

Interference Mitigation Using Uplink Power Control for Two-Tier Femtocell Networks

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Abstract

This paper proposes two interference mitigation strategies that adjust the maximum transmit power of femtocell users to suppress the cross-tier interference at a macrocell base station (BS). The open-loop and the closed-loop control suppress the cross-tier interference less than a fixed threshold and an adaptive threshold based on the noise and interference (NI) level at the macrocell BS, respectively. Simulation results show that both schemes effectively compensate the uplink throughput degradation of the macrocell BS due to the cross-tier interference and that the closed-loop control provides better femtocell throughput than the open-loop control at a minimal cost of macrocell throughput.

Index Terms

Femtocell, uplink power control, two-tier CDMA network, interference mitigation

I. INTRODUCTION

Femtocells have emerged as a solution to increase both the capacity and coverage while reducing both capital expenditures and operating expenses. Femtocells, which consist of miniature personal base stations and stationary or low-mobility end users deployed in an indoor environment, are located within an existing cellular network; a two-tier network is

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deployed. Since femtocells operate in the licensed spectrum owned by wireless operators and share this spectrum with macrocell networks, limiting the cross-tier interference from femtocell users at a macrocell base station (BS) is an indispensable condition for deploying femtocells in the uplink. In addition, since a network operator can not control the femtocell locations, femtocells need to sense the radio environments around them and carry out self-configuration and self-optimization of radio resources from the moment they are set up in by the consumer [1].

Previous studies have developed cross-tier interference control methods by using transmit power control [2],[3] and time hopping coupled with antenna sectoring [4] for a two-tier CDMA network. A signal-to-interference ratio (SIR) based power control scheme is shown to promote uplink performance, but does not consider the wall penetration loss [2]. On the other hand, under the assumption that macrocell BS knows the positions of the overlaid users, a power control scheme has been proposed to minimize the total transmitted power while satisfying the SIR requirement and considering the wall penetration loss [3]. The schemes in [2] and [3] have different effects on the uplink performances according to the underlying femtocell locations; they require site-specific engineering in which the system parameters are manually tuned and optimized by technicians. Therefore, these methods are not applicable to femtocells that should carry out the automatic self-configuration of radio resources.

This paper proposes two interference mitigation strategies in which femtocell users adjust the maximum transmit power using an open-loop and a closed-loop technique. With the open-loop control, a femtocell user adjusts the maximum transmit power to suppress the cross-tier interference due to the femtocell user, which results in the cross-tier interference less than a fixed interference threshold. The closed-loop control adjusts the maximum transmit power of the femtocell user to satisfy an adaptive interference threshold based on the level of noise and uplink interference (NI) at the macrocell BS. Both schemes effectively compensate the uplink throughput degradation of the existing macrocell BS due to the cross-tier interference. Furthermore, the use of the closed-loop control provides femtocell throughput that is superior to that using open-loop control at a very low macrocell throughput cost.

The remainder of the paper is organized as follows. The two-tier cellular system model and basic power control method is described in Section II. Section III is devoted to describing the proposed open-loop and closed-loop control schemes for the maximum transmit power of femtocell users. In Section IV, the simulation results are presented and discussed. Finally, the conclusions are drawn in Section V.

II. SYSTEM MODEL

A two-tier CDMA cellular network is considered here. A macrocell has a layout of two rings, 19 cells and single sector per cell. In-building femtocells are uniformly distributed in a macrocell. Each femtocell BS is located within the center of the building and provides indoor wireless coverage to femtocell users. Macrocell and femtocell users are uniformly distributed.

