Economic Viability of Femtocell Service Provision

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Abstract. Femtocells can effectively resolve the poor connectivity issue of indoor cellular users. This paper investigates the economic incentive for the cellular operator to add femtocell service on top of its existing macrocell service. We model the interactions between a cellular operator and users as a Stackelberg game: in Stage I the operator determines spectrum allocations and pricing decisions of femtocell and macrocell services, and in Stage II the users with heterogeneous macrocell channel qualities and spectrum efficiencies choose between the two services and decide their bandwidth usages. We show that the operator will choose to only provide femtocell service if femtocell service has full spatial coverage as macrocell service. In this case, the operator can serve more users at a higher price and thus obtain a higher profit. However, with the additional requirement that users need to achieve payoffs no worse than using the original macrocell service, we show that the operator will always provide macrocell service (with or without the femtocell service). Finally, we study the impact of operational cost on femtocell service provision, where we show that the operator will always provide both services. We also show that as such cost increases, fewer users are served by femtocell service and the operator's profit decreases.

Key words: Femtocells, Stackelberg game, spectrum allocations, pricing

1 Introduction

The next generation 4G cellular systems aim at providing end users with high data rates and reliable services by operating at wider and higher frequency bands (*e.g.,* 2496MHz-to-2690MHz for TD-LTE in U.S.). However, severe signal attenuation at these high frequencies often causes poor signal receptions for indoor users, who are far away and separated by walls from outdoor cellular base station in local macrocells.[2]

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[2] A macrocell is the typical cell in a cellular network that provides radio coverage served by a power cellular base station [1].

To solve the poor signal reception problem for indoor users, researchers have proposed the idea of femtocell (*e.g.,* [7–10]). Compared to macrocells, femtocells are short-range, low deployment cost, and low power user-deployed tiny base stations. A user can deploy a femtocell at home and connect it to the wireline broadband Internet connection, *e.g.,* the digital subscriber line (DSL). Femtocells are often managed by the same operator that controls the macrocells, and they can provide better quality of services to indoor users as they are very close to users' cell phones. Despite of the obvious motivation to deploy femtocell service, the operator needs to carefully consider several issues that will affect the economic return of the femtocell service.

First, the femtocell service needs to share the limited licensed bands with the macocell service. There are two types of sharing schemes. The first scheme is "separate carriers", where the femtocells and macrocells occupy non-overlapping spectrum bands (*e.g.,* [11, 13, 14]). The second scheme is "shared carrier" (or "partially shared carrier"), where macrocells and femtocells operate on (partially) overlapping bands (*e.g.,* [10, 15, 19]). The first scheme is easy to manage but reduces the available spectrum for both services. The second scheme requires efficient distributed interference management mechanisms that are still open research problems. In this paper, our analysis will focus on the first "separate carriers" scheme.

Second, when an operator introduces the femtocell service and charges a higher price, some users who originally experience good macrocell service quality may actually experience a decrease in payoff. It is important to ensure the satisfaction of these users by keeping the original macrocell service available at the original price. This will limit the resource allocation to femtocell service.

Third, although femtocells are low in *deployment* costs, the femtocell service may incur additional *operational* cost compared to macrocells. Femtocell users' traffic needs to go through wireline broadband Internet connections. The wireline Internet Service Providers (ISPs) may impose additional charges on the femtocell related traffics [16]. Also, since the femtocell users' traffics will go through the ISP's network before reaching the cellular operator's own network, issues such as synchronization with macrocells become more challenging to resolve [17, 18].

In this paper, we will discuss the economic incentive of the operator's femtocell service provision, by considering three issues discussed above. We want to understand when and how the operator should offer the femtocell service, and the impacts on the original macrocell service. Our main results and contributions include:

- *A Dynamic Decision Model:* We model and analyze the interactions between an cellular operator and users as a two-stage Stackelberg game. Users experience different spectrum efficiencies with the macrocell service, but achieve the same maximum spectrum efficiency with the femtocell service. Thus users have different preferences between macrocells and femtocells. The operator makes spectrum allocations and pricing decisions for both macrocell and femtocell services to maximize its profit.

- *Profit-Maximizing with Femtocell Service Only:* If femtocell service has the same maximum coverage as macrocell service, then a profit-maximizing operator will choose to only offer femtocell service to all its users.
- *Dual Service Provision Considering Users' Reservation Payoffs:* If we consider users' reservation payoffs as what they can achieve with the original macrocell service, then offering femtocell service only may force some users to leave and thus may not be optimal to the operator. In this case, we characterize when and how the operator should provide the femtocell service together with the macrocell service (*i.e.,* dual services) so that all users achieve payoffs no worse than their reservation payoffs.
- *Impact of Femtocell Operational Cost:* When femtocell service incurs operational cost to the operator, the operator will always serve users by dual services. As the cost decreases, more users are served by the femtocell service and the operator obtains a higher profit.

