Can Dynamic Pricing Make Femto Users and Service Providers Happy?

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***Abstract*—Femtocell is a promising technology that will improve wireless resources efficiency through frequency spatial reuse however, its integration with the current cellular systems has been considered a fundamental challenge. In this study, we propose a mechanism by which the femto and macro capacity resources are jointly priced according to a dynamic pricing-based call admission mechanism. We study the performance of the proposed mechanism through a queuing theory approach. Several performance metrics such as the service provider's revenue, call blocking and call deferral probabilities are determined, and the scheme is compared to a regular call admission control serving as a benchmark. The results show how much a joint dynamic pricing scheme can satisfy service providers in terms of increased revenue and congestion control, while keeping users satisfied in terms of their perceived quality of service. The proposed solution can be considered as a new charging model for a two-tier macro-femto network.**

***Index Terms*—Femtocell, Dynamic pricing, Call admission control.**

I. Introduction

Small cells, such as *femtocells*, are considered as one of the the revolutionized technologies that will steer the data traffic explosion problem in dense congested cellular networks. They are low-power, low-cost and short-range solutions that can be conveniently deployed by the users for indoor applications, and they can effectively increase the spectral efficiency through frequency spatial reuse techniques [1]. The technological details of state of the art femtocells and their advantages were addressed in different projects such as [2], [3]. Therefore, in this work, we only consider an *economic-based* approach, rather than a technological approach, to improve the admission mechanism in a two-tier femto-macro network.

As authors discussed in [4], one fundamental challenge for this technology is how to integrate femto into the current macrocells such that both users and wireless service providers (WSPs) benefit from this integrated coexistence. In other words, if we consider profit and communication Quality of Service (QoS) as two satisfaction metrics for WSPs and users, respectively, we will show how these two technologies together can or if they do make both parties satisfied. Other than technological benefits, we note that service charges are crucial elements which may strongly impact WSPs' and users' decisions. High service charges for femto services may disappoint the users while a low service price may simply make the whole integrated system unprofitable for WSPs, and thus offering no motivation for them to incorporate femtocells as part of their network. Restrictive femto usage policies, such as closed-femto, where the access will be limited to certain users, will be a WSPs' way of optimizing their profits, even though it has been proven that open-femto can be highly beneficial for both parties in terms of spectrum efficiency and QoS improvement [5].

Four charging models were proposed for femto in [6]. First, *one-off charging* model that the users pay a flat rate fee to buy their femto base station (femto-BS) as well as their monthly subscription fee. Second, *no charge* model by which the femto-BS is provided by the WSPs for no additional charge, but for a term contract. Third, *decreased monthly charging* model which allows the users to enjoy a certain discount in their monthly bills if they adopt a free femto-BS provided by the WSPs and finally, the forth, *increased monthly charging* model by which the WSPs provide a free femto-BS while they slightly increase the users' monthly bills to cover the costs associated with the technology. The authors in [6] conclude that the femto business models are not mature yet and the economic impact of this technology is still an open issue. To the best of our knowledge, [4] is the only work which tackles the issue of optimal pricing in femtocells. In that study, the authors proposed an economic framework for a two-tier femto-macro system which targets revenue maximization as well as increasing user satisfaction in terms of QoS and pricing. Their framework jointly considers pricing and spectrum allocation strategies to determine the optimal *flat rate* price as well as the optimal spectrum allocations.

As an alternative approach, *dynamic* pricing can be also considered as a potential solution to the aforementioned challenge. The idea of dynamic pricing has recently emerged from the *call admission control* (CAC) schemes in wireless networks as an effective and dual purpose solution for network's congestion problems as well as WSPs' revenue improvement [7]. In this technique, the service price is dynamically determined according to some system parameters such as network load,

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channel quality, or the user priority at the time of admission. Briefly, the idea is to increase the call price when the network is congested. The higher is the announced price, the lower will be the user's willingness to place a call thus, excessive network usage can be controlled.

To assess a dynamic pricing mechanism, determination of two components are essential. First, *price function* which determines how network resources should be dynamically priced. Second, *willingness* (or demand) *function* which models the users' reaction to the instantaneous price. Reference [8] surveys the studies which consider a dynamic pricing approach for CAC in *homogenous* networks as well as their proposed demand and pricing functions.

