Open or Close: On the Sharing of Femtocells

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***Abstract*— The femtocell is an enabling technology to handle exponentially increasing wireless data traffic. Despite extensive attentions paid to resource control, e.g., power control and load balancing in femtocell networks, the success largely depends on whether operators and users accept this technology or not. In this paper, we study the economic aspects of femtocell services with game theoretic models between providers and/or users. We consider three services: users can access only macro BSs (mobile-only), or open/exclusively use their femto BS (open or closed-femto). The main messages include: 1) it is better off for the operator to provide just the open-femto service than a mix of closed and open-femto services; 2) two polices of allowing or blocking the access of mobile-only users to open femto BS are not significantly differentiated in the revenue.**

I. Introduction

The demand for wireless data traffic is dramatically growing and the monthly demand has been forecasted to be 7GB per user or 5.4 times more than today's consumption by 2014 [1], [2]. This unprecedented growth, due to introduction of smart mobile devices and diverse multimedia applications, throws both challenges and opportunities to technical and business communities.

To cope with the growing demand, many capacity enhancement solutions have been proposed. They include the system-wide upgrade to the 4G infrastructure, e.g., LTE and WiMax mainly by adopting enhanced physical layer technologies [3]. Some are proposing an ad-hoc solution such as offloading to WiFi [4], [5]. Others are considering femtocell as a cheap way of achieving high spectral efficiency [6], which is the focus of this paper.

The femtocell technology, utilizing a very small cell and the residential broadband backhaul, is attractive as it can achieve high spectral efficiency at a viable cost. Many researchers have worked on femtocells [7]–[13]. For example, the papers [11], [12] considered interference management through fancy power control algorithms or intelligent BS (Base Station) association for load balancing. However, most of them are technical ones and limited attentions have been paid to its economic or business aspects, which is yet another important area for the success of femtocell technology.

Recently, Shetty and Walrand [14] studied the impacts of user incentives on the revenue of a femtocell operator[1], which inspired our work. In this paper, we study an important, yet under-explored issue in a wider setup: *openness of femtocells*. Since femtocells are typically installed at personal indoor environments, one can expect that utilization is relatively low only with the femto owners' traffic. Then, it may be economically beneficial to the users, providers, or the regulator to allow "guest" users to utilize the femto BSs that are open. However, it is far from clear how beneficial the open femtocell service is, depending on what factors.

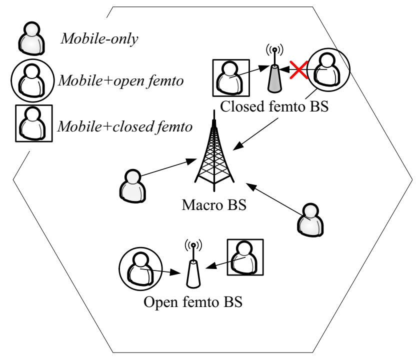

Fig. 1. Femtocell services: *mobile-only*, *mobile+open femto*, and *mobile+closed femto*

As illustrated in Fig. 1, we consider three services on BS access, *mobile-only*, *mobile+open femto*, and *mobile+closed femto*[2]. The provider can offer one of two open-femto polices: *open-to-all* and *open-to-femto*. As the names imply, *mobile-only* corresponds to the users subscribing to only 3G services with macro BSs. Users of *mobile+open femto* and *mobile+closed femto* subscribe to the service allowing access to macro BSs as well as femtocells. Users of *mobile+closed femto* exclusively use their femto BSs. Users of *mobile-only* can access open femto cells in *open-to-all* policy, but not in *open-to-femto* policy.

In this paper, we focus on the monopoly case, where we propose an analytical model based on a sequential game between the operator and users. Two tariffs are studied in our paper: *flat* and *partial volume pricing*. By partial volume pricing we mean that volume pricing is applied only to macro BSs mainly due to difficulty of per-data operation in femto BSs. The major metrics are users' *surplus*, operator's *revenue*, and *social welfare*. In this game model, a single operator leads the market and fully controls the market price to maximize its own revenue. Users just follow the operator's price control and select the service maximizing the utilities.

The main messages of this paper are summarized as follows:

M1) It is beneficial to both providers and users to have open femto BSs rather than closed ones. No users select the closed-femto services and enough subsidy is given to users.

