Femtocell Service Provision with Dual Channel Competition

Lingjie Duan, Jianwei Huang, Biying Shou

Abstract—**Indoor cell phone users often suffer from poor connectivity. One promising solution, femtocell technology, has been rapidly developed and deployed over the past few years. One of the biggest challenges for femtocell deployment is lack of a clear business model. This paper investigates the economic incentive for the cellular operator (also called macrocell operator) to enable femtocell service by leasing spectrum resource to an independent femtocell operator. On the one hand, femtocell services can increase communication service quality and thus increase the efficiency of the spectrum resource. On the other hand, femtocell services may introduce more competition to the market. We model the interactions between a macrocell operator, a femtocell operator, and users as a three-stage dynamic game, and derive the equilibrium pricing and capacity allocation decisions. We show that when spectrum resources are very limited, the macrocell operator has incentive to lease spectrum to femtocell operators, as femtocell service can provide access to more users and efficiently increase the coverage. However, when the total spectrum resource is large, femtocell service offers significant competition to macrocell service. Macrocell operator thus has less incentive to enable femtocell service.**

Index Terms—**Femtocells, Microeconomics, Stackelberg game, Subgame Perfect equilibrium.**

I. Introduction

Today there are over 5 billion cell phone users in the world (Global mobile statistics 2011), and many of them experience poor indoor reception at home or office. This is because in the current cellular network (also called *macrocell* network), a base station covers an area of a radius from several hundred to several kilometers. The high-frequency and low-power wireless signals often have difficulty in effectively traveling from an outdoor macrocell base station to indoor cell phones through (several layers of) walls. As a result, indoor cell phone users often experience dropped calls and reduced wireless data rates (Sandler 2009).

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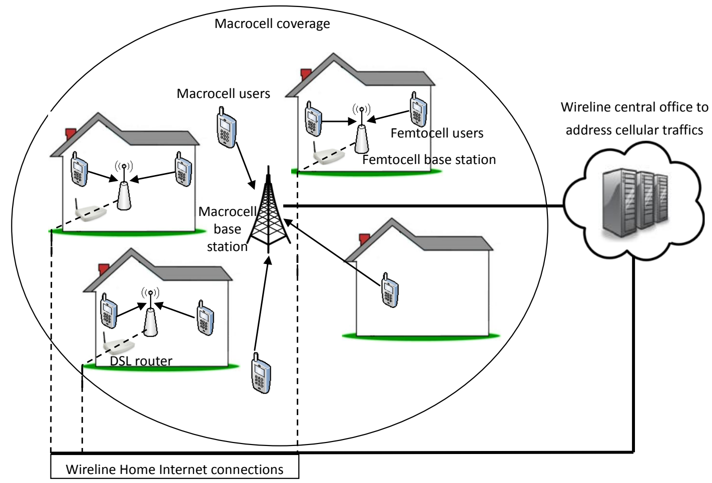

Fig. 1. Coexistence of femtocell service and macrocell service, where a macrocell and three femtocells are deployed

As one promising solution to the indoor reception problem, *femtocell technology* has been rapidly developed and deployed over the past few years. Figure 1 provides an illustration of four homes covered by one macrocell base station, and three of them have installed femtocell base stations. Femtocell is a small base station with a size similar to a wireless router. An indoor femtocell base station is much closer to users' indoor cell phones. It can pick up the cell phones' signals much more effectively, and deliver the voice and data signals to the cellular network through users' home wireline Internet connection. Femtocell technology can significantly increase the quality of voice calls and improve the speed of data communications (Shetty et al. 2009).

