Utility-Aware Refunding Framework for Hybrid Access Femtocell Network

Yanjiao Chen, *Student Member, IEEE,* Jin Zhang, *Member, IEEE,* and Qian Zhang, *Fellow, IEEE*

***Abstract*—Femtocell technology addresses the problem of poor indoor coverage, benefiting both wireless service provider (WSP) and end users. With the introduction of femtocell, the cross-tier interference between macro link and femto link becomes a major factor which greatly impacts the network performance. Different access control approaches, by generating different interference patterns, also severely affect the overall throughput of the network and need to be carefully investigated. Among all the access control mechanisms, hybrid access is the most promising one, which allows roaming unregistered users (referred to as macro users) to access the nearby femto base station (BS) while reserving certain resource for registered home users (referred to as femto users), improving overall network capacity. However, to successfully leverage hybrid access is challenging because the femto holders (FHs) are selfish, unwilling to share their femto facilities and spectrum resource with macro users without any incentive mechanism. In this paper, we propose a novel utility-aware refunding framework to motivate hybrid access in femtocell. Within the framework, both WSP and FHs are assumed to be selfish, and target at maximizing their own utilities. WSP provides certain refunding to motivate FHs to open their resource for macro users. FHs decide the resource allocation among femto and macro users according to the amount of refunding WSP offers. Under this framework, the optimal strategies of both WSP and FHs are analyzed by formulating the problem as a Stackelberg Game. A unique Nash Equilibrium is achieved and a hybrid access protocol is designed according to the analysis. Extensive simulations have been conducted and the results show that the utilities of both WSP and FHs are significantly improved exploiting the hybrid access mechanism.**

***Index Terms*—Femtocell, hybrid access, refunding framework, Stackelberg game.**

I. Introduction

BY reducing the distance between base stations and end users, femtocell provides increasing data rate and better indoor coverage. The small size of femtocell also improves spectrum reuse, which contributes to higher spectrum efficiency. Femtocell technique offers WSP an exciting and promising market. On the one hand, the enhancement of indoor service quality increases WSP's competition edge by reducing the churn rate (the probability of users leaving the network) of macro users. On the other hand, WSP may transfer some traffic from expensive macrocell to low-cost femtocell. In this way, more users can be served with existing macrocell infrastructure. Femtocell also benefits end users from various aspects. Users can enjoy better-performance, high-speed 3G voice and data services through femtocell. Compared with existing Wi-Fi technology, femtocell operates on licensed spectrum with guaranteed quality of service (QoS) and users do not have to own a dual-mode cellphone. Due to the above mentioned benefits, a number of WSPs around the world have already launched their femto products. On March 24th, AT&T released 3G MicroCell, its first femtocell. In UK, Vodafone provides its users with femto device called Sure Signal. Nevertheless, femtocell still faces several fundamental technical and commercial challenges which haven't been well-addressed.

The co-existence of femtocells and macrocells introduces cross-tier interference between concurrent femto transmissions and macro transmissions, which severely affects the overall network performance. The choice of access control mechanism in femtocell is crucial, because it determines whether a user can access a nearby femto BS or not, thus determining the degree of interference. There are three categories of access control mechanisms that have been proposed: closed access, open access and hybrid access [1]. In case of closed access, only a few femto users who have been authorized by FHs can leverage femto BS for transmission, while macro users are not allowed to access the femto BS. Closed access is easy to implement and control. Besides, privacy and performance of femto users can be warranted. Therefore, some existing femtocells that have been put into market adopt closed access, such as the Sure Signal of Vodafone. However, closed access suffers from dead-zone problem, which arises because macro users who are far away from macro BS but close to a femto BS receive strong femto-macro interference in both uplink and downlink. Open access is just the opposite of closed access, where any wireless users can make use of the femto BS to transmit data. Open access of femtocell is a good solution for dead-zone problem. Usually the femto BSs deployed by WSP as a supplement for macro BS in some rural areas adopt this access control mechanism. However, lack of access control in case of open access may result in traffic congestion, putting great pressure on the backhaul and leading to QoS degradation.

As both closed and open access have drawbacks, hybrid access is proposed to exploit the benefit of the two yet overcome their shortcomings. On the one hand, roaming macro users are allowed to employ femto BSs for transmission with the permission of FHs. On the other hand, hybrid access allows FHs to reserve part of the capacity for their femto users to guarantee their performance. Hybrid access provides improved overall network performance while ensuring the QoS of femto

Manuscript received January 1, 2011; revised March 29 and May 21, 2011; accepted July 11, 2011. The associate editor coordinating the review of this paper and approving it for publication was M. Buehrer.

Y. Chen and Q. Zhang are with the Department of Computer Science and Engineering, Hong Kong University of Science and Technology, Hong Kong (e-mail: chenyj.thu@gmail.com, qianzh@cs.ust.hk).

J. Zhang is with Fok Ying Tung Graduate School, HKUST, Hong Kong (e-mail: jinzh@ust.hk).

Digital Object Identifier 10.1109/TWC.2012.031212.110002

users. Existing works [2] [3] have shown that hybrid access outperforms closed and open access by greatly reducing cross-layer interference and guaranteeing the performance of the femto users. Due to these benefits, we focus on this kind of access control mechanism in this paper. In spite of all the merits of hybrid access, to boost its adoption is challenging, because FHs have no incentive to share their femto facilities and spectrum resource with macro users altruistically. Since the capacity of a femtocell is bounded by bandwidth, transmission time, channel condition etc, if a proprietary femto BS opens to macro users, the utility of femto users will be lessened because part of the femto resource is occupied by macro users. So, FHs naturally favor closed access instead of hybrid access, if they can not get any reward for providing macro users with femto resource. Therefore, to promote the adoption of hybrid access, the incentive mechanism should be investigated from the economic perspective. However, as far as we know, there is no existing work on hybrid access addressing this problem.

In this paper, we propose a utility-aware refunding framework that promotes the adoption of hybrid access. Under this framework, both WSP and FHs are assumed to be rational and selfish entities, who merely care about their own interest. To enhance the overall network performance, WSP is willing to provide certain amount of refunding to FHs which adopt hybrid access and open their resource for macro users' access . The FHs, with the expectation to receive refunding, are also willing to open their redundant femto facilities and spectrum resource to macro users. Therefore, both WSP and FHs have the incentive to exploit hybrid access. However, there are still several questions need to be answered under this framework. First, how much refunding should be provided by the WSP? The more refunding provided, FHs are more willing to help with the macro users' transmission. But WSP will lose more money. Second, how should FHs allocate the resource among femto users and macro users? The more a FH reserves for its femto users, the better performance the femto users can achieve, however, the money it receives from the WSP will reduce due to decremented contribution to macro users. Moreover, what's the impact of refunding amount selected by the WSP on the resource allocation decision made by the FHs? We will answer all the questions by leveraging game theory analysis. We will formulate the refunding framework as a Stackelberg game and analyze the game by reverse induction. The optimal strategies for both WSP and FHs are achieved and a sophisticated protocol based on game theory analysis is designed to help WSP and FHs exchange certain information in order to make right decisions. The main contributions of the paper are as follows:

- We propose a utility-aware refunding framework to motivate both WSP and FHs to be engaged in the hybrid access in femtocell network. As far as we know, it is the first framework that addresses the incentive problem of hybrid access. Within the refunding framework, WSP provides certain refunding to motivate FHs to open their resource for macro users. FHs allocate their resources among femto and macro users according to the amount of refunding WSP provides. Both WSP and FHs are selfish, targeting at maximizing their own utility by selecting the optimal strategies.
- We formulate the framework as a Stackelberg game, in which WSP acts as leader and FHs act as followers. We analyze the cooperation and competition relationship between FHs and WSP through different stages of the game. Backward induction is used to obtain the Nash Equilibrium and we prove that the Nash Equilibrium is unique.
- We design a protocol to implement the utility-aware refunding framework. The protocol is based on the game theory analysis, which enables WSP to determine the optimal refunding amount and also allows FHs to decide which access control mechanism to adopt and how to assign transmission time to femto and macro users in case of hybrid access. By carrying out the protocol, both WSP and FHs can achieve maximum utility.
- We conduct numerical simulations to evaluate the refunding framework. The results verify that the utilities of both WSP and FHs are notably enhanced, which provides strong motivation for WSP to implement the refunding policy and FHs to adopt hybrid access.

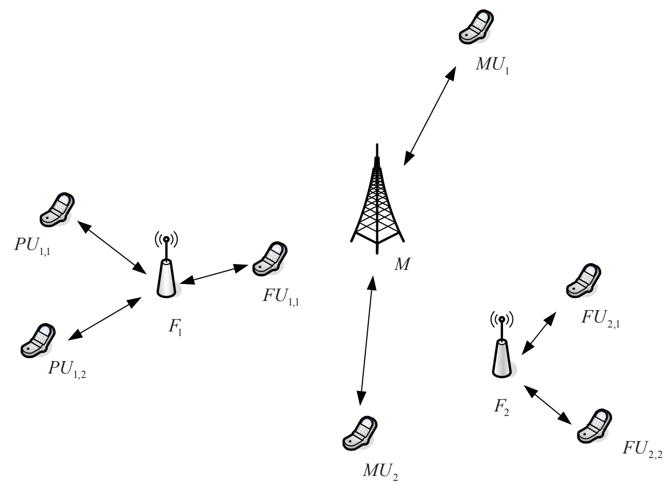


Fig. 1. System model for femtocell hybrid access.

The paper is organized as follows. First, we describe the system model in section II. The refunding framework is proposed in section III. In section IV, we use game theory to analyze the framework and give the Nash Equilibrium. We propose a protocol based on the game theory analysis of the refunding framework in section V. Extensive simulations are presented in section VI. We review the related work in section VII and finally summarize our work in section VIII.

II. System Model

In this section, we describe the system model of our problem, including network architecture, channel model and basic parameters.

Fig.1 depicts a two-tier macro-femto network, consisting of a macro BS, which is owned by WSP, and a number of femto BSs, which are possessed by FHs. There are K femto-BSs in total, denoted by $\{F_i\}_{i=1}^{K}$, and correspondingly their holders $\{FH_i\}_{i=1}^{K}$. A femto BS can serve multiple users who have been authorized by FH to get access to femtocell. Let

$\{FU_{i,j}\}_{j=1}^{K_{fi}}$ represent the femto users of femto BS F_i, in which K_{fi} is the number of femto users supported by F_i. To guarantee QoS, a femto BS supports a maximum number of $K_{fi,max}$ femto users so that $K_{fi} \leq K_{fi,max}$. Macro users who happen to be in vicinity of a femto BS hope to transfer their traffic to that femto BS in order to have higher signal-to-interference ratio (SINR). Assume that there are K_{mi} macro users near F_i who may get permitted to access F_i and $K_{mi} \leq K_{mi,max}$ to avoid traffic congestion. Let $\{MU_{i,j}\}_{j=1}^{K_{mi}}$ denote these macro users.

Time division multiple access (TDMA) strategy is utilized for data transmission. Data transmission is divided into frames, which are further divided into time slots. FH_i is in charge of distributing time slots to users who are transmitting through F_i. Each frame consists of two parts, namely transmission period reserved for femto users and transmission period open to passer-by macro users. Assume that FH_i plans to open a fraction of α_i in each frame to macro users and transmission time for macro user $MU_{i,j}$ is $\gamma_{i,j}$, satisfying $\Sigma_{j=1}^{K_{mi}}\gamma_{i,j} = \alpha_i$. The rest $(1-\alpha_i)$ fraction is dedicated to femto users' transmission. Femto user $FU_{i,j}$ gets $\beta_{i,j}$ time and $\Sigma_{j=1}^{K_{fi}}\beta_{i,j} = 1-\alpha_i$ is satisfied. Closed access can be viewed as a special case of hybrid access with $\alpha_i = 0$ so that no time is distributed to macro users by FH_i. In this paper, we concentrate in the downlink data transmission and uplink data transmission can be analyzed in similar way.

We presume that WSP acquires split spectrum scheme, where macro BS and femto BSs operate on different frequencies and do not interfere. Users of the same femtocell adopts TDMA for data transmission, causing no interference for each other. Different femto BSs may reuse the same spectrum and we assume that the femto-femto interference received by F_i is only determined by the density of femto BSs, denoted by $I_i(K)$. We model the wireless channel between femto BS and femto users as log-normal distributed shadowing channel [4]. The received Signal to Interference Ratio (SINR) is expressed as

$$\eta_i = \left(\frac{P_i}{N_0 + I_i(K)}\right) S d^{-n} |h|^2 \tag{1}$$

in which P_i is the transmission power of F_i, N_0 is the Gaussian noise, S is the log-normal shadowing component with $10logS$ having mean of $0dB$ and standard deviation $\sigma_S(dB)$, n is the path fading exponent, and $|h|$ is the Rayleigh-distributed fading magnitude, satisfying $E(|h|^2) = 1$. Every femto BS adopts power control to satisfy the targeted SINR of its femto users. We assume that femto users of F_i require an SINR of $\eta_{f,i}$. Once macro users are permitted to access F_i, they are provided with a fixed SINR of $\eta_{m,i}$, which is generally higher than the SINR provided by macro BS. Therefore, we can obtain the aggregated transmission rate of femto and macro users who are served by femto BSs respectively by multiplying the transmission time and channel capacity.

$$R_{f,i} = (1-\alpha_i)C_{f,i}, \tag{2}$$

$$R_{m,i} = \alpha_i C_{m,i}, \tag{3}$$

where $C_{f,i} = log(1+\eta_{f,i}), C_{m,i} = log(1+\eta_{m,i})$, are the channel capacity of femto and macro users separately.

III. Refunding Framework

In this section, we propose a utility-aware refunding framework within which WSP hopes to motivate FHs to adopt hybrid access through refunding. By utilizing femto resource, WSP is able to expand its network capacity and increase user satisfaction. FHs trade spare femto resource for refunds, improving their utilities on the whole. In this way, a win-win situation establishes between WSP and FHs.