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[1]We use 'operator' and 'provider' interchangeably throughout this paper.

[2]We simply use *open-femto* and *closed-femto* to refer to *mobile+open femto* and *mobile+closed femto*, respectively.

TABLE I

SUMMARY OF MAJOR NOTATION (EXTERNAL PARAMETERS AND SYSTEM VARIABLES ARE SEPARATED)

External Parameter	*Description*
N	Number of users per one macro BS
$\gamma, \bar{\gamma}, \theta$	user type, max. of user type, price sensitivity
β	fraction of a femto BS's coverage
δ_o	probability that a user is outside
C_M, C_F	capacities of macro and femto BSs
c_f	maintenance cost of a femto BS
q_o	fraction of coverage of all open femto BSs
U_j, Φ_j	expected utility and service fee of service type j
$\boldsymbol{\alpha} = (\alpha_m, \alpha_o, \alpha_c)$	user subscription ratios
R, S, W	revenue, user surplus, social welfare

M2) The differences to users and the provider are not significant whether or not the provider limits the access of femto BSs to *mobile-only* users.

II. SYSTEM MODEL

Consider a wireless network consisting of macro and femto BSs, where N users/macro-cell are served by a monopoly operator. We assume a simple model on BSs that macro and femto BSs provide the fixed capacities C_M and C_F, respectively. Users are always guaranteed to be under the coverage of a macro BS, but not of a femto BS. We also assume that femtocell equipments are identical and the coverage size of a femto BS is the β fraction of that of a macro BS. We do not consider the hand-over effect for the users. We adopt this simple model to purely focus on the economic aspects of the system and to enable tractable analysis.

1. Monopoly Operator and Services

As mentioned in Section I, the operator provides three services: (a) *mobile-only*, (b) *mobile+open femto*, and (c) *mobile+closed femto*, and two femto open policies: *open-to-all* and *open-to-femto*. We use $\{m, o, c\}$ to indicate the service types.

The operator charges $\phi_j^k(x)$ for generating traffic rate x in the BS type k. The index k in the charging function is intended for showing the dependence of charging on the serving BS type. We consider two types of tariffs: *flat pricing* and *partial volume pricing*. We use $\{M, O, C\}$ to index to macro, open-femto, and closed-femto BS.

In flat pricing, users' payments are constant regardless of data usage, i.e., for any BS type $k \in \{M, O, C\}$,

$$\phi_j^k(x) = p_j, \ \ j \in \{m, o, c\},$$

p_j is a constant charge for service $j \in \{m, o, c\}$.

In partial volume pricing, users pay p_v^M per the unit data rate when they are served by macro BSs, whereas they pay a fixed service fee p_m, p_o, p_c for using femto BSs. This hybrid setup is motivated by the practical reasons that low-cost femto BSs may not be appropriately equipped with complex per-data operation. In other words, for all $j \in \{m, o, c\}$

$$\begin{aligned} \phi_j^M(x) &= p_v^M x + p_j, \\ \phi_j^k(x) &= p_j, \ k \in \{O, C\}, \end{aligned}$$

2. Users

We assume an iso-elastic[3] utility function $u(x;\gamma)$ for traffic x or

$$u(x;\gamma) = \gamma x^{\theta},$$

where γ is a user type value, which is assumed to be uniformly distributed over the interval $[0, \bar{\gamma}]$, and price-sensitivity $\theta \in [0, 1]$. As $\theta \to 1$ the utility function becomes linear, while it approaches a step function as $\theta \to 0$.

As the service rates are not the same for macro, open and closed femto BSs, we introduce *expected* utility and service fee functions U_j and Φ_j of service type j as follows:

$$\begin{aligned} U_j(\boldsymbol{x};\gamma) &= \mathbb{E}\Big[u(x^k;\gamma)\Big] = \gamma \sum_{k \in \{M,O,C\}} (x^k)^{\theta} \pi_j^k, \\ \Phi_j(\boldsymbol{x}) &= \mathbb{E}\Big[\phi^k(x^k)\Big] = \sum_{k \in \{M,O,C\}} \phi_j^k(x^k) \pi_j^k, \end{aligned}$$

where π_j^k is the fraction of time or probability that users of the service type j use a type k BS to get a service.

