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Promoting femtocell cooperation through incentive for improving data rate of indoor users in underlay heterogeneous network

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Abstract: This study proposes an incentive-based femtocell cooperation scheme for indoor macrocell users (MUs) in an underlay two-tier heterogeneous network which helps the indoor MUs to achieve higher data rate through time sharing access from the femtocell. Due to underlay spectrum sharing nature of the femtocell, the network suffers from severe cross-tier interference. To manage this cross-tier interference, a price-based power control scheme is also proposed for the femtocell access point (FAP) whereby the macrocell base station (MBS) controls the transmit power of the FAP by pricing their resulted cross-tier interference power level subject to a maximum tolerable interference limit. A Stackelberg game has been formulated and analysed for joint pricing-based power control and incentive-based cooperation game. Numerical results show the performance of the proposed scheme in terms of achievable rate of indoor users and utilities of both the MBS and the FAP for different locations of the femtocells.

1 Introduction

Recent studies have suggested that more than 50% of all voice calls and 70% of data traffic originates from indoors [1]. Due to wall penetration loss inside buildings it becomes very difficult for the macrocell to serve those massive indoor users with high service demands. As an efficient solution the application of so called femtocell access points (FAPs) in indoors have been considered [1, 2]. Femtocells are small-coverage, low cost and low power wireless network system deployed by the users inside a building to provide good coverage and improved data rate. Femtocells are usually connected to the broadband network through optical fibre or digital subscriber line or separate radio-frequency backhaul link while on the air interface they use standard cellular technology (e.g. global system for mobile communication (GSM), universal mobile telecommunications system (UMTS), worldwide interoperability for microwave access (WiMAX), long term evolution (LTE) etc.) [3].

The main problem that arises during the deployment of femtocells is the interference between the macrocell and femtocells which is known as the cross-tier interference. On the other hand, the mutual interference among different femtocells is termed as co-tier interference. Chen *et al.* [4] proposes two frequency partitioning methods to mitigate the interference between the macrocell and femtocells. A dynamic cross-tier interference coordination scheme is proposed in [5]. Park *et al.* [6] proposes a beamforming codebook restriction strategy to reduce the cross-tier interference and improve the aggregate throughput of two-tier femtocell networks. The work in [7] proposes a scheme for both co-tier and cross-tier interference mitigation in two-tier networks through cognitive radio techniques. A fractional frequency reuse-based interference mitigation technique is introduced in [8] while Deb *et al.* [9] has proposed algorithms for enhanced inter-cell interference coordination in LTE heterogeneous networks. In [10], the authors have suggested an interference avoidance strategy for two-tier femtocell network in code division multiple access (CDMA)-based system. Many other techniques have been proposed in the literature in order to manage the interference issues in femtocell networks such as using power control [11, 12], resource allocation [13, 14], using multiple antennas [15–18] and so on. Along with interference mitigation by power control our work mainly deals with the cooperation of femtocells with macrocell to increase the data rate of indoor macrocell users (MUs). Some notable research works on femtocell–macrocell cooperation can be found in the literature. The work in [19] proposes a framework for macrocell–femtocell cooperation under a closed access policy. The femtocell user acts as a relay for MUs. In return, the MU grants the femtocell user a fraction of its superframe. A novel cognitive WiMAX architecture with femtocells, in which the base station and users being equipped with cognitive radios so as to intelligently adjust power, channel and other resources has been proposed in [20]. It exploits the locally available spectrum opportunities within one hop to perform communication by taking the advantage of the location dependent characteristics of WiMAX femtocells. The work in [21] proposes a cooperation framework for LTE femtocells' efficient integration in order to reduce the intercell interference between the macrocell and the femtocells as well as to improve the signal-to-interference-plus-noise ratio (SINR) of MUs located in the vicinity of femtocells. The work in [22] applies the idea of interference alignment where the cooperation between MUs with the closest femtocell base stations is used to align the received signals of MUs in the same subspace at multiple femto-base stations simultaneously. The paper [23] considers a cognitive radio model for femtocell network in which a femtocell user acting as a secondary user can cooperatively transmit with the MU in order to improve the effective data rate of the MU.

Femtocells are the unlicensed users and in order to operate they need to share the spectrum of the primary macrocell in a cognitive way. Here we consider underlay spectrum sharing [24] between the macrocell and femtocells which means that the femtocells are reusing the licensed spectrum of the macrocell simultaneously. This gives rise to cross-tier interference. The co-tier interference problem can be eliminated by using a graph colouring-based frequency allocation technique [25] so that no two mutually interfering femtocells are assigned the same frequency. Therefore, we confine our attention to a particular femtocell within a macrocell. We consider that both the macrocell and the femtocell are using orthogonal frequency division multiple access (OFDMA) technology. In an OFDMA system, total available bandwidth is divided into orthogonal subcarriers which are then grouped into sub-channels. The femtocell is assumed to share a particular sub-channel in the uplink band of the macrocell as in underlay spectrum sharing. The reason for sharing the uplink band of the macrocell instead of the downlink band is because the interference is generated at the macrocell base station (MBS) during uplink and it is easier to control the interference at MBS which is fixed at a particular location and equipped with better sensitive devices that can decode the signal even in presence of high interference. In this work, the whole analysis is carried out considering that the femtocell is operating in downlink mode; the analysis is similar for femtocell in uplink mode also.

In a femtocell-based heterogeneous network, three main access control policies for femtocells have been defined [26]: closed, open and hybrid. In the closed access policy, femtocell users (FUs) constitute a closed subscribers group and are only allowed to access the femtocell. In the open access policy, MUs can also access the femtocell and in hybrid access policy, MUs can access the femtocell but only under some particular circumstances. Here in this work the femtocell is assumed to be operating in hybrid access mode. As in underlay spectrum sharing the concurrent transmission of FAP would cause cross-tier interference at the MBS. The MBS allows a little interference from FAP but charges a price for it. So, the selection of proper transmission power is necessary for the FAP which not only will maintain a good SINR but also creates as little interference to the MBS as possible. It must also be ensured that the interference from FAP to MBS does not exceed a predefined threshold decided a priori by the MBS. In addition, the MBS offers some incentives to FAP if it can cooperate and provides downlink service to any indoor MU, which may happen to come inside that femtocell coverage. The FAP can provide downlink access to the indoor MU by taking out some fraction of its own service time through some scheduling scheme. Basically it is a time sharing scheme in which in each slot interval, τ fraction is allocated to the indoor MU and the remaining $(1-\tau)$ fraction of time is reserved for a FU. On the basis of the incentive value, the FAP has to decide the time fraction τ as well as the power it would transmit to the indoor MU. It is to be noted that the uplink frequency of this indoor MU should be different from the downlink frequency of the FAP; otherwise there would be severe interference to the corresponding FU. The FAP sub-channel allocation algorithm is assumed to take care of that which we will not be discussing here. A Stackelberg game has been formulated to jointly maximise the utilities of MBS and FAP. The utilities are defined in Section 3. Game theory is very useful in situations where two or more selfish users want to increase their individual payoffs in which the decision of one user can significantly affect the other users. In our scheme, the MBS and the FAP are the selfish players who want to increase their own utilities. A solution needs to be found out for such systems where one user cannot change its decision unilaterally to get better payoff and the system will then be in equilibrium.