Major operators worldwide are enthusiastic about the femtocell technology due to its capability of improving customers' experiences. One of the biggest challenges to an operator's large scale femtocell deployment, however, is the lack of a clear business model. The purpose of this paper is to develop a quantitative model to examine the business trade-off of femtocell deployments. In particular, we look at the following research questions:

- *Should a macrocell operator deploy femtocell services? How would the operator allocate bandwidth (capacity) resources and make pricing decisions?* There are two common approaches to the deployment of femtocell service. In an *integrated* system, a macrocell operator directly provides femtocell service to users and fully controls bandwidth resource allocation and femtocell service price. We have a comparison paper focusing on the economic operation of such an integrated system (Duan et al. 2011a). In a *distributed* system, a macrocell operator leases its spectrum resources to a femtocell operator. The femtocell operator determines the service provision and pricing independently. Examples of distributed systems are abundant in the industry: Sprint leases licensed spectrum to Virgin Mobile USA to provide femtocell service (Fitchard 2009), and BT Mobile is using Vodafone's resource to provide femtocell service (Atkinson 2011). Research results on the distributed system started to emerge recently (e.g., Hong and Tsai 2010 and Chen et al. 2011), and this paper focuses on the distributed system. In such a system, a macrocell operator may increase its revenue by leasing resources to the femtocell operator, meanwhile it will have less resources for its own services and face an increased market competition from the femtocell operator.
- *How would users choose between femtocell and macrocell services?*[1] By using the indoor femtocell base station, users can avoid the poor indoor reception problem and achieve the maximum quality of service (QoS). In contrast, when users choose to use the outdoor macrocell base stations, the QoS highly depends on the user locations and the communication environments (which is summarized by a user-dependent spectrum efficiency parameter). Apparently such QoS differentiation justifies different prices of the two services. A user needs to balance the QoS with the payment when choosing between macrocell and femtocell services.

Most existing work on femtocell deployment in the telecommunication literature (*e.g.,* Chandrasekhar and Andrews 2009) focus on various technical issues in service provision such as access control, resource management, and interference mangement. Only a few papers discuss the economic issues of femtocells (*e.g.,* Claussen et al. 2007, Yun et al. 2011, Shetty et al. 2009, Chen et al. 2011), examining the impact of network deployment costs and femtocells' openness to macrocell users. The key difference between our paper and such existing literature is that we study the provision of dual services in terms of both spectrum allocations and pricing decisions. We also characterize the impact of the femtocell operational cost and limited femtocell coverage on the service provision.

Our main results are summarized as follows:

- *Characterization of equilibrium decisions:* We derive a threshold structure in terms of the spectrum efficiency parameter, which separates users who prefer femtocell to macrocell services. We further characterize the femtocell operator's femtocell price and the macrocell operator's capacity allocation and pricing decisions at the equilibrium.
- *Sensitivity analysis of macrocell's total capacity:* Wireless spectrum is a very scarce resource, so macrocell operators often face capacity constraints. In the U.S. 700MHZ spectrum auction in March 2008, the total bid price is nearly $20 Billion (WNN Wi-Fi Net News 2008). One of our key (counter-intuitive) findings is that macrocell operator has more incentive to lease spectrum to the femtocell operator when its capacity is *small*, but chooses to offer only macrocell service when its capacity is *large*.

The rest of the paper is organized as follows. In Section II, we introduce the network model of femtocell service deployment. In Section III, we analyze how the users decide which service to choose and how much bandwidth to request. In Sections IV and V, we investigate how the macrocell operator and the femtocell operator make capacity and pricing decisions to maximize their own profits. Section VI presents numerical results. Finally, Section VII concludes the paper.

II. Three-Stage Femtocell Deployment Model

Throughout this paper, we focus on the monopoly case in a two-tier market with a single macrocell operator and a single femtocell operator. This is motivated by some monopoly examples in macrocell services worldwide (e.g., America Movil (the world's fourth largest mobile network operator) in Mexico and many places in Latin America, and MTS in some central Asian countries). Also, since femtocell service just emerged from last

[1] Throughout this paper, femtocell service means femtocell-plus-macrocell service: the femtocell service for indoor usage and macrocell service for outdoor usage, while macrocell service means only macrocell service for both indoor and outdoor usages.