The radio links between the BS and the users are divided into outdoor, indoor, and outdoor-to-indoor links according to the radio environment. The propagation loss L caused by slow fading at the uplink is modeled based on an ITU and COST231 path loss model [5][6]:

- Outdoor link (macrocell user \rightarrow macrocell BS)

$$L = 10^{4.9} \left(\frac{d}{1000} \right)^4 f^3 10^{S/10}, \quad (1)$$

- Outdoor-to-indoor link (macrocell user \rightarrow femtocell BS, femtocell user \rightarrow macrocell BS)

$$L = 10^{4.9} \left(\frac{d}{1000} \right)^4 f^3 10^{S/10} 10^{(L_i+L_e)/10}. \quad (2)$$

- Indoor link (femtocell user \rightarrow femtocell BS)

$$L = 10^3 d^{3.7} 10^{S/10} 10^{L_i/10}, \quad (3)$$

Here, d and f are the amount of transmitter-receiver separation in meter and the frequency in MHz, respectively. S represents log-normal shadowing with a standard deviation of 8 dB and a shadowing correlation of 0.5 in (1) and (2), and that with a standard deviation of 10 dB and a shadowing correlation of 0.7 dB in (3). L_e denotes the external wall loss modeled as a Gaussian distribution with a mean of 7 dB and a standard deviation of 6 dB. L_i is internal wall loss given by $L_i = 4I$, where I is Bernoulli random variable with success parameter $p = 0.5$.

In the conventional uplink open-loop power control, the uplink path loss (including shadowing) between a user and a macrocell BS can be estimated by both the received downlink signal power measured at the user and the broadcast information on the effective isotropic radiated power (EIRP) of the macrocell BS. With further knowledge of the required signal-to-interference-and-noise ratio (SINR) of the current transmission and with broadcast information on the average power level of the noise and interference at the BS, the required uplink transmit power P_r is derived as follows:

$$P_r = L \cdot NI \cdot \gamma_0, \quad (4)$$

Here, L , γ_0 , and NI are the uplink propagation loss, the required SINR for the current modulation and coding rate, and the estimated average power level of the noise and interference at the BS without considering the BS antenna gain, respectively. Finally, the transmit power of the user $P_t = (P_r, \bar{P}_{max})$ is determined not to be in excess of the maximum transmit power \bar{P}_{max} , where the maximum transmit power \bar{P}_{max} can not be adaptively adjusted because it is the fixed value satisfying the spectrum emission mask and the error vector magnitude requirement.

In this paper, the upper limit of transmit power $P_{max} (\leq \bar{P}_{max})$ is introduced to control the cross-tier interference caused by femtocell users, and the transmit power of the user is determined not to be in excess of P_{max} as follows:

$$P_t = \min(P_r, P_{max}). \quad (5)$$

The additional cross-tier interference at a macrocell BS due to femtocell users leads to a higher P_r as shown in (4), which leads to a NI rise at the macrocell BS, which results in uplink throughput degradation in the macrocell. Therefore, adjusting P_{max} according to the cross-tier interference level can limit the NI rise and thus compensate for the uplink throughput degradation in the macrocell. In the following chapters, the maximum transmit power is used for naming P_{max} .

III. UPLINK POWER CONTROL IN A FEMTOCELL

In this section, an uplink power control scheme for femtocell users is proposed that adjusts the maximum transmit power P_{max} as a function of the cross-tier interference level in an open-loop and closed-loop technique.

A. Open-Loop Control for P_{max}

In the proposed open-loop control for P_{max} , a femtocell user estimates its additional cross-tier interference to the macrocell BS and adjusts the maximum transmit power P_{max} such that the additional cross-tier interference power is less than the predetermined maximum allowable interference level.

A femtocell user estimates the received signal powers from K macrocell BSs configured

in its neighbor BS list¹ $\{R_k\}_{k=1,\dots,K}$, and evaluates the propagation losses $\{L_k\}_{k=1,\dots,K}$ from the macrocell BSs as follows:

$$L_k = \frac{E_k}{R_k}, \quad (6)$$

where the EIRP of the k th macrocell BS, E_k is obtained by the broadcast information from the BSs. The propagation losses L_k can consider the path loss (including shadowing) in a frequency division duplexing (FDD) system by using the received signal powers $\{R_k\}_{k=1,\dots,K}$ averaged over time. In a time division duplexing (TDD) system, fast fading can be also considered in L_k by using the instantaneous received signal powers $\{R_k\}_{k=1,\dots,K}$ due to the channel reciprocity between uplink and downlink.