Both WSP and FHs are selfish and rational. WSP has strong wish to get support from femto BS to aid in macro users' data transmission, especially when there is great traffic demand from macro users and the macro backhaul is under great pressure. Nevertheless, the utility of FHs will diminish if macro users take up the transmission time available for femto users. Thus, it is impossible for FHs to be so altruistic as to allow macro users to access femto BSs without any remuneration. A refunding mechanism can be designed to solve these problems, which enables WSP to compensate FHs who perform hybrid access and spare transmission time to macro users.

We assume that WSP puts forward a total sum of m refunding amount, which is further distributed among FHs who open their BS to macro users. As different FHs allow macro users to transmit for different fraction of time α_i within a frame, it is reasonable to split the refunds in the way that the FH who contributes the most time achieves highest refunds and who contributes the least achieves lowest. A simple way is to distribute the refunds proportional to the open time of individual femto BSs. Therefore, the refunds obtained by each FH can be derived as the total amount of refunds multiplies the ratio of individual open time to the sum of open time of all femto BSs.

$$m_i = m\frac{\alpha_i}{\sum\limits_{j=1}^{K}\alpha_j}. \tag{4}$$

Larger amount of refunds will stimulate more hybrid access adoption among FHs and yield more benefit for WSP due to capacity expansion and satisfaction improvement of macro users. However, only when such benefit exceeds the refunds itself will it be profitable for WSP to carry out such refunding mechanisim. For this reason, further analysis should be conducted to determine the quantity of m in order to come up with the optimal refunding mechanism that generates maximum utility for WSP.

Once the refunding amount m is broadcast by WSP, FHs react by making decision about whether closed access or hybrid access is more favorable and how much time should be contributed to macro users for data transmission if hybrid access is chosen. Based on the refunding policy of WSP, each FH's utility does not only depend on their own behavior but also affected by the decision of other FHs. Given the same α_i, if $FH_j, j \neq i$ chooses a longer open time, FH_i gets less refunds, vice versa. Every FH tries to maximize its own utility under this condition.

A. The Utility Function of WSP

The utility function of WSP is defined as the benefit from reduced user churn rate minus the refunds given to FHs.

$$U_{wsp} = w_m(1-c) - m. \tag{5}$$

where c is the churn rate of macro users and w_m is the equivalent revenue when c decreases by one percent. Poor QoS causes user dissatisfaction, ending up in user switching WSP for better coverage. If femto BSs are leveraged to increase the capacity of macro BS, WSP is able to provide better QoS, thereby more macro users are willing to stay with the WSP. The Sigmoid function has been widely used for estimating the satisfaction of users with regard to service quality [5]–[8]. The churn rate can be expressed as

$$c = \frac{1}{1+e^{-a(b-\lambda)}}, \tag{6}$$

where a represents the user's sensitivity towards QoS increment and b is the reserved traffic demands of macro users. λ is the achievable data rate for macro users. It is obvious that $c \in (0,1)$. If macro users leverage femto BS for transmission, the achievable data rate λ_f can be derived as

$$\lambda_f = \sum_{i=1}^{K} R_{m,i} + \lambda_0, \tag{7}$$

in which λ_0 is the capacity of macro BS. If all femto BSs are set to closed access, macro users can only transmit through macro BS with a limited capacity λ_0. If some femto BSs share part of resource with macro users, the achievable data rate increases, resulting in reduced churn rate of macro users. Since most macro users require voice service, when the capacity provided by femto BS is already high, further increase in the capacity will contribute little to the decrease of churn rate. The Sigmoid function can perfectly capture this trend. It can be easily derived that the percentage of macro users who stay with the WSP is $\frac{1}{1+e^{-a(\lambda-b)}}$. The more sensitive users are towards upgraded QoS, the more steeper the churn rate falls when the transmission rate goes up, thus the refunding mechanism will be more effective.

B. The Utility Function of FH

The utility function of FH_i consists of two aspects: the transmission rate that femto users have attained and the refunds gained from WSP by opening part of transmission time to macro users. As femto users mostly demand data service from femto BSs, the more capacity they can achieve, the more satisfied they will be. So we assume that the utility of FHs is linearly increasing with the transmission rate of femto users.

$$U_{f,i} = w_f R_{f,i} + m_i, \tag{8}$$

where w_f denotes equivalent revenue the FH receives on one unit transmission rate for femto users.

IV. Game Theory Analysis

In this section, we formulate the refunding framework as a Stackelberg game, in which the WSP acts as the leader and the FHs act as the followers. We prove that a unique Nash Equilibrium exists for the game, which defines the optimal strategy for the WSP and the FHs.

Since both WSP and FHs are selfish and rational entities who target at utility maximization, it is apparent that game theory is the most appropriate tool to analyze the problem. The game should involve two phases, in which WSP initiates the promotion of hybrid access of femtocell by announcing the refunding mechanism and FHs respond to it. Thus, it is reasonable to formulate the process as a Stackelberg game.

The Stackelberg game proceeds through two stages. In the first stage, the WSP attempts to maximize its utility by selecting best refunding amount m, being aware of the influence of its own decision on the behavior of FHs. The refunding amount m is then broadcast to all FHs. In the second stage, based on the information of refunding amount m, every FHs determines concurrently what access control mechanism is more beneficial and how to distribute transmission time between macro users and femto users to achieve maximum utility for itself. As FHs are selfish and rational players who independently make decisions and are concerned about self-interest only, we use non-cooperative game to analyze their behavior.

We use backward induction method, a common tool to study Stackelberg game. To begin with, we show that in the non-cooperative game among FHs, there exists Nash Equilibrium which is further proved to be unique. Then, we give the optimal refunding strategy for WSP based on the analysis of non-cooperative game among FHs.

A. Non-Cooperative Access Control Mechanism Selection Game of FHs

We first analyze the decision making process of FHs. The utility of a specific FH does not only depend on its own choice but also subjects to the behavior of other FHs. Given other FHs' decision, an FH makes effort to seek for the best response that maximizes its utility.

The non-cooperative access control mechanism selection game (NAMG) among FHs can be expressed in normal form as $G = (\{FH_i\}, \{A_i\}, \{u_i(\cdot)\})$. $\{A_i\}$ is the pure strategy space of FH_i, which corresponds to $0 \le \alpha_i \le 1$. When FH_i chooses the closed access, α_i is simply set to be 0. Therefore, the joint set of the strategy space of K FHs is $A = A_1 \times A_1 \times ... \times A_K$. We denote the pure strategy space of FHs that are competitors of FH_i as $A_{-i} = A \backslash A_i$. $\{u_i(\cdot)\}$ is the set of utility function that FHs want to maximize.

Given the strategy α_{-i} of all its components, FH_i always chooses the strategy α_i that can yield maximum utility, namely $\alpha_i = \arg \max_{0 \le \alpha_i \le 1} u_i(\alpha_i, \alpha_{-i})$. This strategy is often called the best response of FH_i. In a non-cooperative game, FH has no incentive to deviate from their best response because any variation will decrease the utility.

