Capacity Comparison for CSG and OSG OFDMA Femtocells

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***Abstract*—The low-power and low-cost femtocells can improve indoor coverage and capacity. However, when femtocells are deployed extensively, the serious two-tier interference problem occurs. The method to access the femtocell is the key to manage the interference in the femtocell systems. In this paper, we investigate the impacts of access methods and directional antenna on link reliability and capacity for the orthogonal frequency-division multiple access (OFDMA)-based femtocell systems. Simulation results show that the open access method can improve the femtocell capacity over the traditional closed access method. Nevertheless, under the link reliability requirement of indoor and outdoor users, the improvement in femtocell capacity due to open access method is minor. Thanks to the narrow-beam pattern, the switched-beam directional antenna can be used to further reduce the interference and enhance the capacity. It is shown that the open access method using the switched-beam antenna can achieve higher femtocell capacity than that using the omnidirectional antenna.**

***Index Terms*—Femtocell, OFDMA, CSG, OSG, two-tier interference, link reliability, switched-beam directional antenna.**

I. INTRODUCTION

Femtocells are low-power and low-cost home base stations that can improve indoor coverage and capacity. The femtocells operate in the licensed spectrum as the conventional cellular systems, and use the home broadband connection as backhaul to the cellular operators' networks. However, as femtocells are densely deployed, the femtocell systems face the serious two-tier interference problem [1], [2]. The femtocell user suffers the femto-to-femto and macro-to-femto interference, while the macrocell user undergoes the femto-to-macro and macro-to-macro interference. Moreover, the more the subcarriers used by femtocells, the higher the mutual interference. Therefore, managing the two-tier interference is a key issue in the femtocell systems.

When the femtoell systems use the same frequency band as the macrocell systems, the way to access the femtocell for the subscriber significantly influences the interference in the femtocell systems [2]. Generally, there are closed subscriber group (CSG) and open subscriber group (OSG) access methods for femtocell systems. The CSG femtocell base station (fBS) provides the service only for the authorized users, thus the system can ensure privacy and security. However, the interference problem is more serious in the CSG femtocell system. On the contrary, the OSG fBS provides the service for any user to mitigate the interference, thereby improving the capacity.

The technical challenges of the femtocell networks have recently been investigated in [3], [4]. In [3], the authors described that the OSG access method can reduce the macrocell load, while the method may cause the strain of the backhaul to provide sufficient capacity due to the the higher number of users communicating with each femtocell. In [4], the authors depicted that the OSG access method can improve the overall capacity of the network because the outdoor macrocell user can choose the one providing stronger signal from the mBS and the nearby fBS. However, the OSG access method increases the number of handoffs and signaling.

In the literature, most femtocell papers investigated the access methods, system capacity, and link reliability of the femtocell systems with the omnidirectional antennas. In [1], the authors compared the CSG and OSG femtocell systems, and showed that the OSG scheme has better coverage than the CSG scheme. The work in [2] proposed a hybrid access approach that providing few subchannels for the connectivity of unauthorized users to improve the average throughput. In [5], the authors showed that one can adjust the number of used subcarriers to maximize the capacity under the link reliability requirement in the OFDMA-based femtocell systems.

To our knowledge, fewer papers considered the femtocell systems with directional antennas, except for [6]. Directional antenna can decrease the interference and strengthen the signal due to the narrow-beam pattern. The work in [6] considered the multi-element antennas in CDMA-based femtocell systems. The authors exploited the antenna pattern selection and the dynamic power adjustment to reduce the unnecessary handover and enhance the indoor coverage. However, that paper [6] focused on the CDMA-based femtocell systems, considering only the shared spectrum allocation scheme. Moreover, they did not investigate the impact of different access methods on link reliability and capacity for femtocells.