Based on the symmetry between the uplink and downlink propagation losses, the k^* th macrocell BS with the minimum propagation loss $L_{\min} = \min(L_1, L_2, \dots, L_K)$ is affected most by the cross-tier inference of the femtocell user. Thus, the maximum cross-tier inference of the femtocell user to the k^* th macrocell BS, I_{k^*} should satisfy the interference power constraint as follows:

$$I_{k^*} = \frac{P_t}{L_{\min}} \leq I_{th,k^*}, \quad \text{and} \quad I_{th,k^*} = \frac{\alpha N_0 W F}{J_{k^*}}. \quad (7)$$

Here, P_t is the transmit power of the femtocell user. I_{th,k^*} is the maximum allowable cross-tier interference power at the k^* th macrocell BS. N_0 , W , and F denote the thermal noise spectral density, the bandwidth, and the noise figure of the macrocell BS, respectively, and the interference-to-noise ratio α is a system-specific parameter known a priori to femtocell users. J_{k^*} denotes the number of active femtocell users that decide the k^* th macrocell BS is affected most by their own interferences. Using the value of k^* reported from each femtocell user, each macrocell BS determines J_{k^*} and broadcasts it to the femtocell users via the femtocell BSs.

The maximum transmit power of the femtocell user determined by an open-loop method, $P_{max,OL}$, is given by

$$P_{max,OL} = I_{th,k^*} \cdot L_{\min}. \quad (8)$$

The transmit power of the femtocell user P_t is determined by (5), in which P_{max} is replaced by $P_{max,OL}$. This guarantees that the maximum cross-tier inference of the femtocell user does

¹The neighbor BS list of each femtocell, which is auto-configured by its serving femtocell BS, contains several macrocell and femtocell BSs that cause the strong interference to the femtocell. Therefore, even for a realistic scenario where there are many femtocells deployed, a femtocell user completely find the neighbor macrocell BSs that are affected most by the cross-tier interference without monitoring all neighbor BSs.

not exceed a the maximum allowable cross-tier interference power of each macrocell BS. Since the actual NI level at each macrocell BS is not considered in the open-loop method, however, even when the NI level at each macrocell BS is sufficiently low, the maximum transmit power of femtocell users must be more limited than necessary. This degrades the uplink throughput in the femtocell.

B. Closed-Loop Control for P_{max}

In the proposed closed-loop control for P_{max} , a femtocell user adjusts the maximum transmit power P_{max} as a function of not only the estimated additional cross-tier interference due to the femtocell user but also the NI level at the macrocell BS. Before the closed-loop control procedure begins, a femtocell user obtains $\{R_k\}_{k=1,\dots,K}$ and $\{E_k\}_{k=1,\dots,K}$ and evaluates $\{L_k\}_{k=1,\dots,K}$ via (6) using the same method used in the open-loop control. Additionally, the K macrocell BSs continuously monitor the uplink interference power from both macrocell users and femtocell users and broadcast the NI levels to the femtocell users via the femtocell BS that are wired to the macrocell BSs.

Fig. 1 shows the detailed closed-loop procedure used to update the maximum transmit power. For the initial step $n = 0$, before the femtocell user becomes active, the user obtains the initial NI level of the k th macrocell BS, $NI_k(0)$ including the uplink interference power from active users of macrocells and femtocells.

For $n > 0$, after the femtocell user becomes active, $NI_k(n)$ includes the additional cross-tier interference due to the femtocell user. This is given by

$$NI_k(n) = NI_k(0) + \frac{T^f}{L_k^f}, \quad (9)$$

where T^f is the transmit power of the active femtocell user and L_k^f is the indoor-to-outdoor propagation loss from the femtocell user to the k th macrocell BS.

The maximum allowable interference power of the k th macrocell BS, $I_{th,k}(n)$ is determined as a function of $NI_k(n)$ and $NI_k(0)$, as follows:

$$I_{th,k}(n) = \begin{cases} \beta \cdot NI_k(0) & n = 0 \text{ or if } NI_k(n) \geq NI_k(0) \text{ for } n > 0 \\ I_{th,k}(0) + \beta (NI_k(0) - NI_k(n)) & \text{if } NI_k(n) < NI_k(0) \text{ for } n > 0 \end{cases}, \quad (10)$$