A few similar works [27–31] on power allocation and cooperation in heterogeneous network may be found in literature but have significant differences from our work. Zhang *et al.* [27] uses non-cooperative game to allocate the power and sub-channel in the uplink of femtocells. The uplink femto-to-macro interference is alleviated by charging each femto-user a price proportional to the interference that it causes to the macrocell. Our work does not consider the sub-channel allocation issue assuming proper sub-channel allocation beforehand, instead focuses on the femtocell cooperation. In paper [28], the authors have solved the uplink power allocation problem in densely deployed femtocells where the main problem is femto-to-femto co-tier interference which is managed by a differenced pricing-based power allocation game. Our work instead focuses on the femto-to-macro cross-tier interference rather than the femto-to-femto co-tier interference. In [29], also a pricing-based resource allocation scheme is proposed for downlink multi-cell OFDMA networks. The coordination among multiple cells is used to mitigate inter-cell interference. Contrary to our work they do not employ game theory to allocate the power but adopt an iterative water-filling algorithm to solve the problem based on the Karush–Kuhn–Tucker conditions. A distributed power control scheme has been proposed in [30] for the uplink transmission of spectrum-sharing femtocell networks based on fictitious game. Unlike their work our scheme does not employ any iterative approach. The game is solved by directly finding the best response of each player. In [31] also, a joint uplink sub-channel and power allocation problem is studied in cognitive small cell network, but they have employed a cooperative Nash bargaining game instead of Stackelberg-based game. In our scheme, apart from transmit power control the femtocell also cooperates with the macrocell to help any indoor MU to increase its data rate in exchange of some incentives.

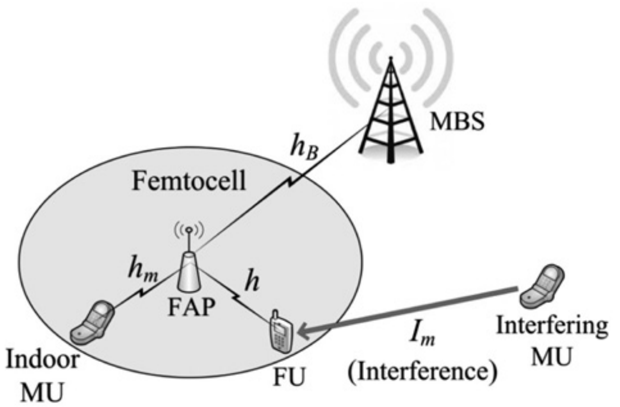

Fig. 1 *System model consisting of a femtocell inside a macrocell containing a FU and an indoor MU*

The main contributions of this paper are summarised as follows:

(i) A price-based power control scheme is proposed for the FAP in an underlay macro–femto heterogeneous network, whereby the MBS controls the transmit power of the FAP by pricing their resulted interference power levels at the MBS subject to a maximum tolerable interference margin.
(ii) An incentive mechanism is also proposed which encourages the FAP to help any indoor MU to increase its throughput through time sharing access from FAP. This mechanism works jointly along with the pricing-based power control scheme. The pricing-based power control part is partially adapted from our previous work [13]. However, the incentive-based femtocell cooperation jointly with power control is entirely a new approach.

The rest of this paper is organised as follows. First the system model of the underlay femtocell containing an FU and an indoor MU is introduced in Section 2. In Section 3, a Stackelberg-based power control and cooperation game among FAP and MBS is formulated. Analysis and solution of the game is given in Section 4. Numerical results are shown in Section 5. Finally, Section 6 concludes the paper.

2 System model

The system model consists of a single femtocell residing within a macrocell as shown in Fig. 1. The femtocell is sharing the uplink frequency band of the macrocell using underlay spectrum sharing technique and it is assumed that there is no co-tier interference from other femtocells. We focus our attention on a single sub-channel in the uplink band of the macrocell. At a particular time instant only one MU can operate in that sub-channel. Let us assume that the given femtocell is also operating in downlink using the same sub-channel when serving to a particular FU. We did not consider other FUs associated with that femtocell because those FUs are assumed to be operating on other sub-channels. The achievable rate of the FU is given by the following equation

$$R_{\mathrm{FU}} = \log_2\left(1 + \frac{hp}{I_{\mathrm{m}} + N_0}\right) \tag{1}$$

By achievable rate we mean the Shannon capacity measured per unit bandwidth. Here h is the channel power gain from FAP to FU, I_{m} is the interference coming from an active outdoor MU operating in the same sub-channel in uplink, p is the transmission power of FAP and N_0 is the additive white Gaussian noise power in the sub-channel

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which is assumed to be constant all over the macrocell area. If h_B is the channel power gain from the FAP to the MBS then the cross-tier interference caused by the FAP to the MBS is $h_B p$ which must meet the condition $h_B p \le I_{\rm th}$, where $I_{\rm th}$ is the tolerable interference threshold at the MBS.

If the FAP takes out τ fraction of time from servicing the given FU and provide downlink service to any indoor MU (with different uplink frequency) within its coverage then the achievable rate of the indoor MU is given by the following equation

$$R_{\rm MU} = \tau \log_2\left(1 + \frac{h_{\rm m} p_{\rm m}}{N_0}\right) \quad (2)$$

where $h_{\rm m}$ is the channel power gain from FAP to indoor MU and $p_{\rm m}$ is the transmission power of FAP for indoor MU. For the time indoor MU is being served by the FAP, the FU remains inactive. So, the achievable rate of the FU, i.e. $R_{\rm FU}$ will be changed to $(1-\tau)\log_2\big(1 + (hp/(I_{\rm m} + N_0))\big)$. We assume that the FAP is equipped with software defined radio technology which enables it to easily shift its operating frequency from its own transmission frequency to the indoor MU's frequency for this τ fraction of time and the same sub-channel is locked at the MBS from using it on any other MU.