In this paper, we investigate the impacts of access methods and directional antenna on interference, link reliability, and capacity in the orthogonal frequency-division multiple access (OFDMA)-based femtocell systems. Because the user in OSG scheme can select the base station with better signal quality among the femtocells and macrocells, the OSG scheme has better link reliability than the CSG scheme. However, the interference from femtocells still significantly degrades the link reliability of outdoor users as the femtocell and the macrocell systems use the same frequency band. In this situation, each femtocell should use only portion of allocated spectrum to mitigate the interference, while this also lowers the femtocell

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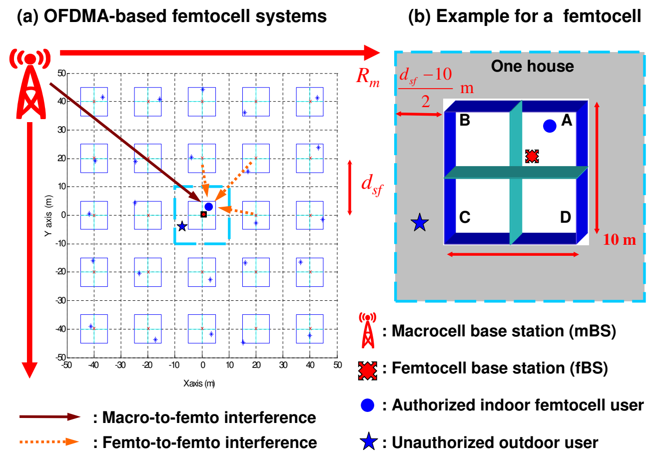

Fig. 1. (a) Two-tier interference for an indoor femtocell user in OFDMA-based femtocell system: macro-to-femto and femto-to-femto interference. (b) Example of a femtocell. The outdoor user is uniformly distributed in the shadowed region with width of $(d_{sf} - 10)/2$ (m) around the considered house.

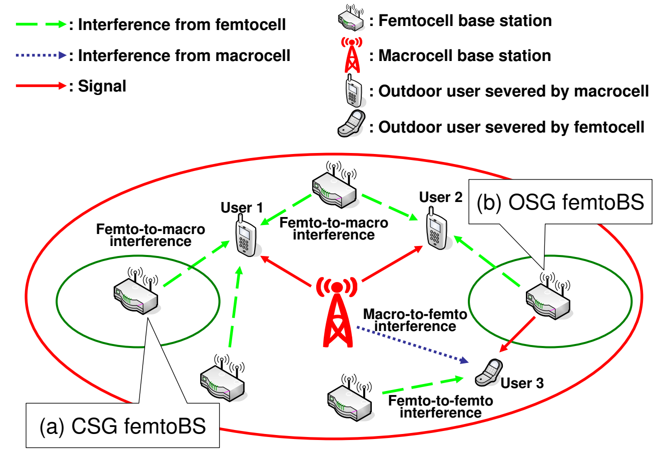

Fig. 2. Two-tier interference for outdoor users with two access methods: (a) Closed subscriber group (CSG) access method; (b) Open subscriber group (OSG) access method.

capacity. Thanks to the narrow-beam pattern, we suggest the switched-beam directional antenna to alleviate the interference and enhance the capacity. Simulation results show that the switched-beam antenna can further improve the capacity for femtocells.

The rest of this paper is organized as follows. Section II describes the system architecture, the access methods, and the switched-beam directional antenna. Section III details the channel models, and the major performance metrics. The simulation results are shown in Section IV. Finally, concluding remarks are given in Section V.

II. SYSTEM MODELS

A. System Architecture

We consider the downlink of the OFDMA-based femtocell system in the campus/community environment, as shown in Fig. 1. We assume a group of 25 femtocells, which is uniformly distributed in a macrocell with a radius of R_m (m). Each house covers an area of 100 square meters and has four 5 m-by-5 m rooms. The fBS is deployed at the center of the house with a shift of (0.1 m, 0.1 m). The separation distance between two neighboring fBSs is d_{sf} (m). Each femtocell serves one user uniformly distributed in the house. In addition, we assume that there is at most one outdoor user around the considered femtocell. The outdoor user is uniformly distributed in the shadowed region with width of $(d_{sf} - 10)/2$ (m) around the considered house, as shown in Fig. 1b.

In this paper, we consider the shared spectrum allocation scheme, where the femtocell and the macrocell systems use the same frequency band. The shared spectrum allocation scheme may increase the spectrum efficiency; however, this scheme faces the serious two-tier interference problem.