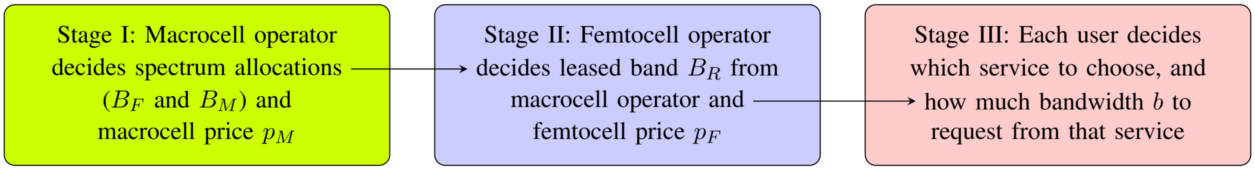

Fig. 2. Three-stage dynamic game between the macrocell operator, femtocell operator, and users..

decade, many fetmocell operators are still local monopolists (e.g., Virgin Mobile USA in US and BT Mobile in UK). We believe that a thorough understanding of the monopoly case is critical before studying the more general oligopoly market in the future. We are interested in understanding the following issues:

- *Strategic decision:* Is it economically beneficial for the macrocell operator to lease spectrum to a femtocell operator, who will compete with the macrocell operator in serving the same group of end users?
- *Operational decisions:* If the answer to the previous question is yes, how should the macrocell operator allocate and price the spectrum resources?

More specifically, we will look at a three-stage dynamic game as in Fig. 2. The macrocell operator has market power and is the leader in the cellular market, while the emerging femtocell operaotr is the follower. In Stage I, the macrocell operator decides bandwidth allocations to femtocell service B_F and macrocell service B_M such that $B_F + B_M = B$. Here we focus on the "separate carriers" scheme, where dual services operate on independent spectrum bands. "Separate carriers" is easy to manage and can avoid interferences between macrocells and femtocells. For example, China Unicom (one of the top 3 wireless service providers in China and the first one deploying femtocell since 2009) is in strong favor of this scheme (China Femtocell Symposium 2011). There exists another scheme called "shared carriers" where dual services operate on the same spectrum bands, which is discussed in Section VII. The macrocell operator also decides the macrocell price p_M, which is charged to both the femtocell operator and end users who choose macrocell services. Note that we assume the same price is charged to both femtocell operator and users of macrocell services, to avoid arbitrage opportunity. For example, if the macrocell operator charges the femtocell operator more than macrocell users, the femtocell operator can pretend to be macrocell users, request spectrum at the macrocell price, and serve its femtocell users. Such an approach has been studied in Tanneur 2003. If the macrocell operator charges the femtocell operator less than macrocell users, then some other intermediate operator, e.g., mobile virtual network operators, can disguise themselves as femtocell operators and obtain spectrum resource at a lower price than macrocell price, and then provide macrocell service to users to make a profit. This eventually decreases the macrocell operator's market share and profit. Such scenarios have been considered in Dewenter and Haucap 2006.

In Stage II, femtocell operator decides how much bandwidth B_R to lease from the macrocell operator such that $B_R \leq B_F$, and pay $B_R p_M$ to the macrocell operator. It also determines femtocell price p_F to end users choosing the femtocell service. In Stage III, each user decides which service to choose and how much bandwith to purchase for the service. If a user's preferred service is not available (when demand is larger than capacity for that service), the user will seek the other service. Here we focus on a large group of users, where a single user's demand is infinitesimal to the total demand. Thus we can ignore cases in which a user purchases bandwidth from both services.

We will analyze this three-stage dynamic game using backward induction. We refer to the setup as *dual services*. Note that the analysis presented in this paper is based on two simplified assumptions:

- The femtocell service does not incur any additional operational cost compared to the macrocell service.
- The femtocell service has the same coverage as the macrocell service, such that each user has the choice between two services.

We are able to relax both assumptions and generalize our results obtained in this paper. The details can be found in our online technical report Duan et al. 2012.

III. Stage III: Users' Service Choice and Bandwidth Demand

The QoS of a wireless communication session depends not only on the resource allocation but also on the condition of the wireless channel between the transmitter and receiver. The channel condition is determined by both the locations of transmitter and receiver and the surrounding environment. As an example, let us consider uplink transmissions from the users mobile phones to the common single macrocell base station (as in Fig. 1). The channel condition in general decreases with the distance between the user and the base station, and can become very weak if the user is inside a house with thick walls. A user with a bad channel condition will not be able to achieve a high data rate even with a large bandwidth allocation.