The net-utility $\tilde{U}_j$ of service type j is then

$$\tilde{U}_j(\boldsymbol{x};\gamma) = U_j(\boldsymbol{x};\gamma) - \Phi_j(\boldsymbol{x}), \ \ j \in \{m, o, c\}.$$

Users move and connect to the different types of BSs over time. Users achieve different data rates, which also depends on the service type. Under our system model, when there are n *open-femto* users, the fraction of area q_o covered by the open femto BSs is given by:

$$q_o \triangleq 1 - (1-\beta)^n. \tag{1}$$

Users' average mobility statistics are assumed to be equal. Denote by δ_i the probability of being "inside," where let $\delta_o = 1 - \delta_i$. To users with femto services, δ_i corresponds to the fraction of time that they are under their own femto BS's coverage. The *mobile-only* users rely on macro BSs even when they are inside due to absence of their own femto BSs. We ignore the possibility that the *mobile-only* users utilize the neighboring femto BSs when they are inside for simplicity. When users are outside, they can access either a macro or an open-femto BS. They access an open-femto BS with probability q_o or a macro BS with probability $1 - q_o$.

Table II shows $(\pi_j^k : j \in \{m, o, c\}, k \in \{M, O, C\}$ under different open policies. Under *open-to-femto* policy, *mobile-only* users cannot access open femto BSs and access only macro BSs, as shown in the first line. The *open-femto* users access open femto BSs with probability $\delta_o q_o + \delta_i$ and macro BSs with probability $\delta_o(1 - q_o)$. The *closed-femto* user case is shown in a similar manner. Under *open-to-all policy*, even *mobile-only* users can access the open femto BSs.

3. Operators and Regulator

According to the user type γ and charging schemes, a user selects a service type and decides on the data demand. Let $\boldsymbol{\alpha} = (\alpha_j : j \in \{m, o, c\})$ be the vector of user fractions subscribing to each service type j. Denote by $j(\gamma)$ and $\boldsymbol{x}(\gamma)$ the service type and traffic rate vector of the user type γ,

[3]An utility function U(x) is said to be *iso-elastic* if for all $k > 0$, $U(kx) = f(k)U(x) + g(k)$ for some functions $f(k), g(k) > 0$.

TABLE II
PROBABILITY π_j^k FOR OPEN-TO-FEMTO AND OPEN-TO-ALL POLICIES

	Open-to-femto			*Open-to-all*		
	M	O	C	M	O	C
m	1	0	0	$\delta_o(1-q_o)+\delta_i$	$\delta_o q_o$	0
o	$\delta_o(1-q_o)$	$\delta_o q_o+\delta_i$	0	$\delta_o(1-q_o)$	$\delta_o q_o+\delta_i$	0
c	$\delta_o(1-q_o)$	$\delta_o q_o$	δ_i	$\delta_o(1-q_o)$	$\delta_o q_o$	δ_i

respectively. Then, the operator's revenue, the social welfare, and the user surplus are computed as

$$R = \int \Phi_{j(\gamma)}(\boldsymbol{x}(\gamma))Nd\gamma - (\alpha_o+\alpha_c)Nc_f, \quad (2)$$

$$W = \int U_{j(\gamma)}(\boldsymbol{x}(\gamma);\gamma)Nd\gamma - (\alpha_o+\alpha_c)Nc_f, \quad (3)$$

$$S = \int \tilde{U}_{j(\gamma)}(\boldsymbol{x}(\gamma);\gamma)Nd\gamma = W - R, \quad (4)$$

where c_f is the cost of a femto BS for the service provider.

III. GAME MODEL

1. Flat Pricing Game

We first consider a two-stage sequential game between the operator and users under the flat pricing scheme. We assume that both operator and users are selfish and try to maximize individual (expected) utility.