In this study, we propose an incorporation of a *joint* dynamic pricing mechanism into admission control of a *two-tier* macro-femto network. We model the pricing as well as the users' reaction to an applicable price. The performance of the proposed model is studied through a queuing theory approach which enables us to determine several performance metrics such as WSPs' generated revenues, call blocking and call deferral probabilities in the admission level. The results show how much a joint dynamic pricing mechanism can satisfy WSPs in terms of revenue increase and congestion control while keeping users satisfied in terms of service price and QoS. The proposed solution then, can be considered as the fifth charging model added to the list which was discussed earlier.

The rest of the paper is organized as follows: Section II presents the system model and parameters used in the analysis, Section III describes the proposed dynamic pricing mechanism and Section IV tackles the performance modeling of the system. Numerical and simulation results are presented in Section V and we conclude the paper in Section VI.

II. System Model

We consider a monopolist WSP which provides its services through a two-tier network consisting of one macrocell and ℓ identical femtocells. An example of this scenario has been shown in Fig. 1 for $\ell = 3$. The radius of macrocell and femtocells are denoted by R and r meters, respectively, and the corresponding areas covered by femto and non-femto radios are given by A_f and A_m square meters. The users' arrival to the areas covered by femto and non-femto radio are modeled with Poisson processes with parameters λ_m and λ_f per square meters, respectively. Intuitively, we assume that $\lambda_f > \lambda_m$ since femtocells are hot spots. Thus, we set

$$\lambda_f = \lambda_m + \lambda_\delta, \tag{1}$$

where λ_δ denotes the extra call arrival rate in the femtocells. A split spectrum allocation scheme is employed by which a proportion of a total spectrum resource C is dedicated for femtocell operation [9]. It is assumed that the macrocell and femtocells operate on different bands and interference is negligible. Thus, if we denote the spectrum resources dedicated for the macro and femto as C_m and C_f, respectively,

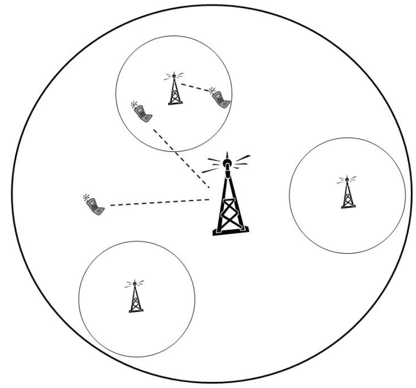

Fig. 1. An example of a two-tier network consisting of one macrocell and $\ell = 3$ identical femtocells.

we have

$$C = C_f + C_m, \tag{2}$$

We assume non-overlapping femtocells, with negligible interference among the ℓ cells, so that ℓC_f determines total capacity resources available for all femtocells. We assume single-class services where a user of femto or macro consumes a fixed amount of spectrum resource b_w and that the service duration is exponentially distributed with parameter μ for both systems. It is assumed that the femto technology is always open to the users which are within the femto-BS coverage. Thus, they have the option to connect to either technology based on the admission policy explained in the next section. The numbers of users served by femto and macro base stations are denoted by n_f and n_m, respectively. Along the paper, dependency on time is dropped for simplicity reasons.

III. Dynamic Pricing Mechanism

As mentioned before, pricing-based CAC is considered as an economic-based approach to deal with network congestion. With this scheme, WSPs may affect the user's behavior to optimally use the network resources while maximizing their generated revenue. In this study, without loss of generality, we adopt the willingness function of semantic work [10] which has been widely used in the related studies in non-heterogeneous networks. According to that study, "willingness" is defined as the percentage of the arriving users who accept an applicable service charge at time t, and it is modeled as the exponential function $w_x(t) = e^{-(\frac{p_x(t)}{p_0}-1)^2}$ where p_0 is a minimum service price. Thus, the applicable charge at time t may be written as $p_x(t) = p_0(1 + \sqrt{-\ln w_x(t)})$. Adopting this price function and denoting the femto and macro users' willingness by w_f and w_m, respectively, we can express the femto and macro dynamic price functions as