Most prior work on femtocells focused on various technical issues in service provision (*e.g.,* access control and resource management [10,11,14,15,19]). Only few papers discussed the economic issues of femtocells (*e.g.,* [13, 20, 21]). The key difference between our paper and the existing literature is that we study the operator's provision of dual services in terms of both spectrum allocations and pricing decisions. We also characterize the impacts of users' reservation payoffs and the femtocell operational costs.

The rest of the paper is organized as follows. We introduce the network model of macrocell service in Section 2, which services as a benchmark for later analysis. In Section 3, we introduce the network model of femtocell service and analyze how the operator provides dual services in terms of spectrum allocations and pricing. Then we extend the results in Section 3 to Sections 4 and 5, by examining the impacts of users' reservation payoffs and femtocell operational costs. We conclude our work in Section 6. **Due to space limit, all proof details are included in the online technical report [23].**

2 Benchmark Scenario: Macrocell Service Only

As a benchmark case, we first look at how the operator prices the macrocell service to maximize its profit before introducing the femtocell service. When we consider the introduction of femtocell service in Sections 3, 4, and 5, the operator should achieve a profit no worse than this benchmark case. Also, what users get in this benchmark case will serve as their reservation payoffs in Section 4.

We consider an operator who owns a single macrocell without frequency reuse.[3] As shown in Fig. 1, we model the interactions between the operator and the users as a two-stage Stackerberg game. In Stage I, the operator determines the macrocell price p_M per unit bandwidth to maximize its profit. Here, subscript M denotes macrocells. In Stage II, each user decides how much bandwidth to

[3] The results of this paper can be extended to a multiple macrocell scenario, where frequency reuse is allowed over macrocells.

Fig. 1. Two-stage Stackelberg game between the operator and users. Stage I: the operator decides macrocell price per unit bandwidth to maximize its profit. Stage II: users choose how much resource to request in order to maximize their payoffs.

purchase to maximize its payoff. This usage-based pricing scheme is widely used in practice [22]. We solve this two-stage Stackelberg game by backward induction [3].

2.1 Users' Requests in Service and Bandwidth in Stage II

Different users experience different channel conditions to the macrocell base stations due to different locations, and thus achieve different data rates when using the same amount of bandwidth. We model the users' channel heterogeneity by a *macrocell spectrum efficiency* θ, which is assumed to be uniformly distributed in $[0, 1]$ (see Fig. 2).[4] A larger θ means a better channel condition and a higher spectrum efficiency *when using the macrocell service*. In Section 3, we will show that all users achieve the same maximum spectrum efficiency with femtocell service. We also normalize the total user population to be 1.

Fig. 2. Distribution of users' macrocell spectrum efficiencies

For a user with a macrocell spectrum efficiency θ, it obtains a utility $u(\theta, b)$ (*e.g.,* data rate) when using a bandwidth b [2],

$$u(\theta, b) = \ln(1 + \theta b).$$

The user needs to pay a linear payment $p_M b$ to the operator, where the price p_M is announced by the operator in Stage I. The user's *payoff* is the difference of its utility and payment, *i.e.,*

$$\pi_M(\theta, b, p_M) = \ln(1 + \theta b) - p_M b. \quad (1)$$

The optimal value of bandwidth (demand) that maximizes the user's payoff with the macrocell service is

[4] The uniform distribution is assumed for analytical tractability. However, a more complicated distribution will not change the main engineering insights obtained in this paper.

$$b^*(\theta, p_M) = \begin{cases} \frac{1}{p_M} - \frac{1}{\theta}, & \text{if } p_M \leq \theta, \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

which is decreasing in p_M and increasing in θ (if $p_M \leq \theta$). The user's maximum payoff with macrocell service is

$$\pi_M(\theta, b^*(\theta, p_M), p_M) = \begin{cases} \ln\left(\frac{\theta}{p_M}\right) - 1 + \frac{p_M}{\theta}, & \text{if } p_M \leq \theta, \\ 0, & \text{otherwise,} \end{cases} \tag{3}$$

which is always nonnegative.

2.2 Operator's Pricing in Stage I

Next we consider the operator's optimal choice of price p_M in Stage I. To achieve a positive profit, the operator needs to set $p_M \leq \max_{\theta \in [0,1]} \theta = 1$, so that at least some user purchases some positive bandwidth in Stage II. The fraction of users choosing macrocell service is $1 - p_M$ as shown in Fig. 2. The total user demand is

$$Q_M(p_M) = \int_{p_M}^{1} \left(\frac{1}{p_M} - \frac{1}{\theta}\right) d\theta = \frac{1}{p_M} - 1 + \ln p_M, \tag{4}$$

which is a decreasing function of p_M. On the other hand, the operator has a limited bandwidth supply B, and thus can only satisfy the demand no larger than B.

The operator chooses price p_M to maximize its profit, *i.e.,*

$$\max_{0 < p_M \leq 1} \pi^{operator}(p_M) = p_M \min\left(B, \frac{1}{p_M} - 1 + \ln p_M\right). \tag{5}$$

Theorem 1 characterizes the unique optimal solution of Problem (5).