In the first stage, the operator decides on the price vector $\boldsymbol{p} = (p_j : j \in \{m,o,c\})$ to maximize the revenue R by solving the following problem:

$$\textbf{Provider}: \quad \max_{p_m,p_o,p_c \geq 0} R. \quad (5)$$

In the flat pricing scheme, the revenue in (2) is simplified as

$$R = N\Big(\sum_j p_j\alpha_j - c_f\cdot(\alpha_o+\alpha_c)\Big). \quad (6)$$

In the second stage, a user of type γ selects the service $j^*(\gamma)$ that maximizes his net-utility:

$$\textbf{User}: \quad j^*(\gamma) = \arg\max_{j\in\{m,o,c\}} \tilde{U}_j(\boldsymbol{x};\gamma), \quad (7)$$

when his maximum net-utility is *positive.* Otherwise, he does not select any service.

We assume that the users are saturated and have sufficient data to transmit whenever possible. The (average) amount of generated data by each user depends on its service type, the capacities C_M, C_F, and the scheduling discipline of BSs for competitive users. In particular, we simply assume that a BS serves its served users, so that the service rates are equal across the served users. Under this fairness assumption, the average service rate of a user served by macro BSs is inversely proportional to the number of users in a macro BSs, given by:

$$x^M = C_M/(1+\sum_{j\in\{m,o,c\}} \pi_j^M\alpha_j N), \quad (8)$$

where the denominator in (8) corresponds to the total number of users in a macro BS while a user is in the macro BS's service. Similarly, the service rates for users with open and closed femto BSs are given by:

$$x^O = C_F/(1+\sum_{j\in\{m,o,c\}} \pi_j^O\alpha_j N/\alpha_o N), \quad (9)$$

$$x^C = C_F, \quad (10)$$

where note that $\pi_j^O\alpha_j N/\alpha_o N$ is the average number of users visiting an open femtocell.

2. Partial Volume Pricing Game

We also consider a two-stage sequential game for the partial volume pricing. The game is slightly different from the flat pricing game in that the provider should decide on the volume-based price, p_v^M, when a user is served by a macro BS, and a user should also decide on the elastic data demand x^M. We only consider the case of $p_m = 0$ and the *open-to-femto* policy for the following reason: First, if $p_m > 0$, from the perspective of the provider (i.e., price controller) the partial volume pricing becomes similar to the flat pricing, because in that case the provider takes small p_v^M and large p_m to maximize the revenue. Second, when $p_m = 0$, in *open-to-all* policy, the *mobile-only* user can use a free *open-femto* service in which case the provider's revenue is significantly reduced due to free-riding.

Now, the game is described. In the first stage, the provider selects the optimal prices that maximize the following problem:

$$\textbf{Provider}: \quad \begin{array}{ll} \max_{p_v^M,p_o,p_c} & R \\ s.t & p_v^M, p_o, p_c \geq 0, \end{array} \quad (11)$$

In the second stage, a user with type γ first determines the data demand at macro BSs $x^M(\gamma)$ by maximizing the corresponding surplus subject to the macro BS capacity constraint.

$$\textbf{User}: \quad \begin{array}{l} x^M(\gamma) = \arg\max_x \gamma x^\theta - p_v^M x, \\ j^*(\gamma) = \arg\max_{j\in\{m,o,c\}} \tilde{U}_j(\boldsymbol{x};\gamma), \end{array} \quad (12)$$

subject to

$$T^M \triangleq N\int \pi_{j(\gamma)}^M x^M(\gamma)d\gamma \leq C_M$$

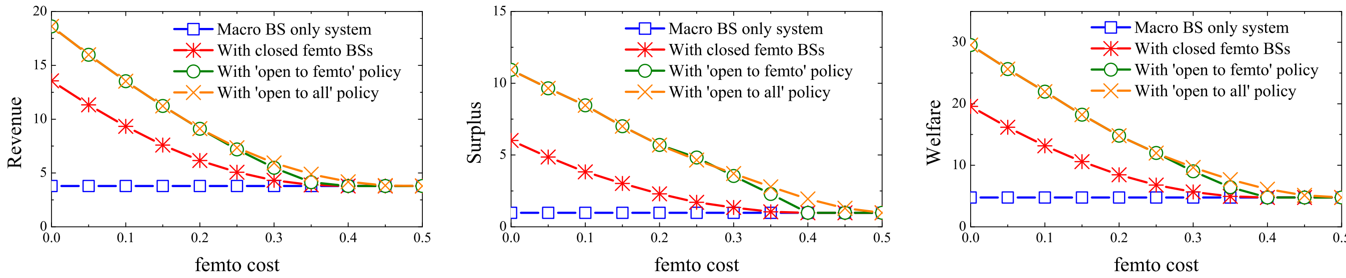
where T^M denotes the total macro BS traffic generated by users. Note that unlike flat pricing where some users exits from the market and subscribe none of the services, every user selects one of the services in partial volume pricing. The revenue of the operator simply reads:

$$R = T^M p_v^M + N\{(p_o-c_f)\alpha_o + (p_c-c_f)\alpha_c\}.$$

IV. NUMERICAL RESULTS

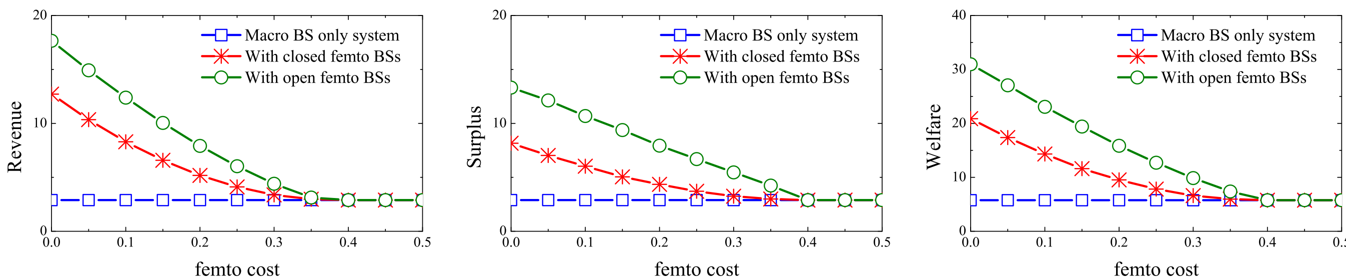
1. Setup

In most of our numerical results, we plot the provider's revenue, user surplus, social welfare and user subscription ratio for different values of femto costs and pricing schemes. The other parameters are summarized in Table III. We varied and tested different values, where we observed similar trends to those in this section.



(a) Revenue (b) User surplus (c) Social welfare

Fig. 2. Flat pricing: value-add of the femto services



(a) Revenue (b) User surplus (c) Social welfare

Fig. 3. Partial volume pricing: value-add of the femto services

TABLE III
DEFAULT PARAMETER VALUES IN NUMERICAL RESULTS

Parameters	Value
N (# of users/cell)	100
C_M (macro capacity)	1
C_F (femto capacity)	2
$\bar{\gamma}$ (max. user type)	1
δ_o (prob. of being outside)	0.7
β (femto's relative coverage)	0.01
θ (price sensitivity)	0.5 (default)

We consider a cellular network with 100 users/cell. The C_M and C_F are set to be 1 and 2. Note that the actual numbers of C_M and C_F are not critical, because revenue, user surplus, and social welfare just scale with those numbers and our main interest lies in investigating the metrics' relative ratios and changes. The ratio of C_M to C_F does not seem unrealistic, considering the reality in 3G network and also users' average distance to macro and femto BSs. The probability of users' being outside is 0.7. This value assumes that except for when users are inactive inside (e.g., sleeping at home), they are outside for 70% of their active time. The value β, femto BS's coverage (normalized by that of a macro BS) is set by 0.01, which is $1/N = 1/100$. For instance, this value is obtained for macro and femto cells with radius 500m and 50m, respectively.

2. *Value-add of Open-Femto Service*

Figs. 2 and 3 show the impact of *open-femto* services on the revenue, user surplus and social welfare. We compare three different cases: *1)* no femto, *2)* only with closed-femto BSs, and *3)* with closed and open femto BSs. We first observe that revenue, user surplus, and social welfare increase with introduction of *closed-femto* services for both pricing schemes, as also reported in [14]. Our focus is more on the impact of *open-femto* services, and we verify that the value-add further increases by enabling users to sharing femto BSs. This is because more open femtocells generally increase the total system capacity, formally called *positive externality* in economics. However, the value-add becomes limited for high femto costs due to reduction of users' subscription to the *open-femto* service. In our environments, for the femto costs higher than 0.5, no value-add is observed. To see that the cost 0.5 is very expensive in practice, refer to the equilibrium price 0.13 that users pay in the system with only macrocells in Fig. 5 (when femto cost is 0.6), i.e., about 4 times larger than the price of the macro-only service.