Here we model the users' channel heterogeneity by a *macrocell spectrum efficiency* θ, which is assumed to be uniformly distributed in $[0,1]$ (see Fig. 3). The uniform distribution is assumed for analytical tractability. A more complicated distribution based on field measurements will not change the main managerial insights obtained in this paper. A larger θ means a better channel condition and a higher spectrum efficiency *when using the macrocell service*.

For a user with a macrocell spectrum efficiency $\theta < 1$, when allocated macrocell bandwidth b, its effective resource allocation is θb. Its *utility* $u(\theta, b)$ (*e.g.,* data rate) can be modeled as (similar to Sengupta and Chatterjee 2009, Wang and Li 2005)

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

which is concave in b representing the diminishing return in bandwidth consumption. The more bandwidth a user obtains, the higher data rate and better QoS it gets. The user needs to pay a linear payment $p_M b$ to the macrocell operator, where the price p_M is announced by the macrocell operator in Stage I. Note that the usage-based pricing is becoming a main trend in macrocell service market (and replacing flat-fee pricing for data traffics) (Goldstein 2011). The user's *payoff* is the difference between the utility and payment, *i.e.,*

$$r_M(\theta, b, p_M) = \ln(1 + \theta b) - p_M b. \tag{1}$$

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

$$b^*(\theta, p_M) = \begin{cases} 1/p_M - 1/\theta, & \text{if } p_M \le \theta, \\ 0, & \text{if } p_M > \theta. \end{cases} \tag{2}$$

When $p_M \le \theta$, $b^*(\theta, p_M)$ is decreasing in p_M and increasing in θ. When $p_M > \theta$, the user chooses not to start the wireless communication as it is too expensive (by considering its macrocell spectrum efficiency θ). The user's maximum payoff with macrocell service is

$$r_M(\theta, b^*(\theta, p_M), p_M) = \ln\left(\frac{\theta}{p_M}\right) - 1 + \frac{p_M}{\theta} \tag{3}$$

if $p_M \le \theta$ and 0 otherwise. Notice that the payoff is always nonnegative.

Since femtocell base stations are deployed indoors and are very close to users' cell phones, it is reasonable to assume that all users using the femtocell service have equally 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* $r_F(b, p_F)$ when using a bandwidth of b under femtocell service,

$$r_F(b, p_F) = \ln(1 + b) - p_F b. \tag{4}$$

The user's optimal demand in femtocells is

$$b^*(p_F) = \frac{1}{p_F} - 1 \tag{5}$$

if $p_F \le 1$ and 0 otherwise. A user's maximum payoff under the femtocell service is

$$r_F\left(b^*(p_F), p_F\right) = \ln\left(\frac{1}{p_F}\right) - 1 + p_F \tag{6}$$

if $p_F \le 1$, and 0 otherwise. which is always nonnegative. Note that some operators have adopted a flat-fee charging scheme for femtocell services to encourage early user adoptions. In this paper, we focus on analyzing the usage-based pricing for femtocell services in a mature market. It should also be noted that usage-based pricing often leads to a higher profit than the flat-fee charging (Courcoubetis and Weber 2003).

We will show that $p_F > p_M$ at the equilibrium, *i.e.,* the femtocell price p_F in Stage II, is always larger than the macrocell price p_M in Stage I. By comparing the user's payoffs in (3) and (6), it is clear that a user with $\theta = 1$ will always choose macrocell service to maximize his payoff. On the other hand, a user with a small θ would choose femtocell service to improve his payoff. As a result, we define the following thresholds of θ that separate the user population into two service groups.

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' finalized partition threshold θ_{th}): The finalized partition threshold θ_{th} is the minimum macrocell spectrum efficiency among all the users actually served by the macrocell service. Users with $\theta \in [\theta_{th}, 1]$ receive the macrocell service, while users with $\theta \in [0, \theta_{th})$ receive either the femtocell service or no service.

The preferred partition threshold θ_{th}^{pr} only depends on prices p_M and p_F. 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 values of B_F, B_M, and B_R in Stages I and II.

By comparing a user's optimal payoff with macrocell and femtocell services in (3) and (6), we obtain the following result.

Lemma 1: Users' preferred partition threshold $\theta_{th}^{pr} = p_M/p_F$.