Proposition 1: Given α_{-i}, the best response of FH_i is

$$\alpha_i^* = \begin{cases} 0 & \text{if } \sum_{j\neq i}^{K} \alpha_j > \frac{m}{w_f C_{f,i}} \quad \text{(9a)} \\ \sqrt{\frac{m \sum_{j\neq i}^{K} \alpha_j}{w_f C_{f,i}}} - \sum_{j\neq i}^{K} \alpha_j & \text{otherwise} \quad \text{(9b)} \end{cases}$$

We can see from (9a) that under certain circumstances, the best response of FH_i is $\alpha_i = 0$, indicating that FH_i can not get higher utility by exchange femto resource for refunds so FH_i chooses closed access. Therefore, macro users around F_i can only leverage macro BS for transmission. When $\alpha_i > 0$, it is more beneficial for FH_i to adopt hybrid access. In this case, the best response α_i is not only related to the condition of F_i but also dependent on the decision of other FHs, i.e., the choice of $\alpha_j, j \neq i$.

Proof: The first and second derivatives of u_i with respect to α_i are

$$\frac{\partial u_i}{\partial \alpha_i} = -w_f C_{f,i} + \frac{\sum_{j\neq i}^{K} \alpha_j}{(\sum_{j=1}^{K} \alpha_j)^2} m \tag{10}$$

$$\frac{\partial^2 u_i}{\partial \alpha_i^2} = -\frac{2\sum_{j\neq i}^{K} \alpha_j}{(\sum_{j=1}^{K} \alpha_j)^3} m \tag{11}$$

The second derivative of u_i with respect to α_i is less than zero so that u_i is concave in α_i. If $\sum_{j\neq i}^{K} \alpha_j < \frac{m}{w_f C_{f,i}}$, maximum u_i can be achieved when the first derivative of u_i with respect to α_i equals zero. However, if $\sum_{j\neq i}^{K} \alpha_j > \frac{m}{w_f C_{f,i}}$, u_i monotonically decreases as the open time α_i increases. In this case, the best strategy for FH_i is to adopt closed access and exclusively serves the femto users. ■

If every FH employs the best response with regard to other FHs' decisions, no FHs have motivation to alter their strategy unilaterally. In this case, the NAMG reaches the Nash Equilibrium.

Proposition 2: There exists a unique Nash Equilibrium for NAMG and the optimal open time for FH_i is given by (12a) and (12b).

Proof: In order to achieve the Nash Equilibrium, every FH must adopt their best responses. Otherwise, there will be FH who has intention to adjust its strategy for higher utility. Therefore,

$$\alpha_i^* = \sqrt{\frac{m \sum_{j\neq i}^{K} \alpha_j^*}{w_f C_{f,i}}} - \sum_{j\neq i}^{K} \alpha_j^*. \tag{13}$$

By transformation (13), we can get

$$\alpha_i^* = \frac{A^*(m - A^* w_f C_{f,i})}{m}, \tag{14}$$

where $A^* = \sum_{j=1}^{K} \alpha_j^*$.

Jointly consider the best response of every FH, that is, sum up all the K equations regarding each FH, we obtain $A^* = \frac{(K-1)m}{w_f \sum_{j=1}^{K} C_{f,i}}$. Then we can easily calculate α_i^* for each FH.

It has been proved in [9] that the Nash Equilibrium is unique if the best response function is positive, monotonic and scalable. It can be easily proved that α_i^* satisfies the above requirements. Therefore, there exists a unique Nash Equilibrium for NAMG. ■

B. Utility Maximization for WSP

Once the WSP declares the refunding amount m, the FHs react by choosing access control mechanism and distributing transmission time among femto and macro users. As the leader of the game, WSP is aware of the impact of refunding amount m on FHs' choice. Taking into consideration the possible response of FHs, WSP is able to derive optimal refunding amount m to procure maximum utility.

When the NAMG of FHs reaches Nash Equilibrium, the utility of WSP can be further derived as

$$U_{wsp} = w_m \frac{1}{1 + e^{-a(\lambda_f^* - b)}} - m, \tag{15}$$

where $\lambda_f^* = \sum_{i=1}^{K} \alpha_i^* C_{m,i} + \lambda_0$.

Proposition 3: When the following conditions

$$\begin{aligned} \lambda_0 &> \frac{\ln 2}{a} + b \\ B &> \frac{5}{4} \\ B &> \frac{1}{2}(1 + e^{-ab}) \end{aligned} \tag{16}$$

are satisfied, WSP maximizes its utility if and only if the refunding amount is set as

$$m^* = \frac{1}{\sum_{i=1}^{K} C_{m,i}\rho_i} [b + \frac{1}{a} \ln(B + \sqrt{B^2 - 1})], \tag{17}$$

in which

$$\rho_i = \begin{cases} \frac{(K-1)[\sum_{j=1}^{K} C_{f,j} - (K-1)C_{f,i}]}{w_f (\sum_{j=1}^{K} C_{f,j})^2} & \text{if } \sum_{j=1}^{K} C_{f,j} < (K-1)C_{f,i} \\ 0 & \text{otherwise} \end{cases}$$

$$B = \frac{w_m a}{2 w_f} \sum_{i=1}^{K} C_{m,i}\rho_i - 1 \tag{18}$$

Proof: α_i^* can be expressed as $\alpha_i^* = \rho_i m$.

$$\alpha_i^* = \begin{cases} 0 & \text{if } C_{f,i} > \frac{\sum_{j=1}^{K} C_{f,j}}{K-1} \quad (12a) \\ \frac{(K-1)m}{w_f(\sum_{j=1}^{K} C_{f,j})^2}[\sum_{j=1}^{K} C_{f,j} - (K-1)C_{f,i}] & \text{otherwise} \quad (12b) \end{cases}$$

The first and second derivatives of U_{wsp} with respect to m are given as follows:

$$\frac{\partial U_{wsp}}{\partial m} = -1 + w_m \frac{ae^{-a(\lambda_f^* - b)}}{[1+e^{-a(\lambda_f^*-b)}]^2} \sum_{i=1}^{K} C_{m,i}\rho_i \quad (19)$$

$$\frac{\partial^2 U_{wsp}}{\partial m^2} = \frac{-(a \sum_{i=1}^{K} C_{m,i}\rho_i)^2 (1-2e^{-a(\lambda_f^*-b)}) w_m e^{-a(\lambda_f^*-b)}}{[1+e^{-a(\lambda_f^*-b)}]^2} \quad (20)$$

When $\lambda_0 > \frac{\ln 2}{a} + b$, the second derivative of U_{wsp} with respect to m is always negative so U_{wsp} is concave on m. We can get optimal m by assigning the first derivative of U_{wsp} to be 0. When $B > \frac{1}{2}(1 + e^{-ab})$, it can be easily proved that $m^* > 0$. WSP gets maximum utility as $U_{wsp}^* = U_{wsp}(m^*)$. ■

If it is actually that $\lambda_0 < \frac{\ln 2}{a} + b$, We can derive from (19) that as m increases, U_{wsp} falls down at the beginning, then at a certain point, U_{wsp} starts to go up and at last, U_{wsp} becomes a decreasing function. In this case, The maximum U_{wsp} can be achieved either in the local maximum point in (17) or the boundary when m equals zero. When $m = 0$, namely there is no refunding policy, no FHs are willing to contribute part of the transmission time to macro users free of charge. WSP can only leverage macro BS for data transmission, which yields utility $U_0 = \frac{w_m}{1+e^{-a(\lambda_0 - b)}}$. If $U_0 > U_{wsp}(m^*)$, the refunding framework is not feasible because WSP is unable to raise its utility and has no incentive to put forward the refunding mechanism.