B. OSG and CSG Access Methods

In general, there are CSG and OSG access methods for femtocells, as shown in Fig. 2. With the CSG method, only the authorized users can be served by the femtocell system, and thus the system can ensure privacy and security. However, the other unauthorized users can not access to the CSG fBS, even if the femtocell may provide stronger signal than the macrocell. Hence, the unauthorized users suffer a higher interference from the neighboring fBSs in the downlink. Contrarily, the femtocell systems with the OSG method are open for all the users, and the outdoor user can select the one providing stronger signal from the mBS and the OSG fBSs. Therefore, the outdoor user can have better link reliability. Nevertheless, the privacy and security issues are difficult challenges for the OSG access method.

The OFDMA-based femtocell system experiences two-tier interference, as shown in Figs. 1 and 2. This paper considers the downlink case. As shown in Fig. 1a, an indoor femtocell user has the interference from the macrocell and adjacent femtocells. For the CSG femtocell system, the outdoor user served by the macrocell (e.g., User 1) has the interference from all adjacent femtocells, as shown in Fig. 2. In the OSG femtocell system, the outdoor user can connect to the macrocell or the femtocell. If served by the macrocell, the outdoor user (e.g., User 2) has the interference from all neighboring femtocells. As connecting to the femtocell, the outdoor user (e.g., User 3) suffers the macro-to-femto and femto-to-femto interference.

C. Switched-beam Directional Antenna

Directional antennas can decrease the two-tier interference to improve femtocell capacity. For now, most of the home base stations are equipped with the omnidirectional antennas. Omnidirectional antennas have lower antenna gain. In addition, each user will be interfered by all adjacent femtocells. On the contrary, with the higher main lobe gain and the narrow-beam pattern, the switched-beam directional antenna can reduce the interference to the adjacent femtocells and achieve the better signal quality.

This switched-beam antenna system consists of transistor-based switch, and post-wall E-plane horns. According to the

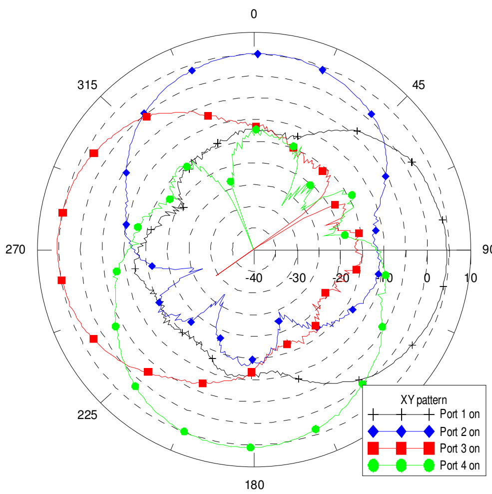

Fig. 3. Each beam pattern of switched-beam antenna.

location of the femtocell user, the switched-beam antenna can dynamically alter the beam pattern to the desired user by the transistor-based switch. Each beam pattern is shown in Fig. 3. Due to the excellent isolation among E-plane horns, this antenna system can have low side-lobe level. The low-cost switched-beam antenna needs only one radio transceiver. The size of this antenna prototype is about $19.2 \times 19.2 \times 9.5$ (cm). It can be further downsized and fine tuned to be more suitable for femtocell applications.

III. Link Reliability and Femtocell Capacity

In this paper, we consider two performance metrics, including the link reliability and the femtocell capacity. In the following, we first discuss the channel models.

A. Channel Models

We consider the impacts of path loss, wall penetration loss, shadowing, and multi-path fading as follows.

1) Path Loss: According to [7], the path loss between the transmitter and the receiver with the propagation distance d (m) is defined as

$$L(d)\ (\mathrm{dB}) = \begin{cases} L_{FS}(d) = 20\log_{10}(\frac{4\pi d}{\lambda}) \ , & d \le d_{BP} \\ L_{FS}(d_{BP}) + 35\log_{10}(\frac{d}{d_{BP}}) \ , & d > d_{BP} \end{cases} \tag{1}$$

where $L_{FS}(d)$ is the free space path loss, and λ is the wavelength. d_{BP} is the break-point distance, which is 5 m for indoor links and 30 m for outdoor links.