Now we introduce the concept of *finalized demand*.

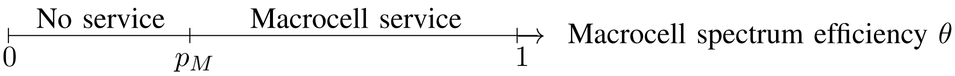

Fig. 3. Distribution of users' macrocell spectrum efficiency θ

Definition 3 (User's Finalized Demand): If a user's demand from his preferred service is satisfied, then his finalized demand equals his preferred demand. If not, the user switches to the alternative service and the new demand becomes the finalized demand.

Note that a user's finalized demand may not be realized, *e.g.,* when the price is set too low and the total finalized demand is larger than the supply.

IV. Stage II: Femtocell Operator's Spectrum Purchase and Pricing

Now we analyze Stage II, where the femtocell operator determines B_R and p_F to maximize its profit. In this stage, the macrocell operator's decisions on p_M and B_F (and $B_M = B - B_F$) are determined and known to the femtocell operator. Let us denote the femtocell operator's equilibrium decisions as $B_R^*(p_M, B_F)$ and $p_F^*(p_M, B_F)$, both of which are functions of p_M and B_F.

To maximize profit, the femtocell operator needs to know which users will choose femtocell service and their characteristics. Users with macrocell spectrum efficiency $\theta \in [0, \theta_{th}^{pr}) = [0, p_M/p_F)$ will choose femtocell service first. Some other users may also choose femtocell service if their demands cannot be satisfied by the macrocell services. The following lemma, however, shows that the macrocell operator will reserve enough bandwidth B_M during Stage I, such that all users who prefer to use macrocell service will be able to do so.

Lemma 2: At the equilibrium of the three-stage dynamic game as in Fig. 2, the macrocell operator satisfies all preferred demands from users with $\theta \in [\theta_{th}^{pr}, 1] = [p_M/p_F, 1]$ in macrocell service.

Lemma 2 is true regardless of the femtocell operator's decision, and thus is true at the equilibrium as well. We can use Lemma 2 to derive femtocell operator's equilibrium decisions in Stage II.

Since femtocell operator only serves users with $\theta \in [0, p_M/p_F)$, its profit is

$$\begin{aligned}&\pi^{Femto}(p_F, B_R)\\ =&p_F \min\left(B_R, \int_0^{\frac{p_M}{p_F}} \left(\frac{1}{p_F} - 1\right) d\theta\right) - p_M B_R\\ =&\min\left((p_F - p_M)B_R, (1-p_F)\frac{p_M}{p_F} - p_M B_R\right). \quad (7)\end{aligned}$$

The femtocell operator's profit-maximization problem is:

$$\begin{aligned}&\max_{p_F \geq 0, B_R \geq 0} \pi^{Femto}(p_F, B_R)\\ &\text{subject to } B_R \leq B_F. \quad (8)\end{aligned}$$

By solving Problem (8), we have the following result.

Lemma 3: In Stage II, the femtocell operator's equilibrium femtocell price is

$$p_F^*(p_M, B_F) = \max\left(\frac{2p_M}{1+p_M}, \frac{-p_M + \sqrt{(p_M)^2 + 4B_F p_M}}{2B_F}\right), \quad (9)$$

and its equilibrium femtocell bandwidth purchase is

$$B_R^*(p_M, B_F) = \min\left(\frac{1-(p_M)^2}{4p_M}, B_F\right), \quad (10)$$

which equals users' total preferred demand in femtocell service. Then users' preferred partition threshold equals equilibrium partition threshold (*i.e.,* $\theta_{th}^{pr} = \theta_{th}$).