$$p_f = p_{f_0}(1 + \sqrt{-\ln w_f}), \tag{3}$$

and

$$p_m = p_{m_0}(1 + \sqrt{-\ln w_m}), \tag{4}$$

respectively, where p_{f_0} and p_{m_0} are defined as the minimum service prices at which the femto and macro users initiate their services with willingness probability of one. Please note that this is the first time that the willingness function is used for a heterogeneous network since the legacy willingness functions may not be necessarily applicable to a heterogeneous environment where the users have multiple communication options. On the other hand, an accurate willingness function should be obtained from real statistics of user behavior which to the best of the authors knowledge, it does not exist even for homogenous networks. Further, the general conclusions of this work are independent of the employed willingness modeling. We also assume that the femto minimum service price is set as a fraction of macro minimum service price, i.e.,

$$p_{f_0} = \alpha p_{m_0}, \tag{5}$$

where α is defined as the femto minimum service price coefficient.

Next, we present the networks' utilities. In terms of economics, the utility is defined as the users' level of satisfaction with the perceived quality of service or goods. In the literature, several utility functions have been suggested to study the dynamic pricing approaches in telecommunication networks [8]. For example, the authors in [10] propose a utility function which is a decreasing exponential function of new call and handoff call blocking probabilities in a homogeneous network. Thus, higher blocking probabilities indicate a lower user utility and thus lower user satisfaction with the provided service. In this study, we propose the following utility functions for the femto and macro services:

$$u_f = 1 - \left(\frac{n_f b_w}{\ell C_f}\right)^\beta, \quad u_m = 1 - \left(\frac{n_m b_w}{C_m}\right)^\beta, \tag{6}$$

which represent the user's utility as a decreasing function of the percentage of the occupied resources for each service. According to (6), a user may receive a higher utility in the network with more free capacity resources. Fig. 2 plots macro utility u_m as a function of the number of its users. From general settings given in Table I, it is assumed that macro-BS has 90 capacity resources and that each user is using 1 resource for its call. As observed in this figure, the proposed utility function is taking a value of one whenever less than 80% of macro-BS capacity resources are occupied. However, when the network congestion goes beyond this value, the utility is decreasing with a sharp slope. We note that a higher utility indicates a more satisfied user and consequently a higher willingness for him to pay for or join to that network. Thus, we may interpret the proposed utility functions as the user willingness in association with each technology, i.e.,

$$u_f = w_f, \quad u_m = w_m. \tag{7}$$

Equations (3), (4), (6) and (7) provide us a framework to jointly and dynamically price the two-tier femto-macro network's resources. As a result, we propose the following joint CAC mechanism:

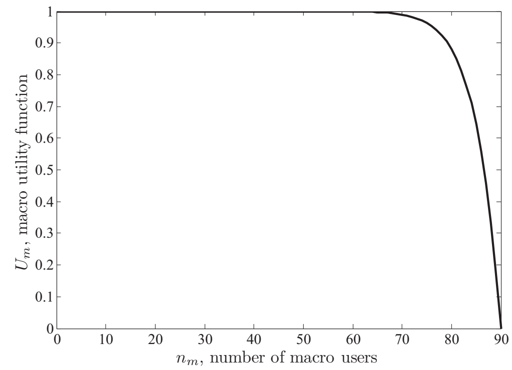

Fig. 2. Macrocell utility function, u_m, as a function of the number of macro users, n_m.

- *Area covered solely by macro-BS*: when a user makes a call request in this area, the macro network determines the user utility u_m and announces the applicable macro service charge p_m to that user. The user may decide to join to the network according to the willingness probability w_m.
- *Areas covered by femto and macro BSs*: users arriving to these areas will send a request to both systems. Thus, each system determines its own utility from above equations and announces its applicable charge to that user. Consequently, the user will select the service with the lower offered price and may join it with the corresponding willingness probability.

Finally, the applicable charge is assumed to be constant for the duration of a call even if the network utility changes since this is considered as a general requirement in all call admission control mechanisms.