where β is a system-specific parameter known a priori to femtocell users. If the NI level of the k th macrocell BS increases due to the additional cross-tier inference of a new active femtocell user, i.e., $NI_k(n) \geq NI_k(0)$, the maximum allowable interference power, $I_{th,k}(n)$,

is determined on the basis of the NI level if there are no active femtocell users, $NI_k(0)$. This decreases the transmit power of the femtocell user by lowering the maximum transmit power. On the other hand, if the inference of active macrocell users decreases, the NI level of the k th macrocell BS decreases regardless of the additional cross-tier inference of a new active femtocell user, i.e., $NI_k(n) < NI_k(0)$. In this case, $I_{th,k}(n)$ increases to be $\beta(NI_k(0) - NI_k(n))$ greater than $I_{th,k}(0)$, which increases the maximum transmit power and thus improves the uplink throughput in the femtocell.

The maximum transmit power of the femtocell user by the closed-loop method, $P_{max,CL}$ is given by

$$P_{max,CL}(n) = I_{th,k^*}(n) \cdot L_{min}, \quad (11)$$

where $I_{th,k^*}(n)$ is the maximum allowable interference power of the k^* th macrocell BS with the minimum propagation loss $L_{min} = \min(L_1, L_2, \dots, L_K)$. The transmit power of the femtocell user P_t , which is determined using $P_{max,CL}$ from (5), enhances the uplink throughput in the femtocell while bringing the total NI level of the macrocell BS under control.

IV. PERFORMANCE EVALUATION

System parameters based on CDMA2000 1xEV-DO Revision A (DO Rev. A) [7] is used for the performance evaluation. For a system occupying a bandwidth of 1.25 MHz with a center frequency of 2.5 GHz, an omnidirectional antenna with a gain of 0 dBi are used for both user and BS. At each drop, 10 macrocell users are uniformly distributed in each sector with a R of $800/\sqrt{3}$ meters. They are connected to the macrocell BS with the lowest path loss among all possible links to the macrocell BSs. Four femtocell users are uniformly distributed in a building with a width and length of 50 meters, and a single femtocell BS is located in the center of the building. Each physical layer packet is transmitted over 4 contiguous slots (1 slot = 1.667 ms). The proportional fair scheduler in each macrocell and femtocell BS determines one user sending full-buffer traffic. The update rate of the transmit power of the users is 150 Hz (once per 4 slots) as in DO Rev. A. Fast fading channels (3 km/hr, 1-path) of all possible links including both the desired and interference links are generated using the modified Jakes model [8]. Effective data rates and required per-bit signal-to-noise ratio (Eb/Nt) are shown in Table I. For fair comparison between the open-loop control and the closed-loop control for P_{max} , the identical interference threshold of two schemes, i.e.,

$I_{th,k^*} = I_{th,k^*}(0)$, is considered. This is achieved by $\beta = \frac{\alpha N_0 W F}{J_{k^*} N I_{k^*}(0)}$. Here, α is set to be 3, and $N_0 W F$ is -109 dBm.

A. Single femtocell

Although an assumption of single femtocell per macrocell is not realistic, it provides insight regarding the proposed algorithms' performance according to wall penetration loss and macro-to-femto distance. To evaluate the performance of the proposed algorithms, two performance metrics of the degradation ratio of macrocell throughput (DRMT) L_T and the achievement ratio of femtocell throughput (ARFT) A_T are defined as follows:

$$L_T = \frac{T_{m,0} - T_m}{T_{m,0}} \quad \text{and} \quad A_T = \frac{T_f}{T_{f,0}}, \quad (12)$$

where T_m and $T_{m,0}$ are the uplink average sector throughput in the macrocell with and without the femtocell, respectively. $T_{f,0}$ is the uplink average throughput in the femtocell when the femtocell users employ 23 dBm of P_{max} , and T_f is the uplink average throughput in the femtocell using the proposed open-loop or closed-loop power control scheme.