Theorem 1. *The equilibrium macrocell price p_M^* is the unique solution of the following equation:*

$$B = \frac{1}{p_M^*} - 1 + \ln p_M^*. \tag{6}$$

Furthermore, the total user demand $Q(p_M^*) = B$. Finally, the equilibrium price p_M^* decreases with B, and the operator's equilibrium profit $\pi^{operator}(p_M^*)$ increases with B.

Notice that all users with a macrocell spectrum efficiency θ less than p_M^* will not receive macrocell service. When the total bandwidth B is small, the equilibrium macrocell price p_M^* is close to 1 and thus most users will not get service. This motivates the operator to adopt the femtocell service so that it can serve these users and generate additional profits.

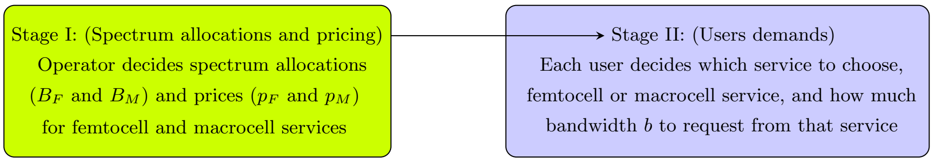

Fig. 3. Two-stage Stackelberg game between the operator and users. Stage I: the operator decides spectrum allocations and prices of macrocell and femtocell services; Stage II: users choose which service to access and how much resource usage to request from the operator.

3 Provision of Femtocell Service

We now consider how femtocell service can improve the operator's profit. The analysis in this section is based on several simplified assumptions:

– All users have a zero reservation payoff, and thus will accept the femtocell service as long as its payoff is positive. This assumption will be relaxed in Section 4.
– The femtocell service does not incur any additional operational cost compared to the macrocell service. This assumption will be relaxed in Section 5.
– The femtocells have the same maximum coverage as the macrocell service, and each user can access to both macrocell and femtocell services. This assumption will be relaxed in our technical report [23].

We are interested in answering the following two questions:

– Is it economically viable for the the operator to introduce the femtocell service?
– If so, how should the operator allocate bandwidth for and price macrocell and femtocell services?

Under the assumptions in this section, we will show that the operator will choose to only provide femtocell service (*i.e.,* no macrocell service) to all users and charge a higher price p_F^* than the optimal macrocell price p_M^* derived in Section 2.

More specifically, we will look at a two-stage Stackelberg game as in Fig. 3. In Stage I, the operator determines bandwidth allocated to femtocell service (femtocell band B_F) and to macrocell (macrocell band B_M), with $B_F + B_M = B$. The operator also determines the femtocell price p_F and macrocell price p_M. In Stage II, each user decides which service to choose and how much bandwidth to purchase. If a user's demand cannot be satisfied by its preferred service, it will switch and purchase bandwidth from the other service.[5] We will again analyze this two-stage Stackelberg game by using backward induction.

[5] Here we focus on a large group of users, where a user's demand is infinitesimal compared to the total demand. Thus we can ignore the case where a user purchases bandwidth from both services.

3.1 Users' Requests in Service and Bandwidth in Stage II

If a user has a macrocell spectrum efficiency θ, its optimal payoff by using the macrocell service is given in (3). Next we consider users' payoffs by using the femtocell service.

Since femtocell base stations are deployed indoors and are very close to the users' cell phones, we assume that all users using the femtocell service have equal good channel conditions and achieve the same *maximum* spectrum efficiency. This means that independent of the macrocell spectrum efficiency θ, each user achieves the same payoff $\pi_F(b)$ when using a bandwidth of b,

$$\pi_F(b, p_F) = \ln(1 + b) - p_F b. \tag{7}$$

The user's optimal demand in femtocells is

$$b^*(p_F) = \begin{cases} \frac{1}{p_F} - 1, & \text{if } p_F \leq 1, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

A user's maximum payoff with the femtocell service is

$$\pi_F\left(b^*(p_F), p_F\right) = \begin{cases} \ln\left(\frac{1}{p_F}\right) - 1 + p_F, & \text{if } p_F \leq 1, \\ 0, & \text{otherwise,} \end{cases} \tag{9}$$

which is always nonnegative.

It is clear that a user with small macrocell spectrum efficiency θ can get a better payoff by using the femtocell service instead of the macrocell service. We can imagine a threshold of θ that separates the users of two services. Next we define two different types of thresholds.

Definition 1 (Users' *preferred* partition threshold θ_{th}^{pr}). *Users with $\theta \in [0, \theta_{th}^{pr})$ prefer to use the femtocell service, and users with $\theta \in [\theta_{th}^{pr}, 1]$ prefer to use the macrocell service.*

Definition 2 (Users' partition threshold θ_{th}). *The partition threshold θ_{th} is the minimum macrocell spectrum efficiency among all the users served (may not prefer to be served) by the macrocell service. Users with $\theta \in [\theta_{th}, 1]$ receive the macrocell service finally, while users with $\theta \in [0, \theta_{th})$ receive either the femtocell service or no service.*

If all users' demands from their preferred services are satisfied, then users' preferred partition threshold equals users' partition threshold (*i.e.*, $\theta_{th}^{pr} = \theta_{th}$). However, in general θ_{th} may be different from θ_{th}^{pr}, depending on the operator's choice of B_F and B_M in the first stage.