IV. Performance Modeling

In this section, we model the performance of the proposed price-based joint CAC through a queuing theory approach. Let (n_f, n_m) denote the state of the system. Depending on the service price of femto system, we have the following observations regarding the state transition rates:

- *Case 1 When the femto service is cheaper than macro service*: in this case, arriving users in femto-covered areas are willing to join femtocells. Thus, the transition rates out of state (n_f, n_m), i.e. $(n_f, n_m) \rightarrow (n_f + 1, n_m)$ and $(n_f, n_m) \rightarrow (n_f, n_m + 1)$ are given by $\lambda_f A_f w_f$ and $\lambda_m A_m w_m$, respectively.
- *Case 2 When the femto service is more expensive than macro service*: In this case, arriving users in femto-covered areas are willing to join macrocell. Thus, the aforementioned transition rates out of state (n_f, n_m) are given by $\lambda_f A_f w_m$ and $\lambda_m A_m w_m$, respectively. We note that no femto service is requested in this case.

In both cases, the transition rates into state (n_f, n_m), i.e. $(n_f + 1, n_m) \rightarrow (n_f, n_m)$ and $(n_f, n_m + 1) \rightarrow (n_f, n_m)$ are given by μ.

Next, let $P(n_f, n_m)$ denotes the joint probability distribution function of the system state at the steady state. The system described above can be modeled with a 2D Markov process [11] with the state space

$$S = \{\forall n_f, n_m | n_f b_w < \ell C_f, n_m b_w < C_m\}. \tag{8}$$

Finding a straightforward solution for the system of global balance equations with the given rates above is not an easy task, mainly because of the complexity and conditional dependencies of the arrival rates on random variables n_f and n_m which were set through equations (3), (4), (6) and (7). Furthermore, the state dimension is expected to be quite large. Thus, we proceed with an alternative solution as an approximation. We note that when $p_f < p_m$, the system can be modeled with a 2D $m/m/\infty$ queue with the arrival rates $\lambda_f A_f w_f$ and $\lambda_m A_m w_m$, and departure rate μ as described in case 1 above. On the other hand, when $p_f > p_m$, the 2D queue of the system can be simplified to a single $m/m/\infty$ queue with a total arrival rate of $(\lambda_f A_f + \lambda_m A_m)w_m$, and a departure rate of 2μ (case 2). As a result, we propose the following solution:

$$\begin{aligned} P(n_f, n_m) &= p_{00}\left[U(p_m - p_f)\frac{{\rho_1}^{n_f}{\rho_2}^{n_m}}{n_f! n_m!}\right. \\ &+ \left. U(p_f - p_m)\frac{{\rho_3}^{n_f+n_m}}{(n_f+n_m)!}\right], (n_f, n_m) \in S \end{aligned} \tag{9}$$

where in the above

$$\rho_1 = \frac{\lambda_f A_f w_f}{\mu}, \quad \rho_2 = \frac{\lambda_m A_m w_m}{\mu}, \tag{10}$$

$$\rho_3 = \frac{(\lambda_f A_f + \lambda_m A_m) w_m}{2\mu}, \tag{11}$$

and p_{00} is a normalization coefficient which can be found by normalizing (9) for all $(n_f, n_s) \in S$. Finally, $U(.)$ denotes a step function and the values of p_m and p_f for each system state (n_f, n_m) can be found through the equations (3), (4), (6) and (7). We have noticed that the proposed solution (9) satisfies the global balance equations of the system with errors less than 0.5%.

Next, we determine the probability that a call originating in femto or macro cells are blocked. Call blocking probability is an important QoS indicator for service users and it can be found by determining the percentage of the arrivals which are not admitted to each system as a result of congestion. Denoting this probability as q_{b_f} and q_{b_m} for femto and macro systems, respectively, q_{b_m} can be found as

$$q_{b_m} = \frac{\sum\limits_{(n_f,n_m)\in\tilde{S}} \lambda_m^* P(n_f, n_m)}{\sum\limits_{(n_f,n_m)\in S} \lambda_m^* P(n_f, n_m)}, \tag{12}$$

where $\tilde{S}$ is a subset of S such that for each n_f in S, the n_m takes its maximum value, i.e.,

$$\tilde{S} = \{\forall (n_f, n_m) \in S | P(n_f, n_m) \neq 0 | P(n_f, n_m + 1) = 0\}, \tag{13}$$

and λ_m^* denotes the actual arrival rate to the macro queue, i.e.,

$$f(z) = \begin{cases} \lambda_m A_m w_m & \text{for} \quad p_f < p_m \\ (\lambda_f A_f + \lambda_m A_m) w_m & \text{for} \quad p_f > p_m \end{cases} \tag{14}$$