The DRMT versus the distance between the macrocell BS and the femtocell BS, D , for the fixed maximum power ($P_{max} = 23$ dBm), the closed-loop control, and the open-loop control schemes are compared in Fig. 2 when a external wall loss $L_e = 10$ and 1 dB, and a internal wall loss $L_i = 0$ dB. The DRMT decreases as D increases for all of the considered schemes as the cross-tier interference at the macrocell BS decreases as D increases. Both the open-loop and the closed-loop control schemes are observed to perform consistently better compared to the fixed maximum power. Additionally, the performance gain of the two proposed schemes over the fixed maximum power increases as D and L_e decrease. This is because the cross-tier interference at the macrocell BS caused by the fixed maximum power increases as D and L_e decrease, but those with the open-loop and the closed-loop control schemes are consistently below the threshold value, irrespective of the D and L_e . It is especially observed that both the open-loop and the closed-loop control schemes achieve a DRMT of less than 0.05 regardless of the D and L_e .

Fig. 3 shows the ARFT of the open-loop and the closed-loop control schemes as a function of D when $L_e = 1$ and 10 dB, and $L_i = 0$ dB. The closed-loop control scheme provides better ARFT than the open-loop control at the cost of the macrocell throughput for all of the considered cases. However, a close observation of Fig. 2 shows that the degradation of the

macrocell throughput with the closed-loop control is minimal compared to that of the open-loop control. The advantages of the closed-loop control over the open-loop control increase as D and L_e decrease, i.e., as the cross-tier interference dominates the NI at the macrocell.

B. Multiple femtocells

For performance evaluation under realistic conditions, Fig. 4 shows the average sector throughputs of macrocell and femtocell as a function of the number of femtocell BSs per macrocell, M . Increasing M causes more severe cross-tier interference, and thus reduces the macrocell throughput. Furthermore, the macrocell throughput gain of the two proposed schemes over the fixed maximum power increases as M increase. This is because the cross-tier interference at the macrocell BS caused by the fixed maximum power scheme increases as M decrease, but those with the open-loop and the closed-loop control schemes are consistently below the threshold value, irrespective of M . Fig. 4 also shows that the throughput degradation of the femtocell is smaller than that of the macrocell for a large M . This is resulted from the two factors: one is that femto-to-femto interference is smaller than the femto-to-macro cross-tier interference due to additional wall penetration loss, and the other is that the link loss between the femtocell user and the femtocell BS is smaller than that between the macrocell user and the macrocell BS.

Fig. 5 depicts the 5% user throughput (defined as the value of 5% of the CDF of user throughput) as a function of M . The 5% user throughput of macrocell, which represents the throughput of macrocell edge users, shows similar trend with the average throughput of macrocell depicted in Fig. 4 because the cross-tier interference at a macrocell BS commonly affects all corresponding macrocell users. However, the 5% user throughput of femtocell shows different behavior compared with the average throughput of femtocell. Especially, the gain of the closed-loop control over the open-loop control in terms of the 5% user throughput of femtocell is much larger than the gain in terms of the average throughput of femtocell. Since the 5% user throughput of femtocell mostly represents the throughput of the users with low wall penetration loss and close to the macrocell BS, in these conditions, i.e., in the cases of a small D and L_e , the transmit power of the femtocell user is limited by very small $P_{max,OL}$, and thus the use of $P_{max,CL}$ leads to a higher transmit power of the femtocell user. On the other hand, for a large D and L_e , the transmit power is hardly limited by $P_{max,OL}$, which is close to the maximum transmit power of 23 dBm, and thus an increase in the transmit power is minimal despite of the use of $P_{max,CL}$. Consequently, the femtocell users

with a small D and L_e are affected least by an increase of the interference from neighbor femtocells, which result in the higher throughput gain of the closed-loop control over the open-loop control. Additionally, an increase in M leads to a higher number of femtocell users near the macrocell BS, which results in an increase in the gain of the closed-loop control over the open-loop control in terms of the 5% user throughput of femtocell.

Fig. 4 and 5 show that the femtocell throughput gains of the closed-loop control over the open-loop control are maximally 8% and 120% for the average throughput and the 5% user throughput, respectively. Considering both the performance of macrocells and femtocells, the closed-loop control is more effective in terms of 5% user throughput, while the open-loop control is good for the average throughput. On the other hand, compared with the open-loop control, the closed-loop control additionally requires for femtocell users to know the NI level at the macrocell BS, which needs additional downlink overhead for broadcasting the NI level.