By comparing a user's optimal payoff with macrocell and femtocell services in (3) and (9), we have the following result.

Lemma 1. *Users' preferred partition threshold $\theta_{th}^{pr} = p_M/p_F$. Users with a small macrocell spectrum efficiency $\theta < p_M/p_F$ prefer the femtocell service, and users with a large macrocell spectrum efficiency $\theta > p_M/p_F$ prefer the macrocell service.*

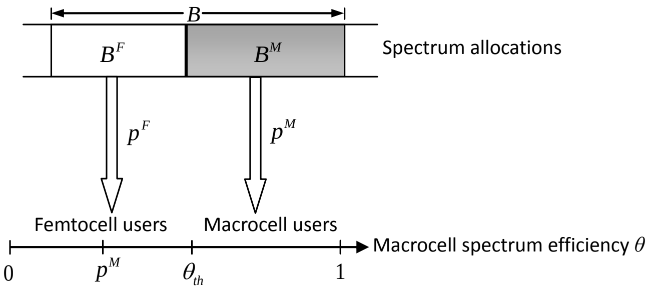

Fig. 4. Operations of macrocell and femtocell services

Now we introduce the concept of *finalized demand.*

Definition 3 (User's Finalized Demand). *If a user's demand from its preferred service is satisfied, then its finalized demand is its prefered demand. If a user's demand from its preferred service is not satisfied, then the user may switch to the alternative service and the new demand becomes the finalized demand.*

3.2 Operator's Spectrum Allocations and Pricing in Stage I

Now we are ready to study Stage I, where the operator determines B_F, B_M, p_F, and p_M to maximize its profit (see Fig. 4). Let us denote the operator's equilibrium decisions as B_F^*, B_M^*, p_F^*, and p_M^*, which lead to the users' equilibrium partition threshold (Definition 2) equal to θ_{th}^*. It is clear that the femtocell price p_F^* is larger than the macrocell price p_M^*, otherwise all users will choose the femtocell service.

Lemma 2. *At the equilibrium, the operator's total bandwidth B equals users' total finalized demand.*

Based on Lemma 2, we can further show that bandwidth allocated to each service equals users' total finalized demand in that service. That is,

$$B_F^* = \int_0^{\theta_{th}^*} \left(\frac{1}{p_F^*} - 1 \right) d\theta = \theta_{th}^* \left(\frac{1}{p_F^*} - 1 \right), \tag{10}$$

$$B_M^* = \int_{\theta_{th}^*}^1 \left(\frac{1}{p_M^*} - \frac{1}{\theta} \right) d\theta = \frac{1 - \theta_{th}^*}{p_M^*} + \ln \theta_{th}^*, \tag{11}$$

and $B_F^* + B_M^* = B$. This means that we only need to solve for the equilibrium decisions of θ_{th}^*, p_M^*, and p_F^*. The operator's profit-maximization problem is

$$\max_{p_M, p_F, \theta_{th}} \pi^{operator}(p_M, p_F, \theta_{th}) = p_F \theta_{th} \left(\frac{1}{p_F} - 1 \right) + p_M \left(\frac{1 - \theta_{th}}{p_M} + \ln \theta_{th} \right)$$

$$\text{subject to} \quad p_M \le \theta_{th} \le 1,$$

$$\theta_{th} \left(\frac{1}{p_F} - 1 \right) + \frac{1 - \theta_{th}}{p_M} + \ln \theta_{th} = B. \tag{12}$$

By examining (12), we have the following result.

Theorem 2. *At the equilibrium, the operator will only provide femtocell service, i.e.,* $B_F^* = B$ *and* $B_M^* = 0$*. All users will use femtocell service, i.e., users' equilibrium partition threshold* $\theta_{th}^* = 1$*. The equilibrium femtocell price is*

$$p_F^* = \frac{1}{1+B}, \tag{13}$$

and the operator's equilibrium profit is

$$\pi^{operator*} = \frac{B}{1+B}. \tag{14}$$

Theorem 2 is easy to understand. As the femtocell service provides a higher QoS to all users,[6] the operator can attract the users with small macrocell spectrum efficiency θ, and sell out the whole bandwidth B at a price $p_F^* = 1/(1+B)$ *higher* than the equilibrium macrocell price p_M^* in Theorem 1. This means that the operator achieves a higher profit by only providing femtocell service.