3 Formulation of joint power control and cooperation game

The price-based power control and incentive-based cooperation of the FAP can be modelled as a Stackelberg game among the MBS and FAP to jointly maximise both of their utilities. Here the MBS acts as a leader of the game which first takes the decision on the interference price and the incentive value. Then, knowing those decisions, the FAP, which acts as a follower, figures out its transmission power strategies and the fraction of time it will help to the indoor MU. Let c be the interference price, i.e. the price per unit amount of interference created at the MBS and $c_{\rm m}$ be the incentive value which is the price the MBS offers to the FAP per unit achievable data rate the indoor MU would get from FAP cooperation. The utilities of the MBS and FAP are formulated below.

MBS: The utility of the MBS is defined as

$$U_M = ch_B p(1-\tau) - c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) + \beta\left(\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - R_{\rm m}\right) \quad (3)$$

The first term $ch_B p(1-\tau)$ is the average revenue earned from the FAP due to the interference created at the MBS. The second term $c_{\rm m}\tau\log_2\big(1 + (h_{\rm m}p_{\rm m}/N_0)\big)$ with a negative sign is due to the incentive it has to provide to the FAP to encourage it to cooperate and provide downlink service to the indoor MU. The third term $\beta\big(\tau\log_2\big(1 + (h_{\rm m}p_{\rm m}/N_0)\big) - R_{\rm m}\big)$ is a satisfaction measure due to the higher achievable data rate it gets from the FAP cooperation. Here $R_{\rm m}$ is the achievable data rate of the indoor MU obtained from MBS without FAP cooperation which is assumed to be constant over the entire femtocell since the femtocell coverage is very small compared with the macrocell area. The constant β is the monetary equivalent of unit amount of increased achievable data rate. Without FAP cooperation the MBS utility will be $U_M = ch_B p$. The MBS has to choose proper values of c and $c_{\rm m}$ to maximise its utility with the constraint that the utility of the MBS after FAP cooperation is higher than or at least equal to the utility it would obtain without FAP cooperation otherwise there would be no meaning for the MBS to provide incentive to the FAP for cooperation. The optimisation problem for the MBS then can be written as

$$\max_{c,c_{\rm m}} U_M = ch_B p(1-\tau) - c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) + \beta\left(\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - R_{\rm m}\right) \quad (4a)$$

$$\text{s.t.} \quad ch_B p(1-\tau) - c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) + \beta\left(\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - R_{\rm m}\right) \ge ch_B p \quad (4b)$$

$$\text{and} \quad c, c_{\rm m} \ge 0 \quad (4c)$$

FAP: The FAP acts as a follower in the Stackelberg game. The utility of the FAP is defined as

$$U_F = \mu(1-\tau)\log_2\left(1 + \frac{hp}{I_{\rm m} + N_0}\right) - ch_B p(1-\tau) + c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - kp_{\rm m}\tau \quad (5)$$

The first term $\mu(1-\tau)\log_2\big(1 + (hp/(I_{\rm m} + N_0))\big)$ is due to the achievable rate of the FU where μ is the monetary equivalent of the unit achievable rate. The second term $ch_B p(1-\tau)$ with a minus sign is due to the price it has to pay to the MBS for creating interference. The third term $c_{\rm m}\tau\log_2\big(1 + (h_{\rm m}p_{\rm m}/N_0)\big)$ is the incentive it gets from the MBS for providing access to the indoor MU for τ fraction of time. Finally the last term is the energy cost due to the power it has to transmit to the indoor MU. This energy cost is proportional to $p_{\rm m}$ and τ; the proportionality constant being k which is the monetary equivalent of the unit energy cost. The utility of the FAP without cooperation is obtained by simply putting $\tau = 0$ in (5). The FAP has to maximise its utility with respect to p, $p_{\rm m}$ and τ with the constraint that the transmit power cannot exceed the maximum value $p_{\max}$ for both p and $p_{\rm m}$. Also, the utility of the FAP with cooperation must be greater than or equal to the utility without cooperation and the achievable rate of the FU must not drop below a threshold value $R_{\rm th}$ during cooperation. Therefore, the optimisation problem for the FAP can be written as

$$\max_{p,p_{\rm m},\tau} U_F = \mu(1-\tau)\log_2\left(1 + \frac{hp}{I_{\rm m} + N_0}\right) - ch_B p(1-\tau) + c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - kp_{\rm m}\tau \quad (6a)$$

$$\text{s.t.} \; (1-\tau)\log_2\left(1 + \frac{hp}{I_{\rm m} + N_0}\right) \ge R_{\rm th} \quad (6b)$$

(see (6c))

$$0 \le p, \quad p_{\rm m} \le p_{\max} \quad (6d)$$

$$\textit{and} \quad 0 \le \tau \le 1 \quad (6e)$$

4 Analysis of joint power control and cooperation game

On the basis of the utilities defined above, we will analyse the game in this section to obtain the Nash equilibrium solution [32]. In a non-cooperative game $G = \big[\mathcal{N}, \{S_i\}, \{U_i(.)\}\big]$, where $\mathcal{N} = \{1, 2, \ldots, N\}$ refers to the set of players, S_i and $U_i(.)$ are, respectively, the strategy set and the utility for player i, the

$$\mu(1-\tau)\log_2\left(1 + \frac{hp}{I_{\rm m} + N_0}\right) - ch_B p(1-\tau) + c_{\rm m}\tau\log_2\left(1 + \frac{h_{\rm m}p_{\rm m}}{N_0}\right) - kp_{\rm m}\tau \ge \mu\log_2\left(1 + \frac{hp}{I_{\rm m} + N_0}\right) - ch_B p \quad (6c)$$

strategy vector $\mathbf{s}^* = [s_1^*, s_2^*, \dots s_N^*]$ is a Nash equilibrium solution if for every $i \in \mathcal{N}$

$$U_i(s_i^*, \mathbf{s}_{-i}^*) \geq U_i(s_i, \mathbf{s}_{-i}^*) \quad \forall s_i \in S_i,\ s_i \neq s_i^* \tag{7}$$

At Nash equilibrium, no user can unilaterally improve its individual utility. Generally the backward induction method is used to find the Nash equilibrium of a Stackelberg game. That means the analysis of the game should start from the follower of the Stackelberg game, i.e. from the FAP and then move on to the leader, i.e. to the MBS.