V. Hybrid Access Protocol

In this section, we propose a protocol for WSP to implement the refunding mechanism to promote hybrid access in femtocell networks. The protocol enables the WSP to dynamically adjust the refunding amount m and the FHs to respond to what they have observed through access control mechanism selection and open time determination. The protocol is designed based on the Stackelberg game analysis. By applying the protocol, WSP and FHs are able to get maximum utility. Since the proposed refunding framework is based on static game, WSP and FHs reach Nash Equilibrium in only two steps. Once the external wireless environment changes, WSP and FHs can also quickly adapt their strategy to re-reach Nash Equilibrium.

According to the game theoretical analysis, both the optimal refunding for WSP and the choice of access control mechanism for FHs are determined by two kinds of factors:

- Independent factors. For instance, w_f, w_m, K, b, a, which are either common knowledge or can be estimated through data mining on historical collected data or investigation. Generally speaking, these parameters are relatively static and tend to stay the same over a long period.
- Interdependent factors. For WSP, to compute the optimal refunding m, the aggregated achievable data rate of macro and femto users transmitting through every femto BS, i.e. $C_{m,i}, C_{f,i}$, must be procured. According to (2) and (3), the transmission rate depends on the transmission power, the channel condition and the position of the user. As the channel condition changes dynamically, these two parameters may fluctuate dramatically, strongly affecting the decision made by WSP. In order to figure out the accurate optimal refunding amount m^*, WSP should periodically collect information about the entire network of both macrocell and femtocell, possibly with the help of FHs. For FHs, their strategies is determined by $\sum_{j=1}^{K} C_{f,j}$ and the total refunding amount m. Although FHs choose access control mechanism in a distributed way and private information about individual FHs should not be disclosed, statistics in terms of the entire network, in particular $\sum_{j=1}^{K} C_{f,j}$, can be proffered to FHs to help them make decisions.

The protocol consists of two parts: Optimal Refunding for WSP and Access Control Mechanism Selection for FHs. It enables WSP and FHs to interact with each other to realize the hybrid access.

Optimal Refunding for WSP

- Each femto BS periodically collects information about the channel condition of femto users it support and macro users within its coverage; Then, they piggyback the gathered information of channel condition $\eta_{f,ij}, \eta_{m,ij}$ on the data frame to WSP through the broadband line;
- With the information from FHs, WSP is able to compute $C_{m,i}, C_{f,i}$. WSP first checks whether conditions (16) are satisfied. If not, it is unprofitable for WSP to run refunding policy, thus $m = 0$; If conditions (16) are satisfied, WSP computes the best refunding amount m according to (17), which yields highest utility for itself;
- WSP broadcasts the refunding amount m to FHs.

Access Control Mechanism Selection for FHs

- WSP piggybacks the aggregated data rate $\sum_{j=1}^{K} C_{f,j}$ on the data frame to FHs through the broadband line;
- FHs choose the access control mechanism. If $\sum_{j=1}^{K} C_{f,j} - (K-1)C_{f,i} < 0$, FH_i selects closed access and simply rejects access request from any macro users. Otherwise, FH_i selects hybrid access;

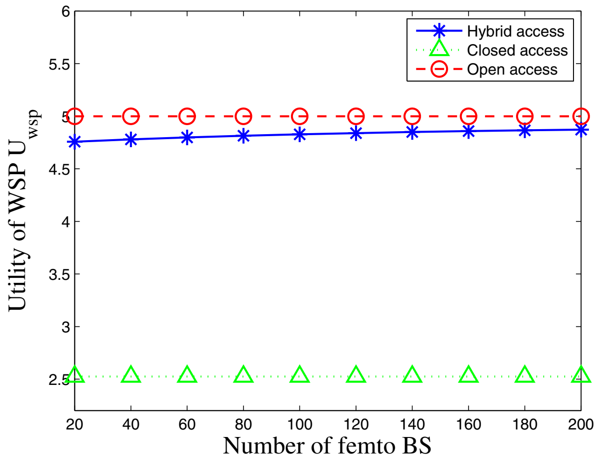


Fig. 2. Utility of WSP U_{wsp} versus the number of femto BS.

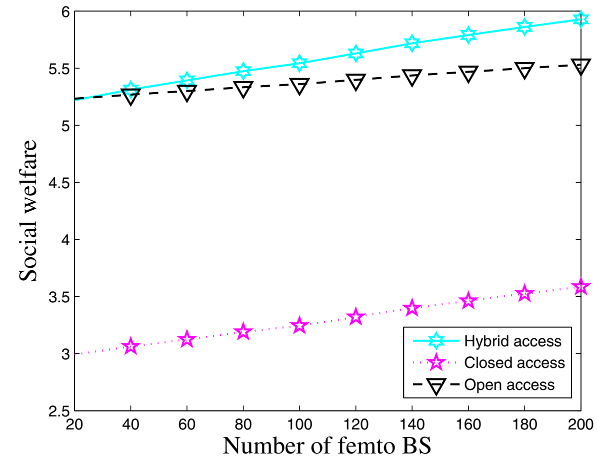


Fig. 3. Social welfare versus the number of femto BS.

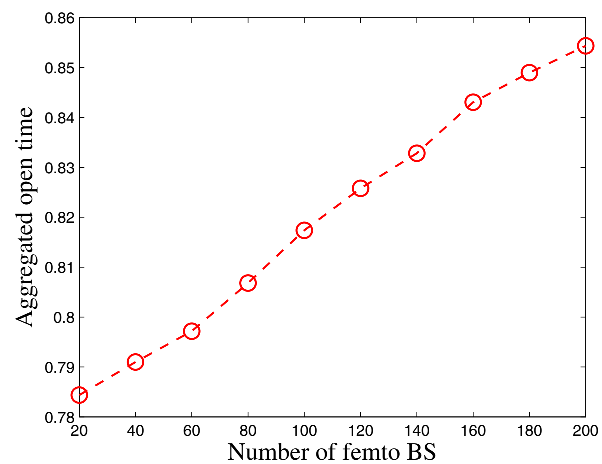


Fig. 4. Aggregated open time versus the number of femto BS.

- FHs who have chosen hybrid access decide the fraction of transmission time α_i that will be open for macro users according to (12a) and (12b);
- Further scheduling among macro and femto users supported by each femto BS is performed by its holders.

VI. Simulation Results

In this section, we conduct numerous simulations in order to evaluate the utility gain of hybrid access that is motivated by the refunding framework.