V. CONCLUSION

This study proposes the open-loop and the closed-loop control schemes for the maximum transmit power of femtocell users. The two schemes suppress the cross-tier interference under a fixed threshold and an adaptive threshold based on the actual NI level at the macrocell BS, respectively. Simulation results show that both schemes effectively compensate the uplink throughput degradation of the macrocell BS. Furthermore, the closed-loop control scheme provides better femtocell throughput relative to the open-loop control at a minimal cost of macrocell throughput.

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TABLE I
UPLINK DATA RATE FORMAT

Payload size (bits)	Effective data rate for 4-slot (kbps)	Eb/Nt for 1% FER (dB)
128	19.2	5.6
256	38.4	5.7
512	76.8	5.8
1024	153.6	7
2048	307.2	5.4
4096	614.4	6.3
8192	1228.8	5.5
12288	1843.2	11.4

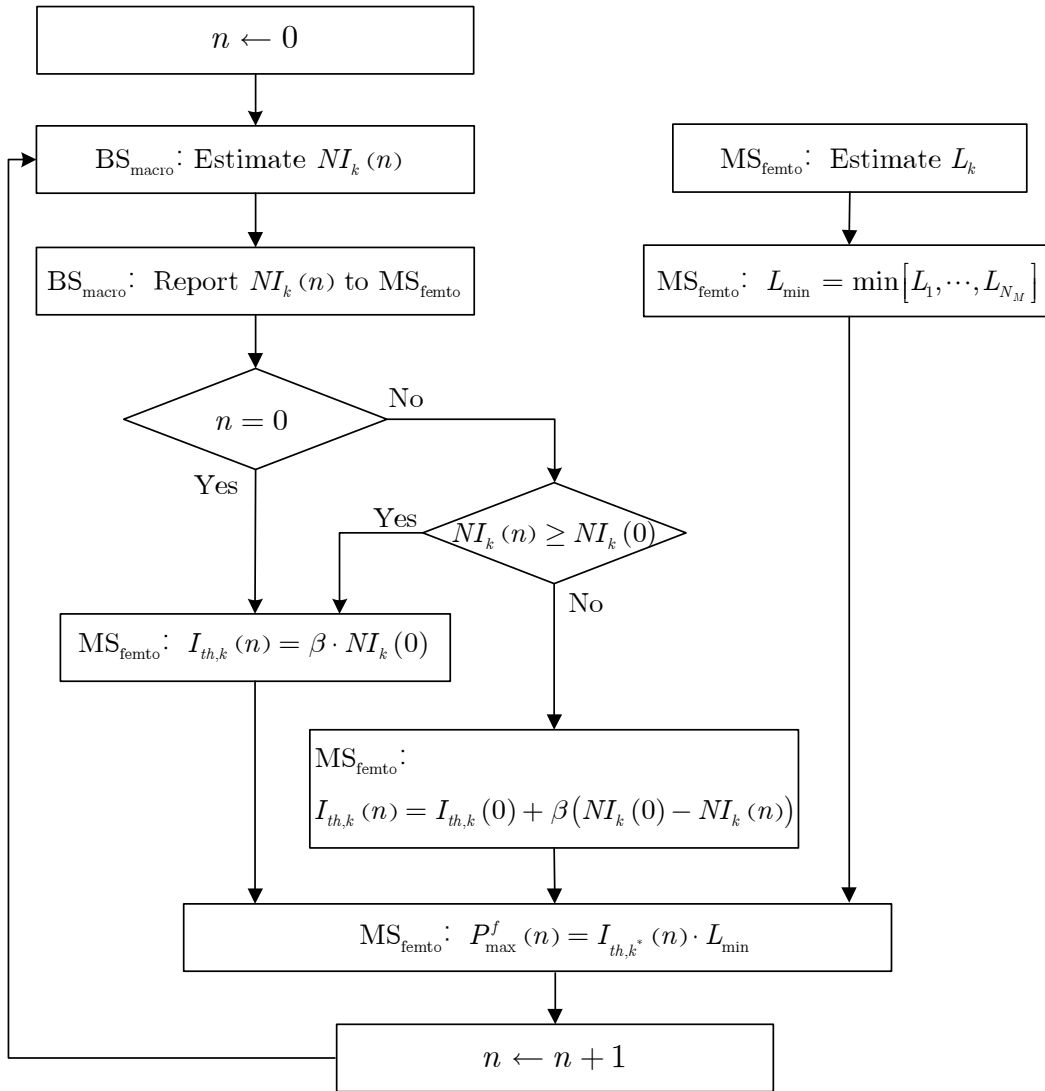


Fig. 1. Flow diagram for the closed-loop power control scheme

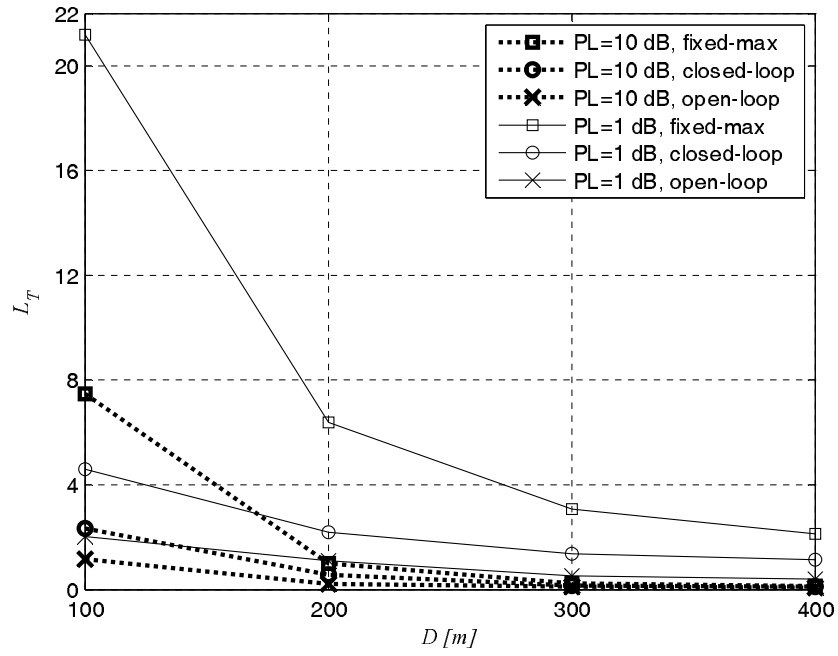


Fig. 2. DRMT L_T versus D for the fixed maximum power transmission, the closed-loop control, and the open-loop control schemes: $L_i = 0$ dB

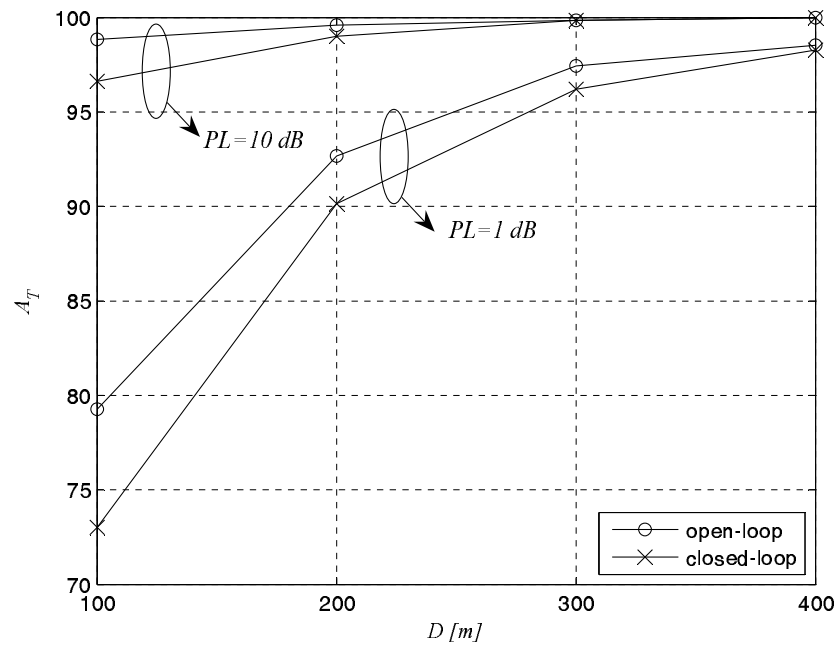


Fig. 3. ARFT A_T versus D for the closed-loop control and the open-loop control schemes: $L_i = 0$ dB