The FAP has to maximise U_F with respect to three variables τ, p and p_m. From (6a) it is seen that for fixed values of p, p_m, c and c_m, U_F is a linear function of τ. A non-zero solution of τ is possible if (6c) is satisfied, i.e.

$$-\mu \log_2\left(1 + \frac{hp}{I_m + N_0}\right) + ch_B p + c_m \log_2\left(1 + \frac{h_m p_m}{N_0}\right) - kp_m \geq 0 \tag{8}$$

That means for a non-zero solution of τ, U_F has to be a non-decreasing linear function of τ. The value of τ must also satisfy two other criteria given by (4b) and (6b), i.e.

$$\tau \geq \frac{\beta R_m}{(\beta - c_m)\log_2\left(1 + (h_m p_m / N_0)\right) - ch_B p} \tag{9a}$$

$$\tau \leq 1 - \frac{R_{th}}{\log_2\left(1 + (hp/(I_m + N_0))\right)} \tag{9b}$$

So for given p, p_m, c and c_m the optimal value of τ is given by the following equation

$$\tau^* = 1 - \frac{R_{th}}{\log_2\left(1 + (hp/(I_m + N_0))\right)} \tag{10}$$

provided that $\tau^* \in [0, 1]$ with condition (8) as well as the following condition hold

$$\frac{\beta R_m}{(\beta - c_m)\log_2\left(1 + (h_m p_m / N_0)\right) - ch_B p} \leq 1 - \frac{R_{th}}{\log_2\left(1 + (hp/(I_m + N_0))\right)} \tag{11}$$

If any of the two conditions (8) and (11) is not satisfied then τ^* is set to be zero meaning that the cooperation of FAP does not yield better result. From (10) it is evident that whenever the FAP cooperates the achievable data rate of the FU will always be R_{th}.

Now to maximise U_F with respect to p and p_m we can decompose U_F as given in (5) into two parts: U_{F1} which is only a function of p and U_{F2} a function of p_m as given below

$$U_F(p, p_m) = (1 - \tau)U_{F1}(p) + \tau U_{F2}(p_m) \tag{12}$$

where from (5), $U_{F1}(p)$ and $U_{F2}(p_m)$ can be written as

$$U_{F1}(p) = \mu \log_2\left(1 + \frac{hp}{I_m + N_0}\right) - ch_B p \tag{13}$$

$$U_{F2}(p_m) = c_m \log_2\left(1 + \frac{h_m p_m}{N_0}\right) - kp_m \tag{14}$$

Thus, to maximise $U_F(p, p_m)$ we have to separately maximise $U_{F1}(p)$ and $U_{F2}(p_m)$ with respect to p and p_m, respectively. The optimal solution for p is derived by taking the derivative of U_{F1} with respect to p and equating it to zero, i.e.

$$\left.\frac{\partial U_{F1}}{\partial p}\right|_{p^*} = \mu(\log_2 e)\frac{h}{hp^* + I_m + N_0} - ch_B = 0$$
$$\text{or,} \quad p^* = \frac{\mu(\log_2 e)}{ch_B} - \frac{I_m + N_0}{h} \tag{15}$$

Now considering the constraint $0 \leq p \leq p_{max}$, the optimal solution in general is given by the following equation

$$p^* = \begin{cases} 0 & \text{if } \dfrac{\mu(\log_2 e)}{ch_B} < \dfrac{I_m + N_0}{h} \\ \dfrac{\mu(\log_2 e)}{ch_B} - \dfrac{I_m + N_0}{h} & \text{if } 0 \leq \dfrac{\mu(\log_2 e)}{ch_B} - \dfrac{I_m + N_0}{h} \leq p_{max} \\ p_{max} & \text{if } \dfrac{\mu(\log_2 e)}{ch_B} - \dfrac{I_m + N_0}{h} > p_{max} \end{cases} \tag{16}$$

The double derivative of U_{F1} with respect to p yields

$$\frac{\partial^2 U_{F1}}{\partial p^2} = -\frac{\mu h^2(\log_2 e)}{(hp + I_m + N_0)^2} < 0 \quad \text{for } p \in [0, p_{max}] \tag{17}$$

Hence $\left.\dfrac{\partial^2 U_{F1}}{\partial p^2}\right|_{p^*} < 0$, which proves that U_{F1} is indeed maximum for p^* given in (16).

In the same way, the optimal solution for p_m is derived by taking the derivative of U_{F2} with respect to p_m and equating it to zero, i.e.

$$\left.\frac{\partial U_{F2}}{\partial p_m}\right|_{p_m^*} = c_m(\log_2 e)\frac{h_m}{h_m p_m^* + N_0} - k = 0$$
$$\text{or,} \quad p_m^* = \frac{c_m(\log_2 e)}{k} - \frac{N_0}{h_m} \tag{18}$$

Now considering the constraint $0 \leq p_m \leq p_{max}$, the optimal solution in general is given by the following equation

$$p_m^* = \begin{cases} 0 & \text{if } \dfrac{c_m(\log_2 e)}{k} < \dfrac{N_0}{h_m} \\ \dfrac{c_m(\log_2 e)}{k} - \dfrac{N_0}{h_m} & \text{if } 0 \leq \dfrac{c_m(\log_2 e)}{k} - \dfrac{N_0}{h_m} \leq p_{max} \\ p_{max} & \text{if } \dfrac{c_m(\log_2 e)}{k} - \dfrac{N_0}{h_m} > p_{max} \end{cases} \tag{19}$$

Now the double derivative of U_{F2} with respect to p_m yields

$$\frac{\partial^2 U_{F2}}{\partial p_m^2} = -\frac{c_m h_m^2(\log_2 e)}{(h_m p_m + N_0)^2} < 0 \quad \text{for } p_m \in [0,\ p_{max}] \tag{20}$$

Hence $\left.\dfrac{\partial^2 U_{F1}}{\partial p_m^2}\right|_{p_m^*} < 0$, which proves that U_{F2} is indeed maximum for p_m^* given by (19).