2) Wall Penetration Loss: We assume that the penetration attenuation is 5 dB per wall for indoor links, and 10 dB per wall for outdoor-to-indoor links. Besides, $\widetilde{PL}_i$ is the total penetration loss between the i-th femtocell and the considered user, and $\widehat{PL}$ is that between the macrocell and the considered user.

3) Shadowing: Shadowing is modeled by a log-normal random variable $10^{\xi/10}$, where ξ is a Gaussian distributed random variable with zero mean. The shadowing standard deviation is $\sigma = 5$ dB for indoor links, 10 dB for the link between the neighboring femtocells and the considered user, and 8 dB for that between macrocell and the considered user.

4) Multi-path Fading: We take the frequency-selective fading channel into account. The multipath fading is described by the Stanford University interim-3 (SUI-3) channel model assuming 3 taps with non-uniform delays [8].

B. Carrier to Interference-and-noise Ratio (CINR)

For the femtocell users, the two-tier interference comes from the macrocell and the other neighboring femtocells. Suppose that $\widehat{G}(\theta)$ is the antenna gain of the macrocell and $\widetilde{G}(\theta_i)$ is that of the i-th femtocell. Due to the frequency selective fading, $|\widehat{H}_m|^2$ represents the link gain between the macrocell and the femtocell user; and $|\widetilde{H}_{i,m}|^2$ is that between the i-th femtocell and the femtocell user. Therefore, the CINR of the m-th subcarrier for the considered femtocell user is defined as

$$\gamma_{F,m} = \frac{\frac{\widetilde{P}_t \widetilde{G}(\theta_i) 10^{\frac{\widetilde{\xi}_i}{10}} |\widetilde{H}_{i,m}|^2}{L(d_i)\widetilde{PL}_i}}{\frac{\widehat{P}_t \widehat{G}(\theta) 10^{\frac{\widehat{\xi}}{10}} |\widehat{H}_m|^2}{L(D)\widehat{PL}} + \sum_{k=1,k\neq i}^{K} \frac{\widetilde{P}_t \widetilde{G}(\theta_k) 10^{\frac{\widetilde{\xi}_k}{10}} |\widetilde{H}_{k,m}|^2}{L(d_k)\widetilde{PL}_k} + N_0} \tag{2}$$

where the first term of the denominator is the interference from the macrocell, and the second one is that from the neighboring femtocells. $\widehat{P}_t$ is the transmission power of macrocell and $\widetilde{P}_t$ is that of femtocells. $\widehat{\xi}$ is the shadowing between the macrocell and the femtocell user, and $\widetilde{\xi}_i$ is that between the i-th femtocell and the considered femtocell user. D is the separation distance between macrocell and the considered femtocell user. d_i is the separation distance from the i-th femtocell to the considered femtocell user. N_0 is the noise power and K is the total number of femtocells.

For the macrocell users, the interference comes from all the adjacent femtocells. The CINR of the m-th subcarrier for the considered macrocell user is expressed as

$$\gamma_{M,m} = \frac{\frac{\widehat{P}_t \widehat{G}(\theta) 10^{\frac{\widehat{\xi}}{10}} |\widehat{H}_m|^2}{L(D)\widehat{PL}}}{\sum_{k=1}^{K} \frac{\widetilde{P}_t \widetilde{G}(\theta_k) 10^{\frac{\widetilde{\xi}_k}{10}} |\widetilde{H}_{k,m}|^2}{L(d_k)\widetilde{PL}_k} + N_0} \ . \tag{3}$$

According to the exponential effective SIR mapping (EESM) method [9], we can map a vector of CINRs for multiple subcarriers to a single effective CINR. Suppose that the femtocell uses N_d subcarriers for transmission. The CINR for each subcarrier is γ_m, $m = 1, 2, \ldots, N_d$. Then, the effective CINRs for the N_d used subcarriers can be calculated by

$$\gamma_{eff}(\gamma_1, \gamma_2, ..., \gamma_{N_d}) = -\beta \cdot \ln(\frac{1}{N_d} \sum_{m=1}^{N_d} \exp[-\gamma_m/\beta]) \tag{4}$$

where β is the calibration factor for the selected modulation coding scheme (MCS) [9]. Table I lists the considered MCSs, the corresponding effective CINR thresholds, and the EESM parameter β. After we obtain the effective CINR, we can determine the MCS and the corresponding theoretical spectrum efficiency η according to Table I.