However, a user who has a large θ (*e.g.,* $\theta = 1$) will achieve a smaller payoff $\pi_F(b^*(p_F^*), p_F^*)$ with femtocell service than the payoff $\pi_M(\theta, b^*(\theta, p_M^*), p_M^*)$ with macrocell service. If we treat $\pi_M(\theta, b^*(\theta, p_M^*), p_M^*)$ as a user's *reservation payoff* below which the user will not accept the femtocell service,[7] then the operator can no longer only provide femtocell service. Next section studies this case in details.

4 Impact of Users' Reservation Payoffs

In this section, we will consider the operator's decisions by assuming that each user with a macrocell spectrum efficiency θ receives a payoff no less than $\pi_M(\theta, b^*, p_M^*)$ as calculated in (3). This means that the operator always needs to provide macrocell service at the same price as p_M^* derived based on (6). Also, all users' preferred demands in macrocell service should be satisfied. Next we consider a two-stage decision process similar to Fig. 3. The only difference here is that the operator needs to satisfy users' reservation payoffs.

In this section only, we assume that the operator has a priority to serve the users with the smallest θ first in femtocells. This is reasonable since femtocell service aims at improving QoS of indoor users especially for those with a small spectrum efficiency. These users cannot use macrocell service and will be happy to pay a high price for the femtocell service. For users with a high macrocell spectrum efficiency, they have the additional choice of macrocell service and will not use femtocell service if p_F is high.

[6] The only exception will be users with $\theta = 1$, who have a zero size support under the uniform distribution assumption of θ.

[7] For example, the user may switch to a different operator who provides macrocell service.

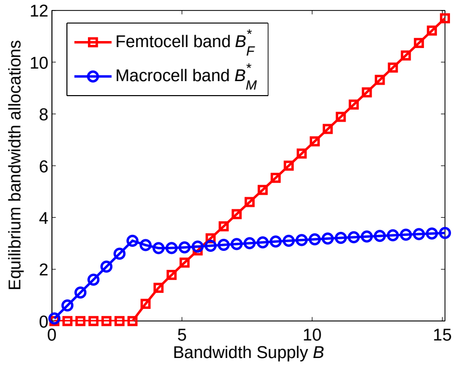

Fig. 5. The operator's equilibrium femtocell band B_F^* and macrocell band B_M^* as functions of supply B considering users' reservation payoffs

We will again use backward induction to analyze the problem. As Stage II is the same as Section 3.1, we will focus on the operator's decisions on B_M, B_F, and p_F in Stage I.

Lemma 3. *At the equilibrium, one of the following is true:*

– *Only users with $\theta \in [p_M^*, 1]$ are served with the macrocell service, and no users are served with the femtocell service.*
– *All users with $\theta \in [0, 1]$ are served, by either the macrocell service or the femtocell service.*

Lemma 3 shows that the equilibrium femtocell band is either $B_F^* = 0$ or $B_F^* \geq \int_0^{p_M^*} (\frac{1}{p_F^*} - 1) d\theta$. This implies that when B is small, the operator needs to allocate all its bandwidth supply B for macrocell service to reach users' reservation payoffs. Only when B is large, the operator can serve all users by dual services (*i.e.,* macrocell and femtocell services).

The operator's profit-maximization problem can be simplified as

$$\max_{p_F, \theta_{th}} \pi^{operator}(p_F, \theta_{th}) = p_F \int_0^{\theta_{th}} \left(\frac{1}{p_F} - 1 \right) d\theta + p_M^* \int_{\theta_{th}}^1 \left(\frac{1}{p_M^*} - \frac{1}{\theta} \right) d\theta$$

$$\text{subject to} \quad p_M^* \leq \theta_{th} \leq p_M^*/p_F,$$

$$\int_0^{\theta_{th}} \left(\frac{1}{p_F} - 1 \right) d\theta + \int_{\theta_{th}}^1 \left(\frac{1}{p_M^*} - \frac{1}{\theta} \right) d\theta \leq B, \tag{15}$$

where p_M^* is computed from (6), and the right inequality of the first constraint means that the operator cannot violate users' preferences in macrocell service. In the second constraint, the first and second terms on the left hand side are the users' finalized total demands in femtocells and macrocells, respectively.

Problem (15) is difficult to solve in closed form, so we use numerical results to illustrate some interesting insights.

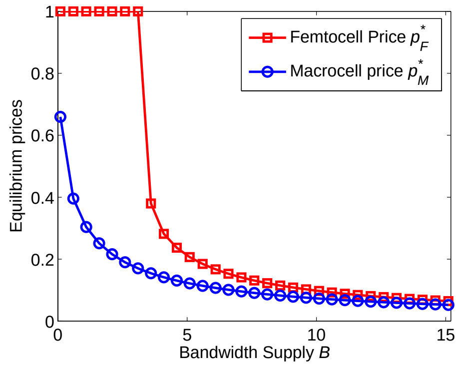

Fig. 6. The operator's equilibrium femtocell price p_F^* and macrocell price p_M^* as functions of bandwidth supply B considering users' reservation payoffs.