Sketch of Proof. We first notice that the first term in the $\min$ operation of $\pi^{Femto}(p_F, B_R)$ in (7) is increasing in both p_F and B_R, while the second term is decreasing in both p_F and B_R. Hence, the equilibrium $p_F^*(p_M, B_F)$ and $B_R^*(p_M, B_F)$ should make these two terms equal (*i.e.,* femtocell operator's capacity equals users' total preferred femtocell demand). Then we can write $B_R^*(p_M, B_F)$ as a function of p_F, *i.e.,*

$$B_R^*(p_F) = \frac{(1-p_F)p_M}{(p_F)^2}, \quad (11)$$

which should be no larger than B_F by a proper choice of p^F. Thus the femtocell operator's profit-maximization problem can be simplified from (8) to maximize $\pi^{Femto}(p_F, B_R^*(p_F))$ such that $B_R^*(p_F) \leq B_F$. Then we can derive the optimal p_F^* and corresponding $B_R^*(p_F^*)$ as in Lemma 3. ∎

Lemma 3 shows that the femtocell operator will also satisfy the users' preferred demands, and it does not want the users to switch to its competitor (*i.e.,* the macrocell operator).

V. Stage I: Macrocell Operator's Spectrum Allocations and Pricing

Now we come back to Stage I, where the macrocell operator determines p_M, B_F, and B_M to maximize its profit. Let us denote the macrocell operator's equilibrium decisions as p_M^*, B_F^*, and B_M^*.

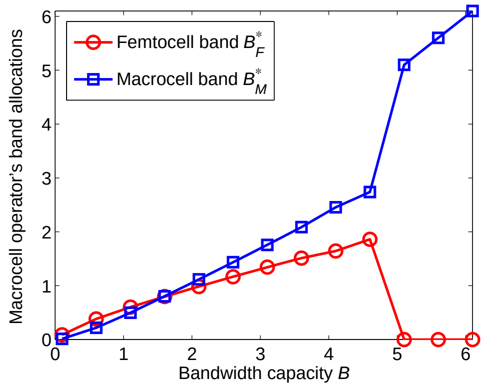

Fig. 4. Equilibrium bands B_F^* and B_M^* as functions of capacity B

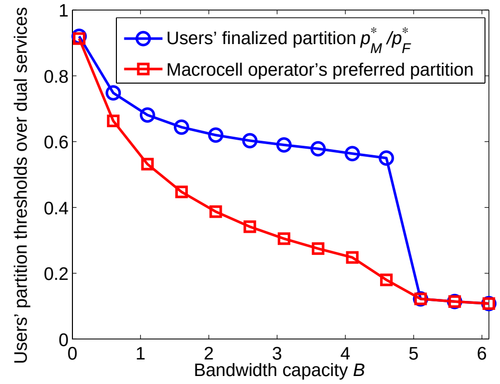

Fig. 5. Users' equilibrium partition threshold $\theta_{th} = \frac{p_M^*}{p_F^*}$ and macrocell operator's preferred $\tilde{\theta}_{th} = \frac{1}{\frac{1}{p_M^*} - \frac{1}{p_F^*} + 1}$ as functions of B

Notice that Lemma 2 shows that it is optimal for the macrocell operator to serve all users with $\theta \in [p_M/p_F^*(p_M, B_F), 1]$ by macrocell service, where $p_F^*(p_M, B_F)$ is the equilibrium femtocell price given in Lemma 3. This means that the macrocell operator does not want users with large macrocell spectrum efficiency θ to choose its competitor (*i.e.,* the femtocell operator). Intuitively, users with a large θ demand more bandwidth in macrocell service than in femtocell service, and thus lead to a larger profit to the macrocell operator if they choose macrocell service.

Since $B_M = B - B_F$, we can write the macrocell operator's profit as a function of p_M and B_F, *i.e.,*

$$\pi^{Macro}(p_M, B_F) = p_M B_R^*(p_M, B_F) + p_M \int_{\frac{p_M}{p_F^*(p_M, B_F)}}^{1} \left(\frac{1}{p_M} - \frac{1}{\theta}\right) d\theta. \tag{12}$$

The macrocell operator's profit-maximization problem is

$$\begin{aligned} \max_{p_M \geq 0, B_F \geq 0} \quad & \pi^{Macro}(p_M, B_F) \\ \text{subject to} \quad & \int_{\frac{p_M}{p_F^*(p_M, B_F)}}^{1} \left(\frac{1}{p_M} - \frac{1}{\theta}\right) d\theta \leq B - B_F, \end{aligned} \tag{13}$$

where $p_F^*(p_M, B_F)$ and $B_R^*(p_M, B_F)$ are given in (9) and (10), respectively. The constraint shows that macrocell band $B_M = B - B_F$ can satisfy users' total preferred macrocell demand.