Similarly, q_{b_f} can be found as

$$q_{b_f} = \frac{\sum\limits_{(n_f,n_m)\in\tilde{S}_1} \lambda_f A_f w_m P(n_f, n_m)}{\sum\limits_{(n_f,n_m)\in S_1} \lambda_f A_f w_m P(n_f, n_m)}, \tag{15}$$

where S_1 is a subset of S such that the femto queue has arrivals, i.e.,

$$S_1 = \{\forall (n_f, n_m) \in S | p_f < p_m\}, \tag{16}$$

and $\tilde{S_1}$ is a subset of S_1 such that for each n_m in S_1, the n_f takes its maximum value, i.e.,

$$\tilde{S_1} = \{\forall (n_f, n_m) \in S_1 | P(n_f, n_m) \neq 0 | P(n_f + 1, n_m) = 0\}. \tag{17}$$

Next, we formulate the collected revenue within a time frame Δt as a satisfaction metric for WSP. This can be estimated by the average number of the users admitted in each system multiplied by the applicable service price within Δt assuming that the system is in steady state. Denote this metric as Rev_f and Rev_m for femto and macro systems, respectively, they can be found as

$$Rev_f = \bar{n}_f p_f \Delta t, \quad Rev_m = \bar{n}_m p_m \Delta t, \tag{18}$$

where

$$\bar{n}_f = \sum_{(n_f,n_m)\in S} n_f P(n_f, n_m), \quad \bar{n}_m = \sum_{(n_f,n_m)\in S} n_m P(n_f, n_m), \tag{19}$$

and the total revenue denoted by Rev is given by

$$Rev = Rev_f + Rev_m. \tag{20}$$

V. Analytical and Simulation Results

In this section, we provide some numerical results to analyze the performance of the proposed dynamic pricing mechanism. An event-driven simulation has been developed using MATLAB to confirm the accuracy of the analysis. We consider a macrocell with normalized radius size and three femtocells. The systems' parameters are listed in Table I.

A conventional joint CAC mechanism, without a dynamic pricing scheme, is also employed (for comparison reasons) which is referred to as the flat rate scenario in the results. The flat rate macrocell service price is set to 1 unit of money. Finally, we consider a traffic profile that the macro user arrival rate, λ_m, is linearly increasing from 0 to 1 calls/sec/m^2 within a time frame $T = 10$ hours.

Fig. 3 presents the average number of admitted calls in femto and macro systems, n_f and n_m, as functions of macrocell call arrival rate, λ_m for dynamic and flat rate pricing schemes. Note that from equation (1), $\lambda_f = \lambda_m + \lambda_\delta$. As observed, the network has almost the same number of admissions for both schemes before approaching the congestion point which is approximately at $\lambda_m = 0.25$ calls/sec/m^2;

TABLE I
PARAMETER SETTINGS

Parameter	Description	Value
C	Total capacity resources	100
C_m	Dedicated capacity resources for Macro-BS	90
ℓ	Number of femtocells	3
R	Macrocell radius	1 m
r	Femtocell radius	0.2 m
$1/\mu$	Average call duration time	100 Sec
bw	Dedicated capacity resources for each call	1
β	Utility functions' exponent	18
λ_δ	Extra call arrival rate in femtocells	$0.5\lambda_m$
p_{m_0}	Macro minimum service price	1 unit of money
α	Femto minimum service price coefficient	0.8

however, after this point the dynamic pricing scheme effectively controls the network congestion by imposing a higher service price thereby discouraging users from placing their calls. As mentioned before, the results highly depend on the utility and price functions given by equations (3), (4) and (6). The dynamic pricing functions were plotted in Fig. 4 for both femto and macro networks as functions of macro call arrival rate. As observed, the CAC mechanism increases the applicable price of each service as soon as the corresponding network approaches the congestion point. There is also a good match between the analytical and simulation results which confirms the accuracy of the presented analysis. We note that the proposed dynamic pricing mechanism may be deployed solely in macro or femto systems depending on WSP needs. For example, a WSP may employ it only for its macrocells to divert extra loads to some flat rate femtocells when the macrocells are congested.

