prove that the inequality in (27) is satisfied easily in some value domain. For example, when $\alpha_M = e$, we can derive a new inequality as follows:

$$\ln\left(B_M / A_F\right) < 2/3 - A_M / A_F$$
$$\Rightarrow 0 < B_M / A_F < e^{(2/3 - A_M / A_F)} . \quad (28)$$

Obviously, (28) is feasible in the value domain of B_M, A_M and A_F. Thus, $\partial U_{MNO} / \partial^2 \alpha_M < 0$ is satisfied. Furthermore, letting $\partial U_{MNO} / \partial \alpha_M = 0$, we can obtain the solution as best response of MNO as follows:

$$\alpha_M^* = e^{\frac{B_M}{A_F * e^{(A_M / A_F - 1)}}} . \quad (29)$$

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 $B_V / A_F \ln \alpha_V < e^{\left[-1/(2+\ln \alpha_V) - A_V / A_F + 1\right]}$.

On the basis of positivity, monotonicity and scalability of respective best response [10], we conclude that FH, MNO and MVNO achieve the Nash Equilibrium.

V. Implementation of Access Permission

In this section, we describe implementation of the refunding policy for access permission. It allows every participant to achieve their own utility maximization, and reach Nash Equilibrium in two steps.

A. Information Collection

In order to select appropriate strategy, MNO and MVNO have to acquire 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. The best way to solve this problem is that the FAP collects these factors 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 also needs to send this information to MNO and MVNO to help them make decisions. Internet backhaul link between FAP and network operators can be used for this information collection.

As for FH, α_M and α_V are crucial factors to make appropriate resource allocation. FH receives α_M and α_V separately from operators. Together with the previous measured η_F, the appropriate allocation scheme can be determined. Moreover, as B_M and B_V are relatively static, we can initialize the value when refunding operation begins.

B. Procedure of Access Permission

On basis of collected factors, 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 permission.
2) The FAP measures the SINR of every UE in its coverage area, and classify these SINRs according to different affiliation of UEs.
3) The FAP gathers the different kinds of SINRs and computes the average values as thresholds for every kind, such as η_F, η_M and η_V. If the SINR of UEs is lower than 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 by using Internet backhaul link.
5) MNO and MVNO receive η_M and η_V, and compute α_M and α_V respectively. If $B_M / A_F \ln \alpha_M < e^{\left[-1/(2+\ln \alpha_V) - A_V / A_F + 1\right]}$ and $B_V / A_F \ln \alpha_V < e^{\left[-1/(2+\ln \alpha_V) - A_V / A_F + 1\right]}$ 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.
6) 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 and Discussions

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

A. Scenario and Parameters

The simulation scenario and system settings are as follows. There is a FAP with fixed coverage radius of 100m and transmission power of 33dBm. Some active SUEs, T-MUEs and V-MUEs are randomly distributed around the FAP. The number of SUEs is set to $P = 5$, the number of T-MUEs is $M = 15$, and the number of V-MUEs is $N = 10$. As SUEs are usually served by FAP with higher priority and better service quality, we set the distance (transformed from SINR threshold) from SUEs to FAP to follow Gaussian distribution with mean 60m and variance 10. Similarly, the distance from T-MUEs or V-MUEs to FAP follows Gaussian distribution with mean 80m 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 for further analysis.

B. Numerical Results and Discussions

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 propsoed refunding policy for applying to three access modes for femtocell: open, closed, and hybrid modes. We set $\Phi_m = 0$ and $\Phi_n = 0$ for close access mode. Consider that the open access mode has random allocation scheme, we simulate a typical scenario in which SUEs are dominant and occupy 50% of total resoruces, the rest resources are allcated 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 announced price-coefficients from MNO and MVNO. Fig.2 shows the social werlfare for three access modes. From Fig.2, we can see that the social welfare for hybrid access is the highest as the utilitiy of every participant is improved compared with that for closed access and open access. Although selecting a typical value for the simulation of open access mode, FH still prefers to adopt hybrid access in other conditions because of less handover and signaling overhead.

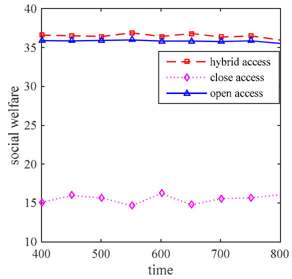


Fig.2. Comparison of social welfare

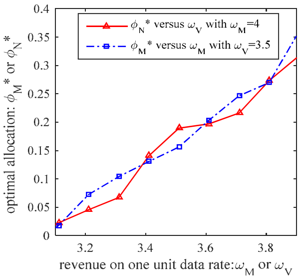
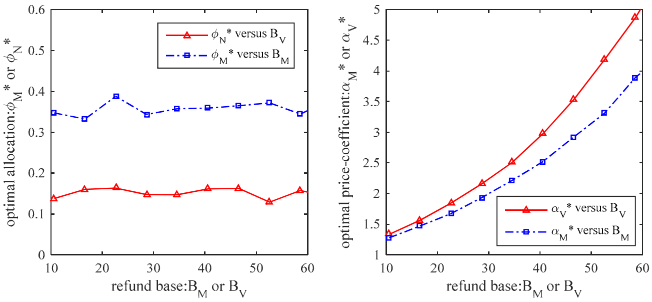


Fig.3. Allocated resource versus ω

In the second experiment, we investigate the change of obtained resources of operators when the equivalent revenue on unit data rate of operators varies. From Fig.3, we can find an interesting phenomenon. Both of two 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 realizes the opponent's strategy and selects the same strategy, the dominant one may lose the advantage, because two curves in Fig.3 overlap approximately. Hence, the reasonable way for network operators to obtain more resources than opponent is providing differentiated services rather than merely increasing service price.



(a) Allocated resource versus refund base (b) Best price-coefficient versus refund base

Fig.4. Allocated resources and price-coefficient versrsus refund base

Finally, we investigate the influence of refund base on best response of FH (allocated resources to MNO and MVNO respectively), and best responses of MNO and MVNO (best price-coefficients). From Fig.4 (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.4 (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 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.

VII. 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 refunding policy to motivate FH to allocate appropriate access resources to MNO and MVNO according to their refunding amount. In the refunding policy, we 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. 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 refunding policy improves the social welfare of network, and every participant achieves the win-win situation by appropriate resource allocation.

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