Problem (13) is not convex and is difficult to solve in closed-form, but can be solved easily using numerical methods. Next we introduce a useful lemma that facilitates our later discussions on numerical results.

The macrocell operator wants to sell its total capacity B at the highest macrocell price p_M. Under a fixed price, the total demand from the users depends on which services they subscribe to. If we can maximize the user demand under any fixed price, then we can achieve the maximum revenue by optimizing the choice of price accordingly.

Recall that a user's demand is $\frac{1}{p_F^*(p_M, B_F)} - 1$ in femtocell service and $\frac{1}{p_M} - \frac{1}{\theta}$ in macrocell service. We have the following lemma.

Lemma 4: The macrocell operator wants users with $\theta \in \left[0, \frac{1}{\frac{1}{p_M} - \frac{1}{p_F^*(p_M, B_F)} + 1}\right)$ to choose femtocell service, and rest of the users with $\theta \in \left[\frac{1}{\frac{1}{p_M} - \frac{1}{p_F^*(p_M, B_F)} + 1}, 1\right]$ to choose macrocell service. That is, it prefers users' partition threshold to be $\tilde{\theta}_{th} = \frac{1}{\frac{1}{p_M} - \frac{1}{p_F^*(p_M, B_F)} + 1}$.

Note that the threshold in Lemma 4 is what the macrocell operator wants to see; however, it may not equal the users' finalized partition threshold $\theta_{th} = \frac{p_M}{p_F^*(p_M, B_F)}$. This is because that the macrocell operator cannot fully control the femtocell operator's decisions. The difference between these two thresholds are due to the market competition between macrocell and femtocell operators.

VI. Numerical Results

Solving Problem (13) numerically, we obtain the macrocell operator's equilibrium femtocell band B_F^*, and macrocell band $B_M^* = B - B_F^*$, and the macrocell price p_M^*. Plugging into (9), we obtain the equilibrium femtocell price p_F^*.

Figure 4 shows the macrocell operator's equilibrium bandwidth allocation. The X axis is total bandwidth capacity B and the Y axis is the macrocell and femtocell bandwidth B_F^* and B_M^*, respectively. It shows that when the total bandwidth capacity B is small, the macrocell operator would lease spectrum to the femtocell operator,

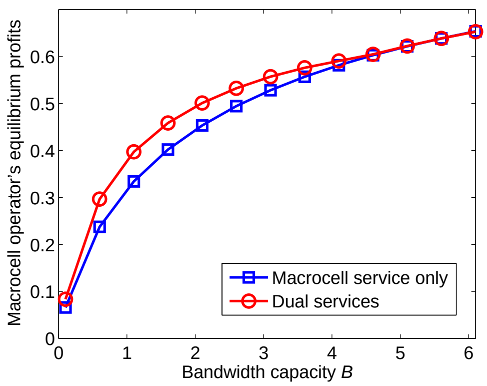

Fig. 6. Macrocell operator's profits in macrocell service only case and current dual service case as functions of capacity B

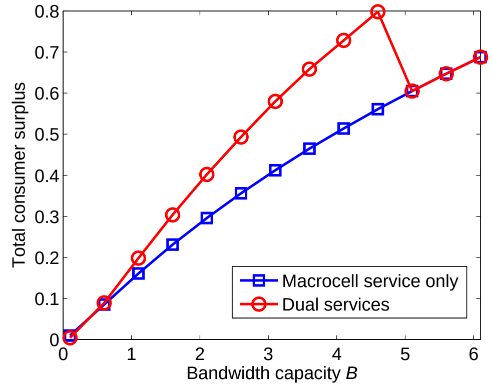

Fig. 7. Comparison of total consumer surplus between dual services and macrocell service only benchmark as functions of B.