After solving the analytical expression of p^*, p_m^* and τ^* in terms of interference price c and incentive value c_m we now move on to the MBS, the leader of the Stackelberg game to find the optimal values of c and c_m. The utility of the MBS U_M in (3) can be decomposed into two parts U_{M1} which depends only on c and U_{M2} which depends only on c_m

$$U_M(c, c_m) = (1 - \tau)U_{M1}(c) + \tau U_{M2}(c_m) - \beta R_m \tag{21}$$

where from (3), $U_{M1}(c)$ and $U_{M2}(c_m)$ can be written as

$$U_{M1}(c) = ch_B p \tag{22}$$

$$U_{M2}(c_m) = (\beta - c_m)\log_2\left(1 + \frac{h_m p_m}{N_0}\right) \tag{23}$$

To maximise $U_M(c, c_m)$ we have to separately maximise $U_{M1}(c)$ and $U_{M2}(c_m)$ with respect to c and c_m, respectively, with p and p_m replaced by p^* and p_m^* in their expressions. In maximising $U_{M1}(c)$, a constraint must also be well taken care of that is the interference created at the MBS by the FAP transmission power p^* must not exceed a predefined threshold, i.e. $h_B p^* \le I_{th}$. Apparently it seems that the constraint has nothing to do with finding the optimal solution c^*. However, as derived before in (16) this optimal value c^* will in turn be used by the FAP to calculate the optimal value of p. So, the first optimisation problem of the MBS can be written as

$$\max_c \; U_{M1}(c) = ch_B p^* \tag{24a}$$

$$\text{s.t.} \quad h_B p^* \le I_{th} \tag{24b}$$

$$\text{and} \quad c \ge 0 \tag{24c}$$

The optimisation problem can be solved in two cases:

Case I: $h_B p_{max} \ge I_{th}$

In this case, the optimal value of p must be less than p_{max} and it is given by (15) provided the following condition is satisfied

$$\frac{\mu(\log_2 e)}{ch_B} \ge \frac{I_m + N_0}{h} \quad \text{or,} \quad c \le \frac{\mu h(\log_2 e)}{h_B(I_m + N_0)} \tag{25}$$

otherwise $p^* = 0$ from (16), i.e. the FAP would stop transmitting to the FU and the MBS would not get any interference price. So, we can write (24) as

$$\max_c \; \mu(\log_2 e) - \frac{ch_B}{h}(I_m + N_0) \tag{26a}$$

$$\text{s.t.} \quad \frac{\mu(\log_2 e)}{c} - \frac{h_B}{h}(I_m + N_0) \le I_{th} \tag{26b}$$

$$\text{and} \quad 0 \le c \le \frac{\mu h(\log_2 e)}{h_B(I_m + N_0)} \tag{26c}$$

The objective function of the optimisation problem (26) is a linearly decreasing function of c with the value of c lower limited by the constraint (26b). So the solution is the value of c for which the equality condition of (26b) is hold, i.e.

$$c^* = \frac{\mu(\log_2 e)}{I_{th} + (h_B/h)(I_m + N_0)} \tag{27}$$

It can easily be verified that c^* satisfies the condition (26c) for positive values of I_{th}.

Case II: $h_B p_{max} < I_{th}$

In this case, p^* is set to the maximum value p_{max} and $U_{M1}(c) = ch_B p_{max}$ will increase linearly with c but only as long as $(\mu(\log_2 e)/ch_B) - ((I_m + N_0)/h) \ge p_{max}$ or, $c \le (\mu(\log_2 e)/(h_B p_{max} + (h_B/h)(I_m + N_0)))$. As c is increased further, the value of $((\mu(\log_2 e)/ch_B) - ((I_m + N_0)/h))$ goes below p_{max} and hence $p^* < p_{max}$ from (16). Therefore, when $c > (\mu(\log_2 e)/(h_B p_{max} + (h_B/h)(I_m + N_0)))$ we get from (22), $U_{M1}(c) = \mu(\log_2 e) - (ch_B/h)(I_m + N_0)$, which is a linearly decreasing function of c. So

1. Initialisation: P_{max}, k, μ, β, N_0 are all assumed to be known to the MBS. The FAP estimates h, h_m, and h_B and inform these values to MBS via backhaul. The FU estimates the interference I_m coming from the interfering MU and through FAP it is informed to the MBS. The MBS also decides a certain tolerable interference threshold I_{th}.
2. If $h_B P_{max} \ge I_{th}$

   Set $c^* = \frac{\mu(log_2 e)}{I_{th} + \frac{h_B}{h}(I_m + N_0)}$

   Else

   Set $c^* = \frac{\mu(log_2 e)}{h_B p_{max} + \frac{h_B}{h}(I_m + N_0)}$

   End If
3. Find the solution x^* of the following equation

   $$log_2(x) - \frac{\beta(log_2 e)}{x} + log_2\left(\frac{h_m(log_2 e)}{kN_0}\right) + log_2 e = 0$$
4. If $x^* \le \frac{k}{(log_2 e)}\left(p_{max} + \frac{N_0}{h_m}\right)$

   Set $c_m^* = x^*$

   Else

   Set $c_m^* = \frac{k}{(log_2 e)}\left(p_{max} + \frac{N_0}{h_m}\right)$

   End If
5. Inform c^* and c_m^* to the FAP

Fig. 2 *Algorithm for MBS*

1. Initialisation: P_{max}, k, μ, β, N_0 are all assumed to be known to the FAP. The FAP estimates h, h_m, and h_B. The FU estimates the interference I_m coming from the interfering MU and informs it to the FAP. The FAP also decides a value for the minimum achievable rate R_{th} during cooperation.
2. Receive c^* and c_m^* from the MBS
3. If $\frac{\mu(log_2 e)}{c^* h_B} - \frac{I_m + N_0}{h} < 0$

    Set $p^* = 0$

    Else if $0 \leq \frac{\mu(log_2 e)}{c^* h_B} - \frac{I_m + N_0}{h} \leq p_{max}$

    Set $p^* = \frac{\mu(log_2 e)}{c^* h_B} - \frac{I_m + N_0}{h}$

    Else

    Set $p^* = p_{max}$

    End If
4. If $\frac{c_m^*(log_2 e)}{k} - \frac{N_0}{h_m} < 0$

    Set $p_m^* = 0$

    Else if $0 \leq \frac{c_m^*(log_2 e)}{k} - \frac{N_0}{h_m} \leq p_{max}$

    Set $p_m^* = \frac{c_m^*(log_2 e)}{k} - \frac{N_0}{h_m}$

    Else

    Set $p_m^* = p_{max}$

    End If
5. If $c^* h_B p^* - \mu log_2\left(1 + \frac{hp^*}{I_m + N_0}\right) + c_m^* log_2\left(1 + \frac{h_m p_m^*}{N_0}\right) - kp_m^* \geq 0$

    If $\frac{\beta R_m}{(\beta - c_m^*) log_2\left(1 + \frac{h_m p_m^*}{N_0}\right) - c^* h_B p^*} \leq 1 - \frac{R_{th}}{log_2\left(1 + \frac{hp^*}{I_m + N_0}\right)}$

    Set $\tau^* = 1 - \frac{R_{th}}{log_2\left(1 + \frac{hp^*}{I_m + N_0}\right)}$

    Else

    Set $\tau^* = 0$

    End If

    Else

    Set $\tau^* = 0$

    End If.