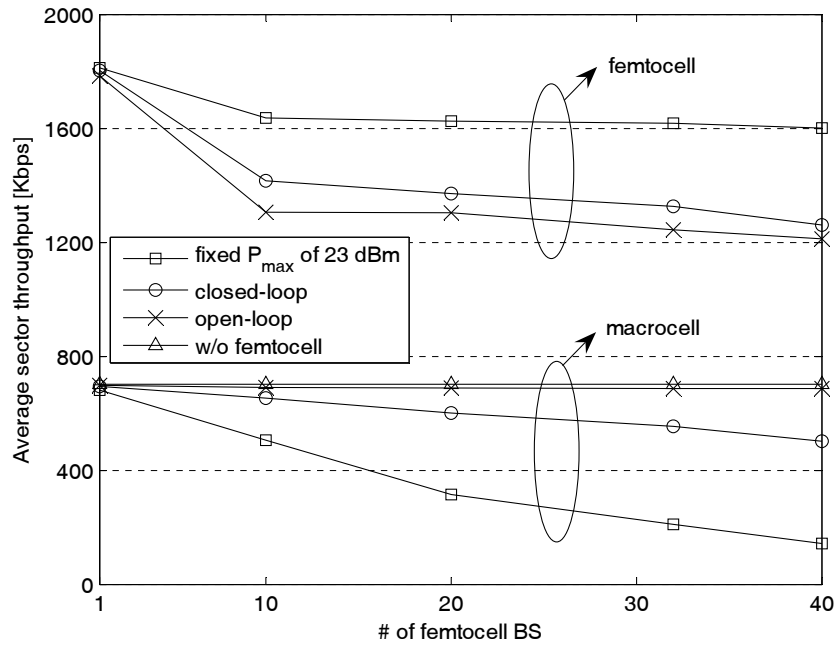


Fig. 4. Average throughput versus the number of femtocell BSs per macrocell, M for the closed-loop control and the open-loop control schemes

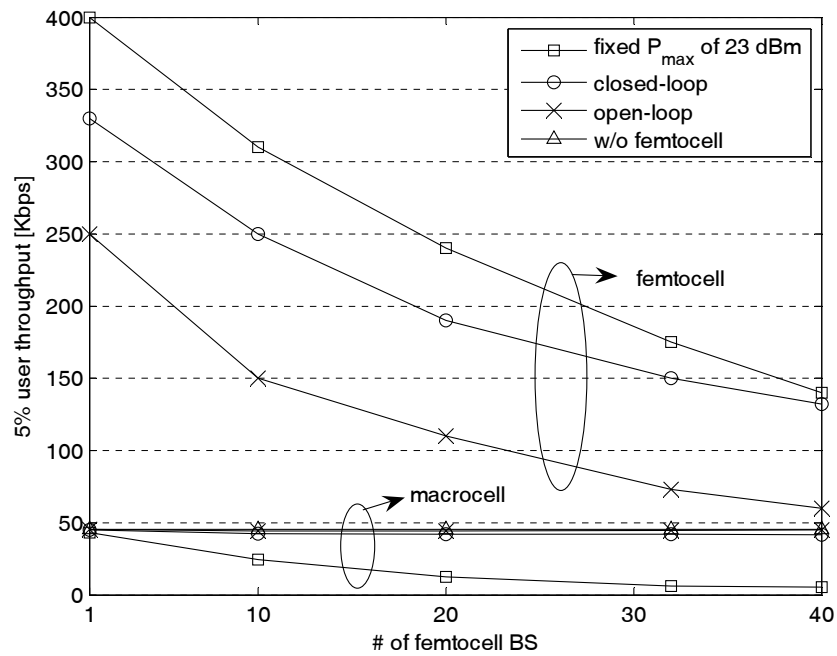


Fig. 5. 5% user throughput versus the number of femtocell BSs per macrocell, M for the closed-loop control and the open-loop control schemes