The simulation settings are as follows: There are a total number of 100 femto BSs owned by different FHs. The targeted data rate (derived from targeted SINR) of femto users of each femto BS follows Gaussian distribution with mean 10 and variance 1. The data rate that FHs offered macro users once these users are permitted to access femto BSs follows Gaussian distribution with mean 5 and variance 1. The equivalent revenue gained from unit data rate is $w_f = 0.1$ for femto users and $w_m = 5$ for macro users. Without the assistance from femto BS, macrocell can only provide $\lambda_0 = 0.21$ traffic capacity. Unless explicitly stated otherwise, the basic traffic demand of macro users is set to be $b = 0.2$ and the sensitivity of macro users towards QoS enhancement $a = 2$. Intuitively, if there's no refunding policy, open access will not be adopted by FHs. However, in order to compare the social welfare in case of three access mechanisms, we assume that FHs equally distribute access time between femto and macro users in open access. We also define the social welfare as the summation of WSP's utility and all the FHs' utility. Above parameters stay the same for the following simulations unless otherwise stated.

The number of femto BS, also the number of FHs, is a highly influential factor as it determines the density of femtocell. Fig.2 shows the utility of WSP when hybrid access, open access or closed access is adopted by FHs. Without the stimulation of refunding policy, no FHs are willing to let macro users access the femto BS. But the utility of WSP is the highest if open access is somehow forced to be implemented. In case of closed access, the burden of macro traffic is entirely borne by macrocell that has a fixed capacity λ_0, which is not affected by the number of femto BS. Therefore, even if the number of femto BS rises, the utility of WSP stays the same. By comparison, the utility of WSP is much higher when hybrid access is promoted by the refunding policy. Although WSP pays FHs for undertaking traffic of macro users, it gets reciprocated as the macro users' churn rate decreases, leading to increasing revenue. The utility of WSP goes up along with the number of femto BS because there are more FHs who will adopt hybrid access and more macro traffic is transferred to femtocell. From Fig.3 we can see that social welfare is the highest in case of hybrid access because both the utilities of WSP and FHs are improved compared to closed access. Although WSP can receive higher utility in open access, FHs have to sacrifice considerably without compensation so they simply will not adopt this access mechanism. Fig.4 shows that the aggregated open time keeps rising along with the number of femto BS. Therefore, it is greatly beneficial for WSP to carry out the refunding policy. Fig.5 shows that the refunding amount m abates when the number of the femto BS increases. As the refunds slightly decreases, the open time of each femto BS also declines. However, the growth of number of femto BS is so enormous that the aggregated open time still comes up in spite of the low refunds. This indicates that WSP also has the motivation to promote the deployment of more femto BSs.

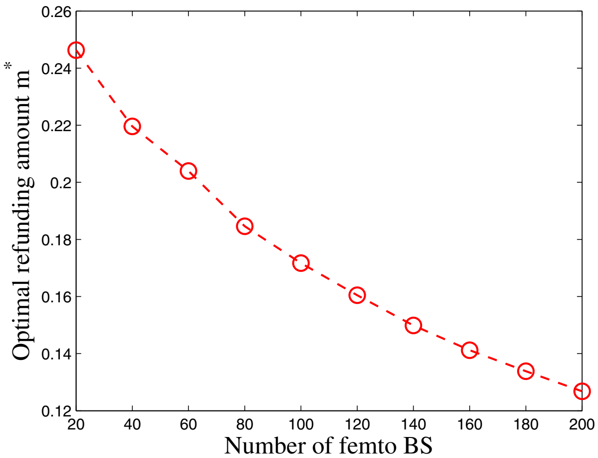


Fig. 5. Optimal refunding amount m^* versus the number of femto BS.

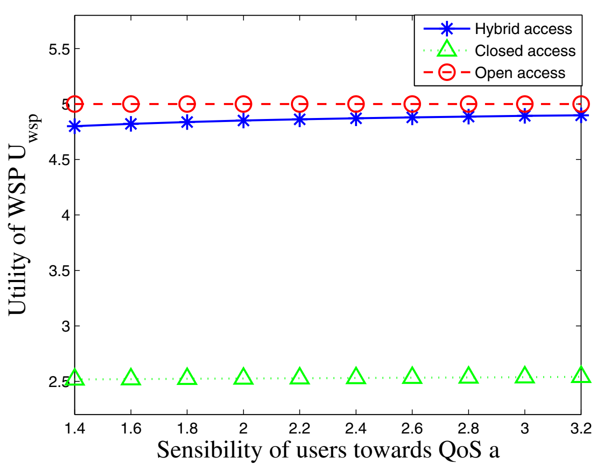


Fig. 6. Utility of WSP U_{wsp} versus the sensibility of users towards QoS a.

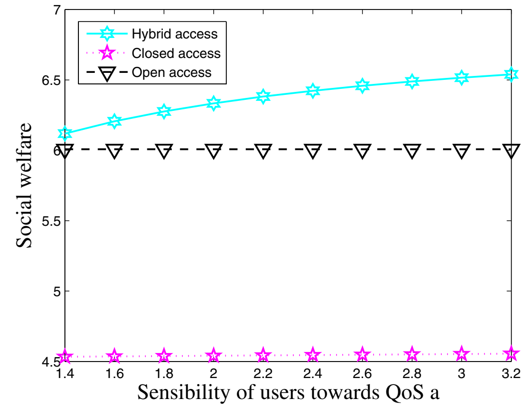


Fig. 7. Social welfare versus the sensibility of users towards QoS a.

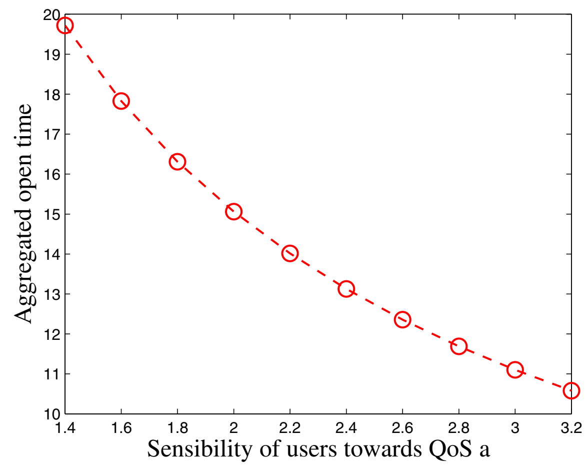


Fig. 8. Aggregated open time versus the sensibility of users towards QoS a.

The sensibility of users towards QoS a is also a key factor that affects the choice of FHs and WSP. The more sensitive users are towards QoS improvement, the more steeply the churn rate falls when QoS is upgraded. Fig.6 shows that the utility of WSP is enhanced because more macro users choose to stay with the WSP as they can experience better QoS due to the expansion of macrocell capacity. Social welfare has similar trend due to the same reason as shown in Fig.7. Since a slight QoS improvement leads to dramatic decrease in churn rate, WSP is able to save money by lessening the refunds, which results in a bit open time abatement as shown in Fig.8 but can still reduce churn rate substantially. As is shown in Fig.9, the refunding amount m decreases when a increases. The rise in user loyalty and the drop in refunds payment contribute to the utility gain for WSP.

A major reason for WSP to advocate hybrid access in femtocell is the limited capacity of macrocell with regard to the ever increasing traffic demand of macro users, which is represented by parameter b in our analysis. Because of the limitation on number of figures, we only show the utility of WSP versus b. Fig.10 indicates that if the traffic demand goes up, the utility of WSP deteriorates whatever femto access control mechanism is. Fortunately, in case of hybrid access, femto BSs help to slow down the falling trend by undertaking some of the macro traffic. However, in case of closed access, the increasing traffic demand brings about significant utility reduction. The larger the traffic demands, the more eager WSP is to encourage femto BS to share some of the macro traffic burden. Hence, both the refunding amount m and the aggregated open time increase.