In Fig. 3, we also observe that the congestion control as a result of dynamic pricing has led to some capacity resource under-utilization. For example, at $\lambda_m = 0.7$, the admitted users in femto and macro were dropped by 10% compared to when the flat rate pricing is in effect. We observed that this gap can be controlled by the exponents of the utility functions, β in (6); however, in general, an optimization problem should be defined since reduction of this gap will increase the blocking probabilities. This has been set as a future work.

On the other hand, Fig. 5 plots the probabilities that the arriving calls to femto and macro systems are blocked as a result of congestion, q_{b_m} and q_{b_m}. Again, the results are plotted as functions of macrocell arrival rate, λ_m for dynamic pricing and flat rate schemes. Call blocking probability is considered as a key metric to assess user satisfaction. As illustrated, the proposed scheme has reduced the blocking probabilities to zero even for highly congested scenarios. This achievement is a result of some users ending their calls when they observe a high service fee. Thus, we may define a new metric as the probability that a user defers his call as a result of pricing. Denote this probability as q_d for the two-tier network, it can be found as the following. The average number of arriving calls to the macrocell queue when flat rate pricing is in effect can be estimated as $n_m^t(flat) = n_m(flat)/(1 - q_{b_m}(flat))$. Similarly, the total number of arriving calls to the macrocell queue when dynamic pricing is in effect will be $n_m^t(dynamic) = n_m(dynamic)$ since q_{b_m} was observed as zero in Fig. 5. Thus, $n_{m_d} = n_m^t(flat) - n_m^t(dynamic)$ gives us the average number of users who defer their calls in macrocell as a result of dynamic pricing. Similarly, the average number of users who defer their calls in femtocells as a result of dynamic pricing, n_{f_d} can be found from a similar expression. Thus, the ratio of total deferred calls $n_{m_d} + n_{f_d}$ to the total number of arrivals determines q_d. Fig. 6 plots this probability, as well as the total WSP revenue for the time T, as a function of femto minimum service price coefficient, α (note that $p_{f_0} = \alpha p_{m_0}$). As observed, the WSP generated revenue increases when femto minimum service price increases, however, the probability that arriving users defer their call increases as well. Since call deferrals can be considered as a user satisfaction metric in a dynamic pricing scheme, this result is helpful for WSPs to select a trade-off between their femto service price with respect to their macro service price (α) and their users satisfaction (q_d).

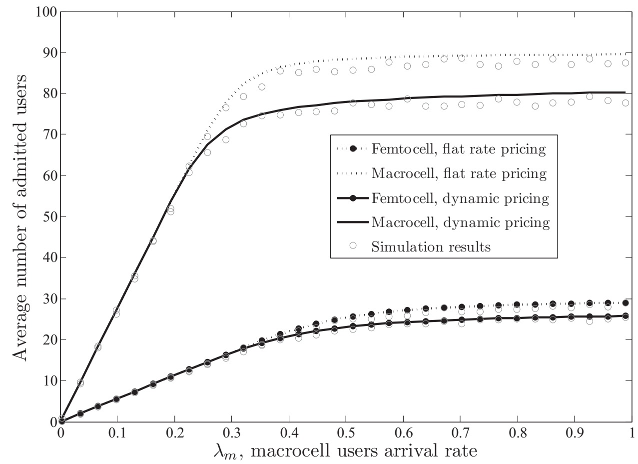

Fig. 3. Average number of admitted calls in femto and macro systems, n_f and n_m, as a function of macrocell call arrival rate, λ_m for dynamic and flat rate pricing schemes.

Finally, we note that in the presented analysis, we did not consider the effect of deferred call retrials since in reality, it is assumed that a user who defers his call retries in a short time. Thus, the amount of time that a user may defer his call can be considered as another QoS metric which needs considerable attention. From the incentive engineering point of view, a potential solution to motivate the femto or macro users to defer their calls during congestion periods could be proposing a cheaper price for the deferred calls. We note that this makes the presented analysis more complex. As future work, we are interested in studying such an incentive-based two-tier network.