Fig. 3 *Algorithm for FAP*

the optimised value of c is

$$c^* = \frac{\mu(\log_2 e)}{h_B p_{\max} + (h_B/h)(I_m + N_0)} \tag{28}$$

In general, the optimal solution for interference price c is written as

$$c^* = \begin{cases} \dfrac{\mu(\log_2 e)}{I_{th} + (h_B/h)(I_m + N_0)} & \text{if } h_B p_{\max} \geq I_{th} \\ \dfrac{\mu(\log_2 e)}{h_B p_{\max} + (h_B/h)(I_m + N_0)} & \text{otherwise} \end{cases} \tag{29}$$

The second optimisation problem for the MBS in order to determine the incentive value c_m can be written as

$$\max_{c_m} \ U_{M2}(c_m) = (\beta - c_m) \log_2\left(1 + \frac{h_m p_m^*}{N_0}\right) \tag{30a}$$

$$\text{s.t.} \quad c_m \geq 0 \tag{30b}$$

In solving the problem, we first assume $p_m^* = (c_m(\log_2 e)/k) - (N_0/h_m) \leq p_{\max}$. Putting the value of p_m^* in the expression for $U_{M2}(c_m)$ we get

$$U_{M2}(c_m) = (\beta - c_m) \log_2\left(\frac{h_m c_m(\log_2 e)}{kN_0}\right) \tag{31}$$

To get the optimal value of c_m we take the derivative of $U_{M2}(c_m)$ with respect to c_m and equate it to zero to get the following equation

$$\log_2(c_m^*) - \frac{\beta(\log_2 e)}{c_m^*} + \log_2\left(\frac{h_m(\log_2 e)}{kN_0}\right) + \log_2 e = 0 \tag{32}$$

The solution of (32) would give the optimal value of c_m but this equation is very difficult to solve analytically. Here we will take the help of numerical techniques to find the solution. It can easily be verified that the solution would indeed yield the maximum of U_{M2} by taking the second derivative of U_{M2} with respect to c_m. Now if the solution does not satisfy the condition $(c_m^*(\log_2 e)/k) - (N_0/h_m) \leq p_{\max}$, i.e. if $c_m^* > (k/(\log_2 e))(p_{\max} + (N_0/h_m))$ then

Table 1 Simulation parameters

Parameters	Values
macrocell coverage radius (R_m)	500 m
femtocell coverage radius (R_f)	20 m
MBS transmission power (P_{mbs})	40 dBm
MU transmission power (P_{mu})	20 dBm
maximum power of the FAP (p_{max})	30 dBm
wall penetration loss (WL)	10 dB
noise power per sub-channel	−120 dBm
minimum achievable rate of FU (R_{th})	6 bits/s/Hz
FAP–FU distance	5 m
FAP – indoor MU distance	10 m
FU – interfering MU distance	80 m
MBS–FAP/indoor MU path loss	$15.3 + 37.6\log_{10}(d) + \text{WL}$
FAP–FU/indoor MU path loss	$38.46 + 20\log_{10}(d) + 0.7d$
FU – interfering MU path loss	$15.3 + 37.6\log_{10}(d) + \text{WL}$

$p_m^* = p_{max}$ and the expression for $U_{M2}(c_m)$ becomes

$$U_{M2}(c_m) = (\beta - c_m)\log_2\left(1 + \frac{h_m p_{max}}{N_0}\right) \quad (33)$$

which decreases linearly if c_m is increased further. The optimal value of c_m is then given by the following equation

$$c_m^* = \frac{k}{(\log_2 e)}\left(p_{max} + \frac{N_0}{h_m}\right) \quad (34)$$

The existence of the Nash equilibrium can be proved following the proposition in [33] but cannot be provided here due to space limitation. The implementation algorithms for the joint power control and cooperation game is given below Algorithms 1 and 2 (see Figs. 2 and 3)

5 Results and discussions

The simulation model comprises of one circular macrocell of 500 m radius with an MBS at the centre and one femtocell located within the macrocell operating in same frequency sub-channel in the uplink band of the macrocell. The femtocell is assumed to be of circular shape with a radius of 20 m consisting of one FAP at the centre and one FU located within the femtocell at a distance 5 m from the FAP. An indoor MU is also located within the femtocell at a distance 10 m from the FAP. There is an interfering MU operating in the same sub-channel causing interference to the FAP downlink transmission at a distance 80 m from the FU. The test scenario for simulation indicating the locations of the FAP, FU, indoor MU and interfering MU is shown in Fig. 4. The values of the constants μ, β and k have huge impact on the performance of this incentive-based femtocell cooperation scheme. Fig. 5 indicates which set of values of μ and β would prompt the FAP to cooperate (lightly shaded zone) and which set of values would not (dark zone) while the value of k is set equal to 1, the distance between the MBS and FAP is kept at 400 m, interference threshold I_{th} at the MBS is set at −100 dBm and all other system parameters are set according to Table 1.

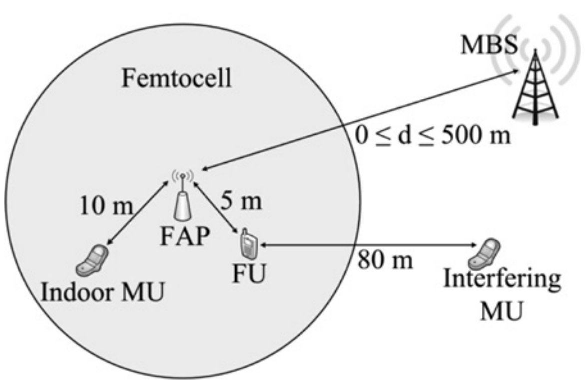

Fig. 4 *Test scenario for simulation indicating the locations of the FAP, FU, indoor MU and interfering MU*