In order to analyze the utility gain and open time α_i of a specific femto holder FH_i, we adjust the simulation as follows. A total number of $K = 6$ femto BSs are in the network. The achievable transmission rate of $FH_j, j \neq i$ is held as constant, i.e., $R_{f,j} = 10, j \neq i$. Femto users' targeted data rate $R_{f,i}$ is varied to analyze the trend of u_i and α_i. Other simulation settings remain unchanged. Let U_{fi} and U_{fi0} denote the utility of FH_i with and without hybrid access respectively. Fig.11 shows that the utility gain of FH_i decreases as the targeted data rate of femto users $R_{f,i}$ increases. If femto users demand a lower targeted data rate, FH tends to share more of their resources. As long as the requirement of femto users is satisfied, FHs are willing to trade transmission time for refunds from WSP. It is intuitive that FHs with high-demand femto users are more likely to choose closed access in order to exclusively serve their femto users. Therefore, the utility gain is more appreciable when $R_{f,i}$ is low. Also, the utility gain is more considerable when

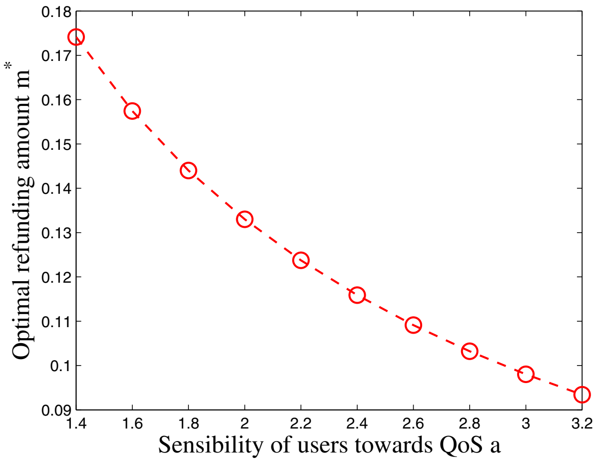


Fig. 9. Optimal refunding amount m^* versus the sensibility of users towards QoS a.

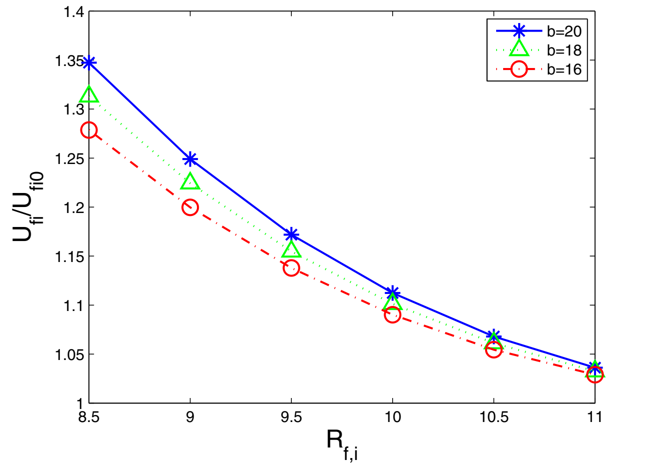


Fig. 11. Utility of FH_i versus $R_{f,i}$ under different traffic demand of macro users.

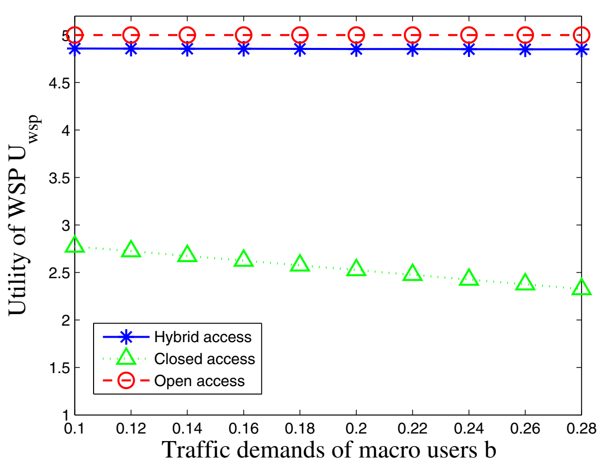


Fig. 10. Utility of WSP U_{wsp} versus the traffic demands of macro users b.

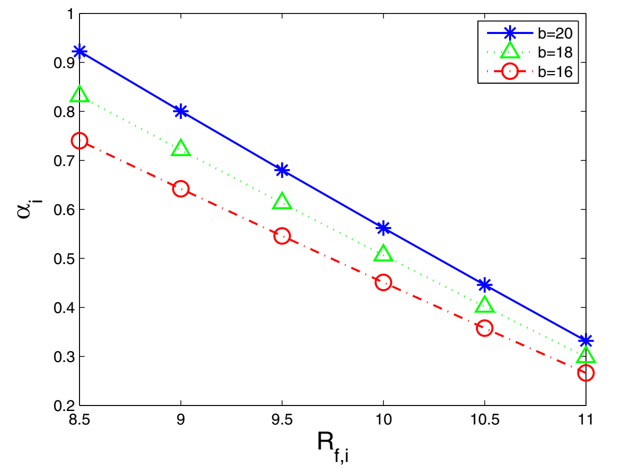


Fig. 12. Open time of FH_i α_i versus $R_{f,i}$ under different traffic demand of macro users.

the traffic demand of macro users is high since WSP raises the refunding amount m in order to encourage FHs to take over more macro traffic. As shown in Fig.12, the open time α_i has the same trend as u_i for the same reasons. Therefore, when the targeted data rate of femto users is low and the traffic demand of macro users is high, FHs have strong incentive to implement hybrid access in their femto BS and support the refunding policy.

VII. Related Work

Under femtocell networks, there are three access control mechanisms that have been proposed: closed access, open access and hybrid access. An overview of access control mechanism is presented in [1]. Basic scenario for hybrid access is introduced in [1] but no framework for implementing hybrid access is given. The advantages and disadvantages of open and closed access for WiMAX femtocells in terms of interference and network performance are studied in [10] by simulations but the case of hybrid access is missing. The choice of either open or closed access control mechanism in case of different multiple access schemes (orthogonal or not) is studied by Ping Xia *et al.* [11]. Still, hybrid access is not taken into consideration. The benefits of hybrid access have been investigated by several works. David Choi *et al.* [2] demonstrated that if the level of hybrid access in femtocell network is adaptively controlled as a function of factors including the instantaneous load on the femtocell, network performance is better than those of open and closed access. In [3], by exploiting the frequency management techniques offered by OFDMA, hybrid access is able to reduce cross-layer interference while guaranteeing a minimum performance to the femto users. However, all these papers focus on the technical aspects, mainly using information theory to analyze the performance gain. Unlike the existing works, the framework proposed by us involves multiple decision-making entities (FHs and WSP), considering not only network performance but also individual economic benefit.