so both macrocell and femtocell services are provided to end users; however, when the total bandwidth capacity B becomes large, only macrocell service is provided (i.e, $B_F^* = 0$ and $B_M^* = B$). The intuition behind this is as follows: with large bandwidth capacity, the macrocell operator can already serve most users by macrocell service. The potential benefit of reaching the remaining small portion of customers through facilitating femtocell service can not compensate the potential loss due to new market competition. Hence the macrocell operator has no motive to lease spectrum to femtocell provider. However, with small capacity B, the macrocell service price p_M^* is high, and thus most users with $\theta \in [0, p_M^*)$ would not request macrocell service. By leasing bandwidth to femtocell operator, the macrocell operator can obtain a larger profit from serving more users (indirectly through femtocell operator). It should be noted that the threshold $B = 4.77$ (between small and large total capacities) is a normalized value, as we have normalized users' population to be 1 in the analysis.

Figure 5 shows users' finalized partition threshold $\theta_{th} = \frac{p_M^*}{p_F^*}$, and compares with the threshold $\tilde{\theta}_{th} = \frac{1}{\frac{1}{p_M^*} - \frac{1}{p_F^*} + 1}$ that macrocell operator prefers. It shows that the gap increases in the total capacity B. This means that femtocell operator attracts more original macrocell users to femtocell service, and competition becomes more intense as B increases.

By summarizing the results in Figs. 4 to 5, we have the following observation.

Observation 1: When the macrocell operator's total capacity B is small, it will lease spectrum to the femtocell operator and thus increase the total users served by both operators. When B is large, the macrocell operator will not lease any spectrum to the femtocell operator to avoid the additional market competition.

Today's macrocell operators have "small" capacities in big cities, in the sense that their capacities are not enough to satisfy users' fast growing wireless data demand. For example, we can witness poor performance of AT&T's macrocell service in New York City and San Francisco due to the lack of spectrum resource (LaVallee 2009, WNN Wi-Fi Net News 2008). Thus macrocell operators have strong incentives to lease spectrum to femtocell operators in big cities (e.g., Sprint to Virgin Mobile USA and Vodafone to BT Mobile) to serve more users. However, in many other places with smaller user densities, femtocell services haven't been deployed yet.

Next we investigate how the introduction of femtocell service affects the macrocell operator's profit, consumer surplus (*i.e.,* users' aggregate payoff), and the social welfare (*i.e.,* summation of the profits of both operators and the payoffs of all users). In each figure, we compare the dual services with the benchmark case where only macrocell service is provided (Duan et al. 2011). Our discussions focus on the dual-service region.

Figure 6 shows the profits of the macrocell operator when both services are provided vs. when only macrocell service is provided, both of which are increasing in capacity B. The provision of femtocell service can substantially increase the macrocell operator's profit, especially when B is small.

Figure 7 shows that the total consumer surplus increases with the deployment of femtocell service. This is mainly because users with low spectrum efficiency (small values of θ) will be able to obtain high quality service by using femtocell. We can also observe that the consumer surplus is larger with the smaller capacity $B = 3.6$ than $B = 5.6$, and we have the following observation.

Observation 2: As a whole, users always benefit from the introduction of femtocell service. With a higher total system capacity, the total consumer surplus may decrease as the macrocell operator chooses not to provide resource to the femtocell operator.

Observation 2 indicates that the telecommunication regulator should advocate femtocell service by encouraging or forcing the macrocell operator to lease spectrum to femtocell operator even when the total system capacity is large. Furthermore, the femtocell operator should seek other flexible ways in obtaining spectrum resource (e.g., from other macrocell operators or through the approach of cognitive radios (Duan et al. 2011b)).

VII. Conclusion

This paper studies the economic incentives for a macrocell operator to deploy new femtocell service in addition to its existing macrocell service. The femtocell service is provided by another party, the femtocell operator, who needs to lease the macrocell operator's capacity. We model the interactions among macrocell operator, femtocell operator, and users as a three-stage dynamic game, and derive the equilibrium capacity allocation and pricing decisions. We show that the macrocell operator has an incentive to enable both macrocell and femtocell services when its total bandwidth is small. Notice that not all users will experience a payoff increase by the introduction of femtocell service in this case. However, when the total bandwidth is large, femtocell service becomes a severe competitor to macrocell service. In this case, only macrocell service is provided to users.

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