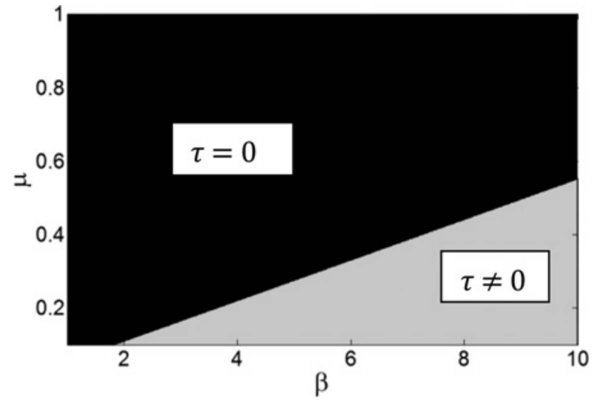

Fig. 5 *Feasible values of β and μ which leads to FAP cooperation when $k = 1$, $I_{th} = -100$ dBm and the distance between MBS and FAP is 400 m*

For the rest of the simulation, we will use the setting $\mu = 0.2$, $\beta = 5$ and $k = 1$. All the simulation parameters are summarised in Table 1. The different path loss models are taken from [7]. The simulation is carried out on this test scenario to compute the optimal fraction τ for which the femtocell would cooperate, the achievable rate of indoor MU and FU as well as the utilities of the MBS and FAP using the previously derived analytical expressions in MATLAB. The performance of this scheme is shown by varying the femtocell distance with respect to the MBS.

In Fig. 6, the plot of optimal value of τ with the femtocell distance from the MBS is shown for different values of I_{th}. At $I_{th} = -90$ dBm the femtocell would cooperate, i.e. optimal τ is non-zero if the FAP is at least ~225 m away from the MBS because for MBS–FAP distance below 225 m the indoor MU gets sufficiently high data rate from the MBS and cooperation would not yield higher utility for the MBS at the same time satisfying the minimum achievable bit rate $R_{th} = 6$ bits/s/Hz for the FU. That means the condition (11) is not satisfied for any time fraction $\tau \in [0, 1]$. It is observed that as I_{th} becomes stricter the femtocell would cooperate only if it is further away from the MBS and the fraction of time it would cooperate also becomes lower. The reason for this is that the condition (11) is valid for a larger MBS–FAP distance at a lower interference threshold I_{th}. Also, the FAP transmit power p must be lowered at a lower interference threshold. So the cooperation time fraction τ must be lowered in order to achieve the minimum achievable bit rate $R_{th} = 6$ bits/s/Hz for the FU. It is also noticed

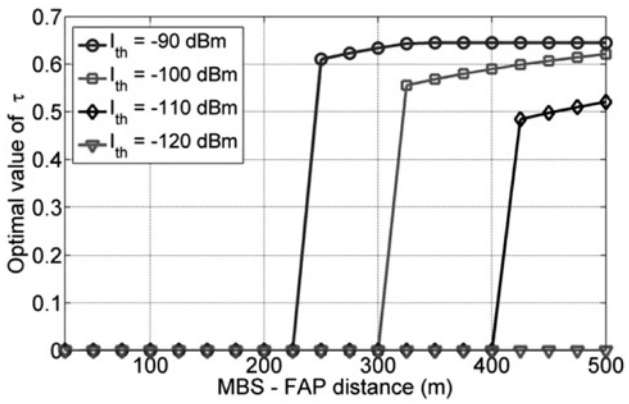

Fig. 6 *Optimal value of τ for different locations of the femtocell*

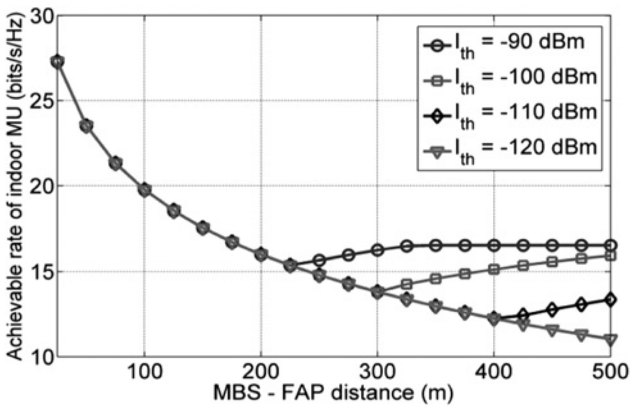

Fig. 7 *Achievable rate of the indoor MU for different locations of the femtocell*

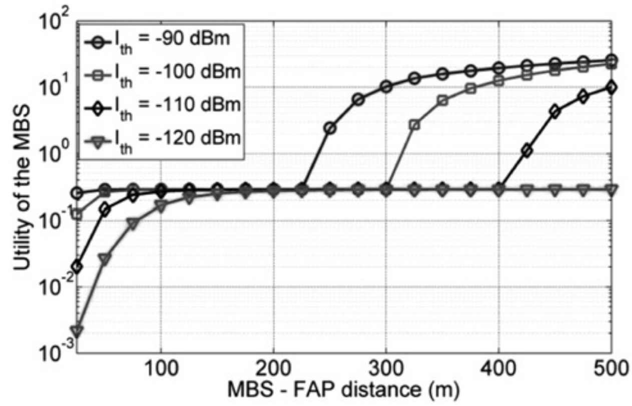

Fig. 9 *Utility of the MBS for different locations of the femtocell*

that when the femtocell cooperates the optimal τ value increases slightly with MBS–FAP distance for a certain I_{th} because at larger distance away from the MBS, the FAP can transmit with higher transmit power p satisfying the interference constraint $h_B p = I_{\text{th}}$ and so it can afford to allocate a higher cooperation time τ to the indoor MU. At $I_{\text{th}} = -90$ dBm it is observed that optimal τ becomes constant beyond ~325 m because at that distance the FAP transmit power p becomes $p_{\max}$ which can no longer be increased resulting in constant optimal τ. At $I_{\text{th}} = -120$ dBm the femtocell does not cooperate at all even at the farthest edge of the macrocell.

Fig. 7 shows the achievable rate of the indoor MU at different distances of the femtocell from the MBS. As long as the optimal $\tau = 0$ the MU would be getting downlink service directly from the MBS and the achievable rate curve shows a decreasing exponential form with increasing distance. As soon as the FAP start cooperating, τ becomes non-zero and the rate curve increasing slowly with distance. For $I_{\text{th}} = -90$ dBm, the fixed achievable rate of the indoor MU beyond ~325 m is due to constant optimal τ as seen in Fig. 6. This increase in achievable rate of the indoor MU comes at the expense of rate drop of the associated FU of the femtocell as evident in Fig. 8. This decrement of rate of the FU is compensated by the incentives the FAP gets from the MBS. From (10) it is evident that during cooperation the FU has to maintain its achievable rate at $R_{\text{th}} = 6$ bits/s/Hz irrespective of tolerable interference threshold I_{th} which is also manifested in Fig. 8. Without the femtocell cooperation at lower distances the achievable rate of the FU increases with distance because as the distance increases, the FAP can transmit with higher power while creating the same interference at the MBS thereby increasing the achievable rate. For $I_{\text{th}} = -120$ dBm when the femtocell does not cooperate, the indoor MU rate curve follows the decaying exponential pattern all throughout (Fig. 7) and the FU rate curve goes on increasing monotonically with distance (Fig. 8).