VI. Conclusion

We have proposed a new joint call admission mechanism for a two-tier femto-macro network in which their resources

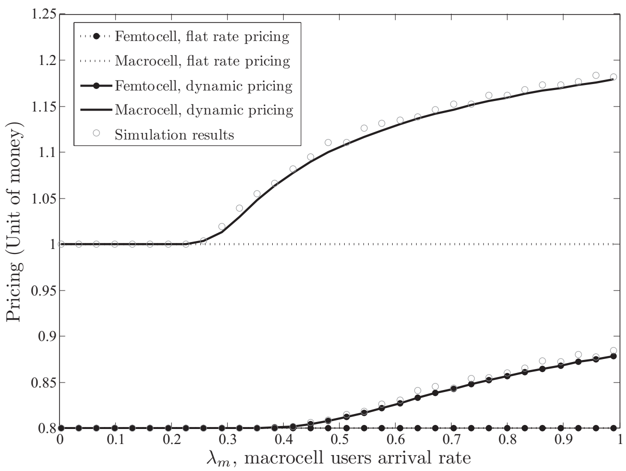

Fig. 4. Femto and macro resources pricing, p_f and p_m, as functions of macrocell arrival rate, λ_m.

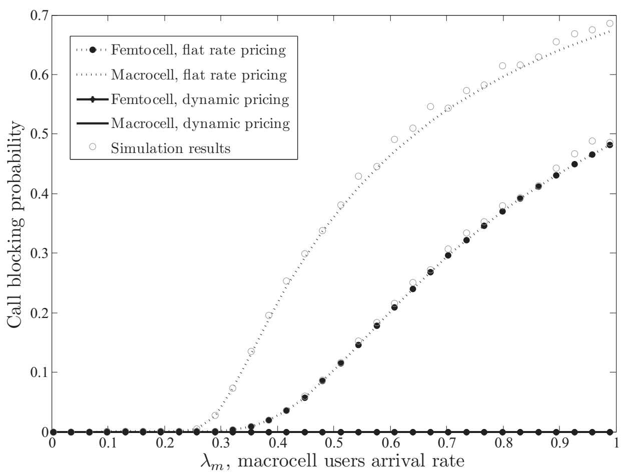

Fig. 5. The probabilities that the arriving calls to femto and macro systems are blocked as a result of congestion, q_{b_m} and q_{b_m} as functions of macrocell arrival rate, λ_m for dynamic pricing and flat rate schemes.

are dynamically priced according to their loads. It was shown that dynamic pricing can effectively control the congestion problem; however it increases the user tendency to defer calls as a result of high congestion pricing. On the other hand, it provides a dynamic framework for the WSPs to control or set trade-offs for the main satisfaction metrics such as their generated revenue and the expected number of call deferrals. Dynamic pricing is an economic-based approach to deal with network congestion and it is relatively a new converging area especially for heterogeneous networks which warrants further attention.

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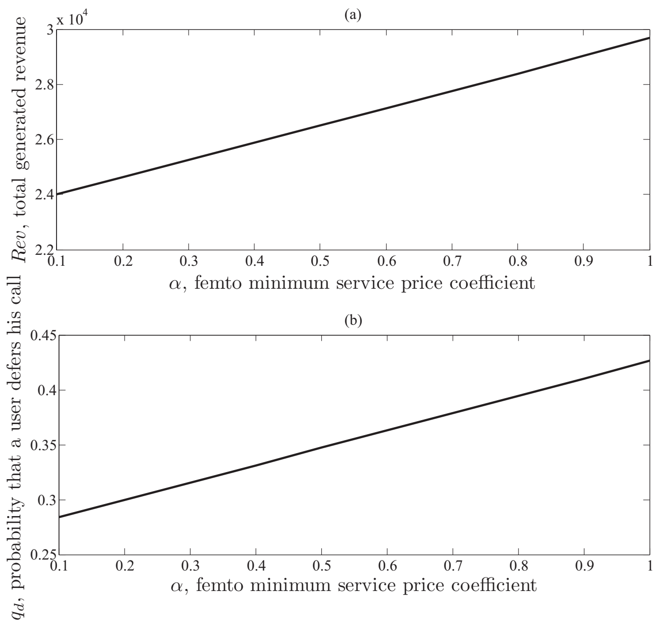

Fig. 6. WSP's and users' satisfaction metrics as functions of femto minimum service price coefficient, α, a) total generated revenue, Rev, b) probability that a user defers his call, q_d.

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