TABLE I
MODULATION AND CODING SCHEMES (MCS)

Modulation	Code Rate	Theoretical Spectrum Efficiency η (bps/Hz)	Minimum Effective CINR (dB)	EESM β (dB)
QPSK	1/2(4)	0.25	γ_{th}= -2.5 dB	2.18
QPSK	1/2(2)	0.5	0.5 dB	2.28
QPSK	1/2	1	3.5 dB	2.46
QPSK	3/4	1.5	6.5 dB	2.56
16-QAM	1/2	2	9 dB	7.45
16-QAM	3/4	3	12.5 dB	8.93
64-QAM	1/2	3	14.5 dB	11.31
64-QAM	2/3	4	16.5 dB	13.8
64-QAM	3/4	4.5	18.5 dB	14.71

C. Performance Metrics

The link reliability P_{rel} is defined as the probability that the effective CINR of the considered user is higher than a predefined effective CINR threshold γ_{th}, that is,

$$P_{rel} = \Pr[\gamma_{eff} \geq \gamma_{th}] \ . \quad (5)$$

The achieved capacity is defined as the total throughput of an OFDMA-based femtocell. Consider that each femtocell uses N_d subcarriers for transmission. Assume that B is the system bandwidth and M is the FFT size. Let η be the theoretical spectrum efficiency. Then, the capacity can be calculated by [10]

$$C = \frac{B}{M}\frac{N_d}{1+G} \cdot \eta \quad (6)$$

where G is the guard fraction.

IV. SIMULATION RESULTS

In this section, we investigate the impacts of access methods and directional antenna on link reliability and femtocell capacity in the OFDMA-based femtocells with two-tier interference. We consider the shared spectrum allocation scheme. We assume a fully-loaded macrocell system, where all the subcarriers are occupied by the macrocell users and the femtocell user is interfered by the macrocell system. Moreover, an outdoor macrocell user uses only one subchannel (i.e., 18 subcarriers) for voice call.

The femtocell layout is shown in Fig. 1. There are 24 femtocells around the considered femtocell. The separation distance between two nearest femtocells is d_{sf} = 20 m. The group of 25 femtocells is uniformly distributed in a macrocell with the coverage radius R_m = 500 m. The normal system parameters for the considered OFDMA-based femtocell are listed in Table II [11]. The predefined effective CINR threshold is $\gamma_{th} = -2.5$ dB. The link reliability requirement is $P_{rel} \geq 90\%$. In the OFDMA-based femtocell systems, the more the OFDMA subcarriers used by a femtocell, the higher the interference. Therefore, we should appropriately adjust the number of used subcarriers to lower the interference. The total number of available data subcarriers is $N_{ds} = 720$. The number of used subcarriers is N_d. We define the subcarrier usage ratio as $\rho = \frac{N_d}{N_{ds}}$.

TABLE II
THE OFDMA-BASED FEMTOCELL SYSTEM PARAMETERS

Downlink OFDMA Parameters	Values
Carrier Frequency	2.5 GHz
Macrocell BS (mBS) Transmit Power	43 dBm
Femtocell BS (fBS) Transmit Power	20 dBm
Macrocell BS Antenna Gain $G(\theta)$	8 dB
Macrocell Radius (R_m)	500 m
Noise Figure (mBS/fBS/MS)	5 dB / 5 dB / 7 dB
System Bandwidth (B)	10 MHz
Sampling Frequency	11.2 MHz
FFT Size (M)	1024
Subcarrier Bandwidth	10.9375 kHz
Null Subcarriers	184
Pilot Subcarriers	120
Data Subcarriers (N_{ds})	720
Guard Fraction (G)	1/8
Predefined Effective CINR Threshold for Link Reliability (γ_{th})	-2.5 dB
Link Reliability Requirement	$P_{rel} \geq 90\%$