Game theory has been widely applied to ad hoc networks. Various works [8], [12], [13] have used Stackelberg game as an analytical tool to study the cooperation and competition between primary users and secondary users in cognitive radio networks. There are also some works that employed game theory for power control [14] and spectrum allocation [15] in femtocell network. In [14], a non-cooperative model is proposed for power control of closed access femtocell networks in a distributed way. Chun-Wei Chen *et al*. proposed a DANCE mechanism for efficient spectrum allocation in femtocell [15]. However, as far as we are concerned, there is no work that addresses the issue of hybrid access in femtocell from a game theory perspective. In this paper, We propose a novel utility-aware refunding framework for hybrid access in femtocell and formulate it as a Stackelberg game. While the aforementioned works developed a one-stage game where only the FHs are the players, our work takes into account WSP and FHs, who are both decision makers, and analyzes the interaction between WSP and FHs through different stages of the game.

VIII. Conclusions

In this paper, we propose a utility-aware refunding framework, which enables WSP to compensate FHs for taking over macro traffic and encourages FHs to share femto resource with macro users. In this way, hybrid access can be achieved which creates a win-win situation for both WSP and FHs. Game theory, in particular Stackelberg game model, is used to analyze the optimal strategies for WSP and FHs to gain maximum utility. A feasible protocol based on the theoretical analysis is proposed to put the refunding framework into practice. Simulation results have illustrated that both WSP and FHs can achieve considerable utility gain under the refunding framework. The more femto BSs there are, the more intensely FHs compete for the refunding and the more macro traffic is transferred to femtocell. The refunding amount decreases with femto BS density and macro users' sensitivity towards QoS enhancement but increases with the macro users' demand. Also, a specific FH is more willing to open its resources when its femto users require lower data rate.

Acknowledgment

The research was support in part by grants from RGC under the contracts CERG 623209 and 622410, the grant from Huawei-HKUST joint lab, and the National Natural Science Foundation of China under Grant No. 60933012

References

[1] G. De La Roche, A. Valcarce, D. López-Pérez, and J. Zhang, "Access control mechanisms for femtocells," *IEEE Commun. Mag.*, vol. 48, no. 1, pp. 33–39, 2010.

[2] D. Choi, P. Monajemi, S. Kang, and J. Villasenor, "Dealing with loud neighbors: the benefits and tradeoffs of adaptive femtocell access," in *Proc. 2008 IEEE GLOBECOM*, pp. 1–5.

[3] A. Valcarce, D. López-Pérez, G. De La Roche, and J. Zhang, "Limited access to OFDMA femtocells," in *Proc. 2010 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 1–5.

[4] A. Nosratinia and T. Hunter, "Grouping and partner selection in cooperative wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 25, no. 2, pp. 369–378, 2007.

[5] H. Lin, M. Chatterjee, S. Das, and K. Basu, "ARC: an integrated admission and rate control framework for competitive wireless CDMA data networks using noncooperative games," *IEEE Trans. Mobile Comput.*, pp. 243–258, 2005.

[6] G. Stamoulis, D. Kalopsikakis, and A. Kyrikoglou, "Efficient agent-based negotiation for telecommunications services," in *Proc. 2002 IEEE GLOBECOM*, pp. 1989–1996.

[7] M. Xiao, N. Shroff, and E. Chong, "Utility-based power control in cellular wireless systems," in *Proc. 2002 IEEE INFOCOM*, vol. 1, pp. 412–421.

[8] J. Zhang and Q. Zhang, "Stackelberg game for utility-based cooperative cognitiveradio networks," in *Proc. 2009 Mobihoc*, pp. 23–32.

[9] R. Yates, "A framework for uplink power control in cellular radio systems," *IEEE J. Sel. Areas Commun.*, vol. 13, no. 7, pp. 1341–1347, 2002.

[10] D. Lopez-Perez, A. Valcarce, G. De La Roche, E. Liu, and J. Zhang, "Access methods to WiMAX femtocells: a downlink system-level case study," in *Proc. 2009 IEEE Singapore International Conference on Communication Systems*, pp. 1657–1662.

[11] P. Xia, V. Chandrasekhar, and J. Andrews, "Open vs closed access femtocells in the uplink," Arxiv preprint arXiv:1002.2964, 2010.

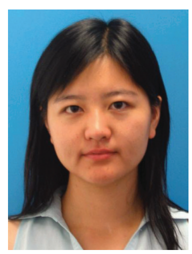
[12] Y. Yi, J. Zhang, Q. Zhang, T. Jiang, and J. Zhang, "Cooperative communication-aware spectrum leasing in cognitive radio networks," in *Proc. 2010 IEEE Symposium on New Frontiers in Dynamic Spectrum*, pp. 1–11.

[13] C. Yang and J. Li, "Capacity maximization in cognitive networks: a Stackelberg game-theoretic perspective," in *Proc. 2010 IEEE International Conference on Communications Workshops*, pp. 1–5.

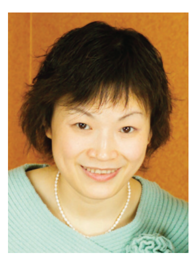
[14] E. Hong, S. Yun, and D. Cho, "Decentralized power control scheme in femtocell networks: a game theoretic approach," in *Proc. 2010 IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, pp. 415–419.

[15] C. Chen, C. Wang, S. Chao, and H. Wei, "DANCE: a game-theoretical femtocell channel exchange mechanism," *ACM SIGMOBILE Mobile Computing and Commun. Rev.*, vol. 14, no. 1, pp. 13–15, 2010.

Yanjiao Chen received her B.E. degree of electronic engineering from Tsinghua University in 2010. She is currently a Ph.D. candidate in Hong Kong University of Science and Technology. Her research interests include spectrum management for Femtocell networks and network economics.



Jin Zhang (S'06-M'09) is currently a research assistant professor with Fok Ying Tung Graduate School in Hong Kong University of Science and Technology. She received her B.E. and M.E. degree in electronic engineering from Tsinghua University, Beijing, in 2004 and 2006 respectively, and received her Ph.D. degree in computer science from Hong Kong University of Science and Technology in 2009. Her research interests include cooperative communication and networking, cognitive radio networks, network economics, body area network and mobile healthcare.



Qian Zhang joined Hong Kong University of Science and Technology in Sept. 2005 where she is a full Professor in the Department of Computer Science and Engineering. Before that, she was in Microsoft Research Asia, Beijing, from July 1999, where she was the research manager of the Wireless and Networking Group. Dr. Zhang has published about 300 refereed papers in international leading journals and key conferences in the areas of wireless/Internet multimedia networking, wireless communications and networking, wireless sensor networks, and overlay networking. She is a Fellow of IEEE for "contribution to the mobility and spectrum management of wireless networks and mobile communications." Dr. Zhang has received MIT TR100 (MIT Technology Review) world's top young innovator award. She also received the Best Asia Pacific (AP) Young Researcher Award elected by IEEE Communication Society in year 2004. Her current research is on cognitive and cooperative networks, dynamic spectrum access and management, as well as wireless sensor networks. Dr. Zhang received the B.S., M.S., and Ph.D. degrees from Wuhan University, China, in 1994, 1996, and 1999, respectively, all in computer science.