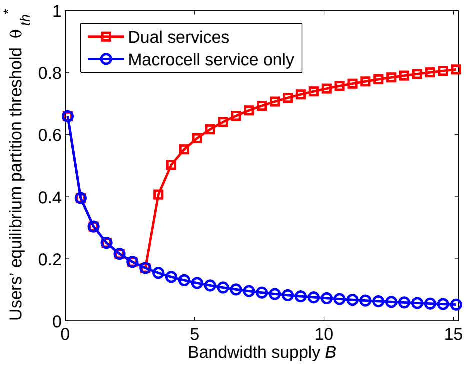

Fig. 7. Users' equilibrium partition thresholds θ_{th}^* as functions of bandwidth supply B in two cases: dual services considering users' reservation payoffs and macrocell service only as in Section 2

Figure 5 shows the operator's equilibrium bandwidth allocations to dual services (*i.e.,* B_F^* and B_M^*) as functions of the total bandwidth supply B. Figure 5 is consistent with Lemma 3, where only macrocell service is available (*i.e.,* $B_F^* = 0$) in the low supply regime (*i.e.,* $B < 3.5$), and both services are available in the high supply regime (*i.e.,* $B \geq 3.5$). In the high supply regime, femtocell band B_F^* increases faster than the macrocell band B_M^* when B increases. This is because the operator can obtain a higher profit by providing femtocell service, which charges users a higher price compared with macrocell service.

Figure 6 shows the operator's equilibrium femtocell price p_F^* and macrocell price p_M^* as functions of total bandwidth B. We can observe that in high supply regime p_F^* decreases faster than p_M^* as B increases, which means that the operator wants to attract more users to femtocell service.

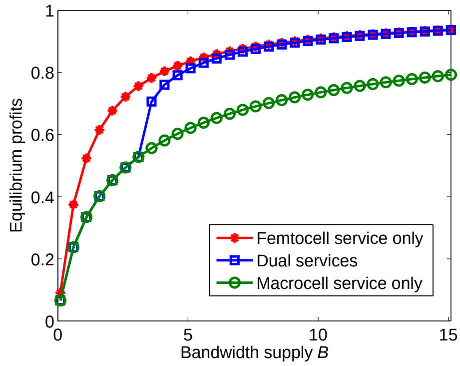

Fig. 8. The operator's equilibrium profits in three cases: femtocell service only as in Section 3, dual services considering users' reservation payoffs, and macrocell service only as in Section 2.

Figure 7 shows the users' equilibrium partition threshold θ_{th}^* with dual services in this section, comparing to the partition threshold of the macrocell service only case in Section 2. In the low supply regime (*i.e.*, $B < 3.5$), both curves overlap with each other, as the dual services degenerate to the macrocell service only in this regime. However, as the total bandwidth B becomes very large in high supply regime, the operator will announce similar femtocell and macrocell prices, and most users will choose to use femtocell service. Comparing with the femtocell service only provision in Section 3 (without considering users' reservation payoffs), here users with a large θ will choose to stay with the macrocell service and are not affected by the introduction of femtocell service.

Figure 8 compares the operator's profits in three different cases: femtocell service only as in Section 3, dual services as in this section, and macrocell service only as in Section 2. In the low supply regime, dual services degenerate to the macrocell service case. In the high supply regime, the profit of the dual services becomes closer to the femtocell service only case as B increases. This means that considering users' reservation payoffs will not lead to significant profit loss when the total resource is abundant. In this case, only users with a θ very close to 1 will stay with macrocell service and all other users will choose the femtocell service.

5 Impact of Femtocell Operational Cost

In Section 3, we have assumed that there is no additional operational cost of the femtocell service. The data from the femtocells will be delivered through the wireline Internet connection of an ISP back to the operator's cellular network, free of charge. However, this is only reasonable when the operator and the ISP belong to the same entity or the ISP is sharing-friendly as in [4,5]. In this section, we consider the case where the ISP will charge the operator usage-based fees for

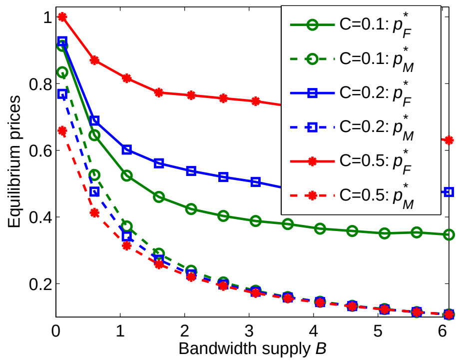

Fig. 9. The equilibrium femtocell price p_F^* and macrocell price p_M^* as functions of supply B and cost C in dual services considering femtocell operational cost.

using the wireline Internet connection. We are interested in understanding how this operational cost affects the provision of femtocell service.

For simplicity, we assume that the operational cost is linearly proportional to femtocell bandwidth with the coefficient C. We focus on the case of $C \in (0, 1)$. It is easy to show that if $C \geq 1$, then the operator will charge a femtocell price $p_F > 1$, and no user will choose the femtocell service based on (8).