3. *User Selection and Subsidy*

Fig. 4 shows the subscription ratios for two open-femto policies in flat pricing. We observe that no users subscribe to the *closed-femto* service for all tested femto costs. This is explained by the following: The operator usually persuades users into subscribing to the *open-femto* service by providing sufficient subsidy measured by $(p_c - p_o)/p_c$. In our numerical results, the subsidy ranges from 16% to 20%, as shown in Fig. 5. Despite sufficient subsidy, the operator can sustain high revenue, because more *open-femto* users lead other femto users to increase their utilities and thus high price is acceptable to users. The fact that no *closed-femto* users exist is expected to highly simplify the business decision process of the provider.

The provider also wants to have a simple metric to decide

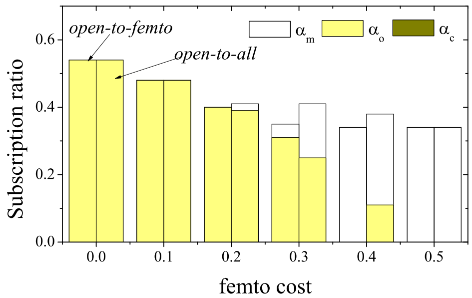


Fig. 4. Users' subscription ratios in flat pricing

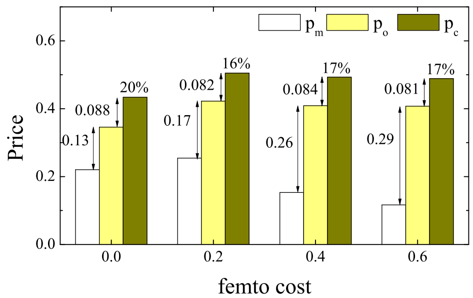


Fig. 5. Prices in open-to-all policy in flat pricing. The percentages on top of the bar graphs represent the subsidy, calculated by $\frac{p_c - p_o}{p_c}$.

on the femto services. One of the possible metrics is "per-user revenue," $(p_o - p_m) - c_f$. However, interestingly the provider may still start the open-femto business despite $(p_o - p_m) < c_f$, which means that the provider should pay more money for installing and maintaining a femtocell than the raised price due to introduction of femtocells. This is illustrated in Fig. 5 for the femto cost > 0.2 and *open-to-all* policy. The reason is again due to positive externality of open femto BSs. Under the regime where we have a non-negligible portion of *mobile-only* users, the provider can increase the price p_m and thus increase the revenue from the *mobile-only* users.

4. Open-to-all vs. Open-to-femto Policies

We now study the impact of two open-femto policies. The key message here is that two policies are not differentiated in practical situations. Recall that comparison study of this subsection is made only for the flat pricing, as only *open-to-femto* policy becomes practical in the partial volume pricing (see Section III-2). In Fig. 2, we observe that the plots for two polices are very close over almost all tested femto costs, where a small economic gain is observed in the *open-to-all* policy over the cost range [0.3, 0.45]. Under this range, *mobile-only* and *open-femto* users can coexist, as illustrated in Fig. 4, so that the system goes into the regime that *mobile-only* users have impact on the economic aspects of the system.

V. Concluding Remarks

In this paper, we developed an analytical framework to study the business and economic aspects of the femtocell services based on a game theoretic model. Under the developed model we drew the following conclusions:

1) It is better off for operators to provide only *open-femto* services than a mix of open and closed femto services.
2) When *open-femto* services are offered, blocking the access of mobile-only users to femto BSs does not significantly impact revenue, user surplus and social welfare.

The aforementioned conclusions are limited by assumptions, some of which include the following:

1) The user type γ is assumed to be uniformly distributed.
2) The iso-elastic utility may not be true in practice, and all users have the equivalent price-sensitivity θ in our model.
3) There is no service differentiation between femtocell owners and guests in open femtocells. In the practical services, users are willing to open their femtocells, yet they may want to be served with high priority, which is an interesting future work.

Moreover, since we only consider monopoly market, we should consider duopoly or oligopoly markets in future works.

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