The variation of utilities of the indoor MU and the FU with femtocell distance are shown in Figs. 9 and 10, respectively. The main contribution to the utility of the MBS when the femtocell cooperates is due to the higher data rate the indoor MU obtains from the FAP. As τ increases with MBS–FAP distance the utility of the MBS increases and with lowering of interference thresholds the utility decreases. When the femtocell does not cooperate the utility of the MBS is nearly constant at $I_{\text{th}} = -90$ dBm. For lower interference threshold, we see a decrease of MBS utility at small MBS–FAP distances during non-cooperation of femtocell. This can be explained from the expression of interference price $c^* = \mu(\log_2 e)/(I_{\text{th}} + (h_B/h)(I_{\text{m}} + N_0))$ in (27) because the cross-tier interference $h_B p^*$ at MBS is constant at I_{th} (Fig. 11) and so the utility $(c^* h_B p^*)$ of the MBS is directly proportional to c^*. For a fixed I_{th} at lower distances, the channel gain h_B is high so that $I_{\text{th}} \ll (h_B/h)(I_{\text{m}} + N_0)$ and $c^* \simeq (\mu(\log_2 e)/(h_B/h)(I_{\text{m}} + N_0))$ which increases with distance. However, at larger distances the channel gain h_B is very small so that $I_{\text{th}} \gg (h_B/h)(I_{\text{m}} + N_0)$ and $c^* \simeq (\mu(\log_2 e)/I_{\text{th}})$ which is a constant. It is evident from the plots that the utilities of both MBS and FAP are increased after cooperation which encourages both of those to employ this incentive-based cooperation scheme. Fig. 11 shows the cross-tier interference at MBS from the FAP. It can be calculated from (16) and (29) that the cross-tier interference $p^* h_B$ is always fixed at the tolerable limit I_{th} if $h_B p_{\max} \geq I_{\text{th}}$. Otherwise it is given by $h_B p_{\max}$. For $I_{\text{th}} = -90$ dBm, the condition $h_B p_{\max} \geq I_{\text{th}}$ is valid upto FAP distance of about 325 m from the MBS and the cross-tier interference is -90 dBm. Beyond 325 m the condition is not valid and the interference is given by $h_B p_{\max}$ which decreases with distance as the channel gain h_B is decreased. For $I_{\text{th}} = -100, -110$

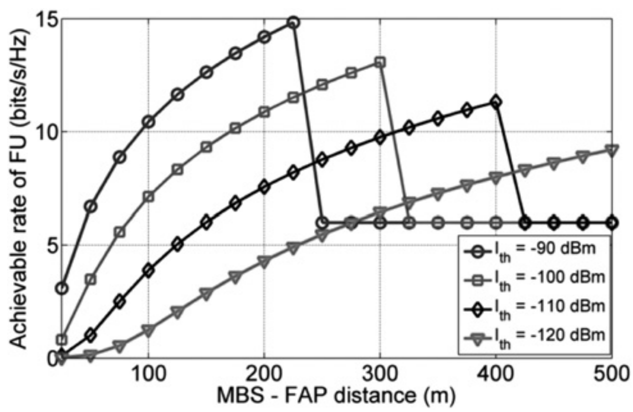

Fig. 8 *Achievable rate of the FU for different locations of the femtocell*

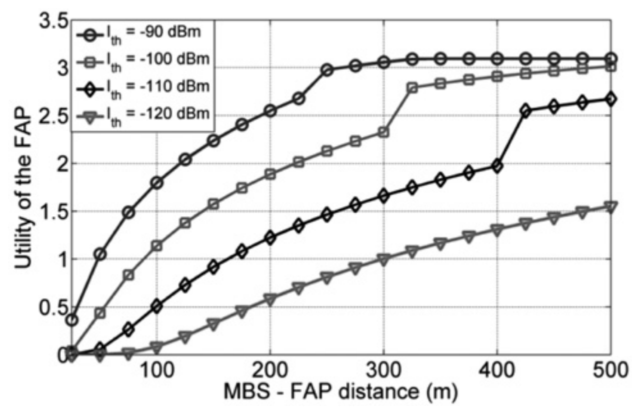

Fig. 10 *Utility of the FAP for different locations of the femtocell*

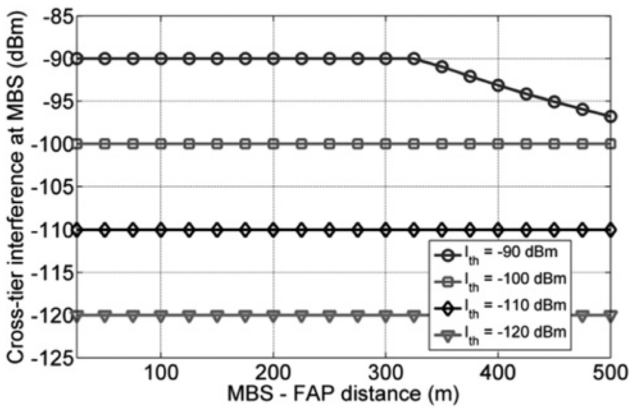

Fig. 11 *Cross-tier interference at the MBS for different locations of the femtocell*

and −120 dBm the condition $h_B p_{\max} \geq I_{\text{th}}$ is valid everywhere and the cross-tier interference is given by $h_B p_{\max}$.

6 Conclusion

This paper proposes an incentive-based cooperation scheme which encourages a femtocell to cooperate with the microcell and provide downlink service to any indoor MU as well as a pricing-based power control scheme for the FAP to manage the cross-tier interference in an underlay two-tier heterogeneous network. The results show that a femtocell can be operated within the macrocell in an underlay spectrum sharing manner providing decent achievable rate to any FU especially at larger distance from the MBS keeping the cross-tier interference below a certain manageable threshold. The incentive-based femtocell cooperation scheme allows any indoor MU to achieve higher data rate although at the expense of lowering the achievable data rate of the FU.

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