We consider a two-stage decision process similar as Fig. 3. The analysis of Stage II is the same as in Section 3.1. Here we will focus on the operator's decisions on B_M, B_F, p_M, and p_F in Stage I. Following a similar analysis as in Section 3, we can show that the total bandwidth B will be fully utilized at the equilibrium (*i.e.,* Lemma 2). Then we can formulate the operator's profit-maximization problem as

$$\max_{p_M, p_F, \theta_{th}} \pi^{operator}(p_M, p_F, \theta_{th}) = (p_F - C)\theta_{th}\left(\frac{1}{p_F} - 1\right) + p_M\left(\frac{1-\theta_{th}}{p_M} + \ln\theta_{th}\right)$$

$$\text{subject to} \quad p_M \leq \theta_{th} \leq 1,$$

$$\theta_{th}\left(\frac{1}{p_F} - 1\right) + \frac{1-\theta_{th}}{p_M} + \ln\theta_{th} = B. \tag{16}$$

Then we have the following result.

Theorem 3. *With a femtocell operational cost $C \in (0, 1)$, the operator always provides both femtocell service and macrocell service at the equilibrium, and $p_M^* \leq \theta_{th}^* < 1$.*

Note that p_M^* is the equilibrium macrocell price, and θ_{th}^* is the users' equilibrium partition threshold with dual services. Intuitively, a positive operational cost C forces the operator to charge a higher femtocell price p_F^* than the value in (13). However, the small payment from users with a large value of θ (who only experience a little QoS improvement) in femtocell service cannot cover the

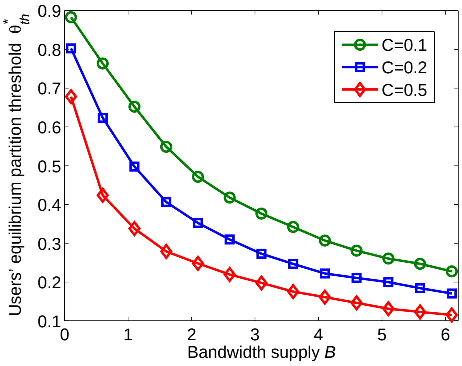

Fig. 10. The users' equilibrium partition threshold θ^*_{th} as a function of supply B and cost C in dual services considering femtocell operational cost.

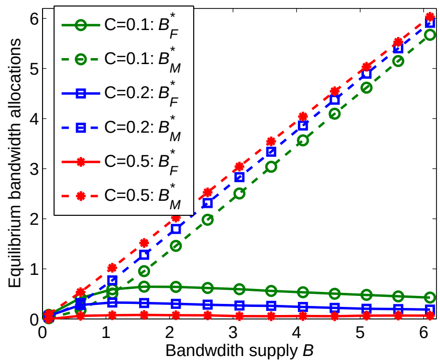

Fig. 11. The equilibrium femtocell band B^*_F and macrocell band B^*_M as functions of supply B and cost C in dual services considering femtocell operational cost.

increased operation cost to the operator. As a result, the operator will serve these users by macrocell service.

Problem (16) is difficult to solve in closed form, so we use numerical results to illustrate some interesting insights.

Figure 9 shows the operator's equilibrium femtocell price p^*_F and macrocell price p^*_M as functions of bandwidth supply B and femtocell operational cost C. The femtocell price p^*_F is always larger than C in order to be profitable. The macrocell price p^*_M does not need to compensate any cost. When B increases, the operator can set p^*_M as low as needed to maximize its profit, while p^*_F is lower-bounded by C. This explains why the $p^*_F - p^*_M$ widens as B increases, and such gap becomes even bigger with a larger C.

Figure 10 shows users' equilibrium partition threshold θ^*_{th} as a function of B and C. The threshold θ^*_{th} decreases in both B and C, which means that more users will choose to use the macrocell service due to the increase of $p^*_F - p^*_M$.

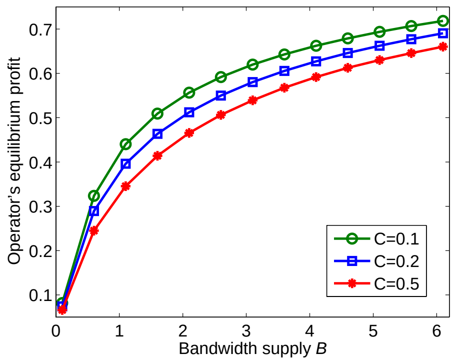

Fig. 12. The operator's equilibrium profit $\pi^{operator*}$ as a function of supply B and cost C in dual services considering femtocell operational cost.

Figure 11 shows the operator's equilibrium bandwidth allocations to dual services as functions of B and C. When B is small, femtocell band B_F^* increases with B since the operator wants to serve more users at higher femtocell price. When B is large, B_F^* decreases with B since the high femtocell price (relative to macrocell price) makes more users choose the macrocell service.

Figure 12) shows that the operator's equilibrium profit increases in B and decreases in C.

6 Conclusion

This paper studies the economic incentive for a cellular operator to add the femtocell service on top of its existing macrocell service. We analyze the operator's equilibrium decisions in terms of spectrum allocations and pricing of both types of services. We show that compared to macrocell service, femtocell service can attract more users at a higher price and increase the operator's profit. However, the requirement of satisfying users' reservation payoffs (*i.e.,* what they can achieve with the original macrocell service) prevents the operator from only providing femtocell service. In the case of small total bandwidth B, the operator actually cannot even provide any femtocell service. Also, in the case where femtocell service has an additional operational cost, it is always a good idea for the operator to provide both femtocell and macrocell services to maximize its profit. In our technical report [23], we further look at the realistic case where the femtocell service has a smaller coverage than the macrocell service.

References

1. J. H. Schiller, *Mobile communications*, Addison Wesley, 2003.

2. H. Shen and T. Basar, “Optimal nonlinear pricing for a monopolistic network service provider with complete and incomplete information,” *IEEE Journal on Selected Areas in Communications*, vol. 25, no. 6, pp. 1216-1223, Aug. 2007.
3. R. B. Myerson, *Game theory: analysis of conflict*, Cambridge, MA: Harvard University Press, 2002.
4. Electronic Frontier Foundation (EFF) Wireless friendly ISP list. `http://www.eff.org/Infrastructure/Wireless_cellular_radio/wireless_friendly_isp_list.html`
5. Speakeasy NetShare. `http://www.speakeasy.net/netshare/`
6. Presentations by ABI Research, Picochip, Airvana, IP.access, Gartner, Telefonica Espana, *2nd Int'l. Conf. Home Access Points and Femtocells*, `http://www.avrenevents.com/dallasfemto2007/purchase_presentations.htm`
7. picoChip Designs Ltd, “The case for home base stations,” White Paper, Apr. 2007. [Online]. Available: `http://www.femtoforum.org/femto/Files/File/picoChipFemtocellWhitePaper1.1.pdf`
8. H. Claussen, L. T. W. Ho, and L. G. Samuel, “An overview of the femtocell concept,” *Bell Labs Technical Journal*, vol. 13, no. 1, pp. 221C245, 2008.
9. V. Chandrasekhar, J. Andrews, and A. Gatherer, “Femtocell networks: a survey,” *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59C67, Sept. 2008.
10. S.-P. Yeh, S. Talwar, S.-C. Lee, and H. Kim, “WiMAX femtocells: a perspective on network architecture, capacity, and coverage,” *IEEE Commun. Mag.*, vol. 46, no. 10, pp. 58C65, Oct. 2008.
11. J. D. Hobby and H. Claussen, “Deployment options for Femtocells and their impact on existing macrocellular networks,” *Bell Labs Technical Journal*, vol. 13, no. 4, pp. 145C160, 2009.
12. “Spectrum policy task force report,” Federal Communications Commission, US, Nov. 2002.
13. N. Shetty, S. Parekh, and J. Walrand, “Economics of femtocells,” *IEEE GLOBECOM'09*, 2009.
14. J.-S. Wu, J.-K. Chung, and M.-T. Sze, “Analysis of uplink and downlink capacities for two-tier cellular system,” *IEE Proceedings- Communications*, vol. 144, no. 6, pp. 405-411, Dec. 1997.
15. V. Chandrasekhar and J. Andrews, “Uplink capacity and interference avoidance for two-tier cellular networks,” *IEEE GLOBECOM'07*, Nov. 2007, pp. 3322C 3326.
16. L. W. McKnight and J. P. Bailey, *Internet economics*, Mit Press Cambridge, Massachusetts, 1998.
17. J. Yoon, J. Lee, and H. S. Lee, “Multi-hop based network synchronization scheme for femtocell systems,” *IEEE PIMRC'10*, 2010.
18. R. Y. Kim, J. S. Kwak, and K. Etemad, “WiMax femtocell: requirements, challenges, and solutions,” *IEEE Communications Magazine*, Sept. 2009.
19. L. Ho and H. Claussen, “Effects of user-deployed, co-channel femtocells on the call drop probability in a residential scenario,” *in Proc. PIMRC'07*, Sept. 2007, pp. 1-5.
20. H. Claussen, L. Ho, and L. Samuel, “Financial analysis of a pico-cellular home network deployment,” *IEEE ICC'07*, Jun. 2007, pp. 5603-5609.
21. S. Yun, Y. Yi, D. Cho, and J. Mo, “Open or close: on the sharing of femtocells,” to appear at *IEEE INFOCOM Mini-Conference*, Apr. 2011.
22. C. Courcoubetis and R. Weber, *Pricing communication networks- economics, technology and modeling.* New York: Wiley, 2003.
23. L. Duan and J. Huang, “Economic Incentives of Femtocell Service Provision,” Technical Report, online at `http://home.ie.cuhk.edu.hk/~jwhuang/publication/FemtocellTechReport.pdf`