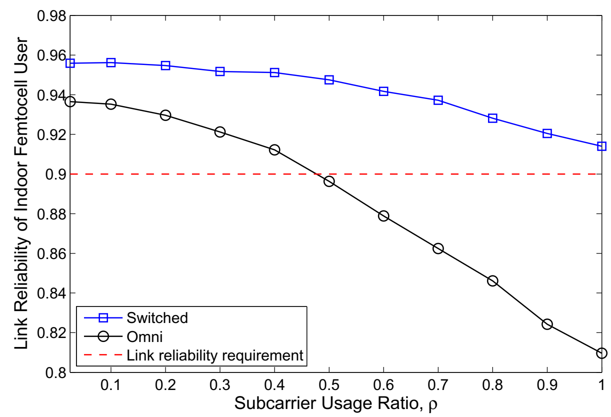

Fig. 4. Link reliability of indoor femtocell user versus the subcarrier usage ratio ρ. The switched-beam directional antenna system and 0-dB omnidirectional antenna system are compared.

A. Impacts of Access Methods and Directional Antenna on Link Reliability and Femtocell Capacity

Figure 4 shows the link reliability of indoor femtocell user against the subcarrier usage ratio ρ. We compare the switched-beam directional antenna and 0-dB omnidirectional antenna systems. Because of the increasing femto-to-femto interference, the link reliability degrades as the number of used subcarriers increases. It is also shown that with the narrow-beam pattern, the switched-beam antenna systems can achieve a better link reliability than the omnidirectional antenna systems. Hence, under a link reliability requirement, the switched-beam antenna systems can use more subcarriers to improve the femtocell capacity. For example, with the link reliability requirement $P_{rel} \geq 90\%$, the maximum allowable subcarrier usage ratio can be $\rho = 1.0$ for the switched-beam antenna with a better link reliability, and $\rho = 0.48$ for the omnidirectional antenna.

Figure 5 shows the link reliability of outdoor user against

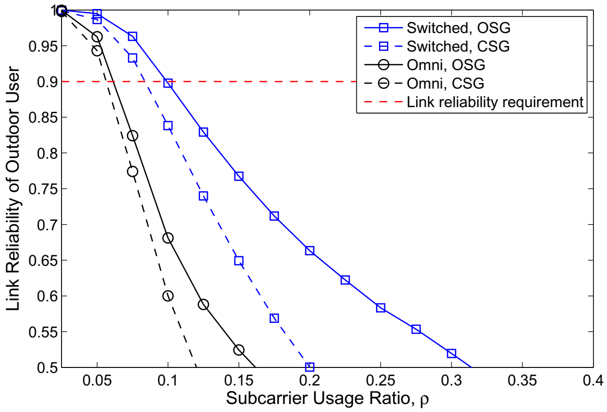

Fig. 5. Link reliability of outdoor user versus the subcarrier usage ratio ρ.

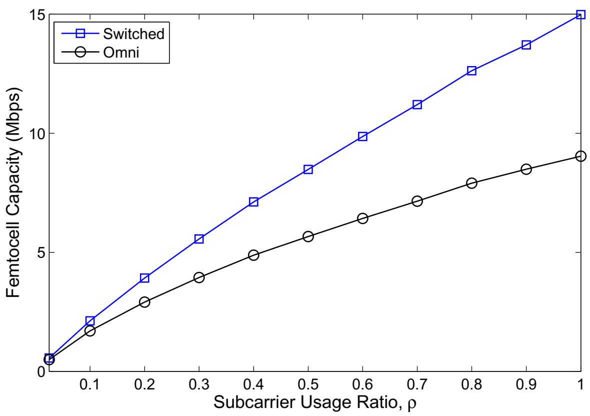

Fig. 6. Femtocell capacity versus the subcarrier usage ratio ρ.

the subcarrier usage ratio ρ. We observe from Figs. 4 and 5 that the outdoor user has lower link reliability than the indoor femtocell user for a given subcarrier usage ratio. This is because the outdoor user experiences a stronger interference from the neighboring femtocells, due to lower total wall-penetration loss. Figure 5 also shows that the OSG access method can achieve higher link reliability for the outdoor user than the CSG method. The reason is that in the OSG access method, the outdoor user can select the base station with the stronger signal strength among the mBS and the fBSs. However, if the OSG method is used in the omnidirectional antenna system, the improvement of the link reliability for the outdoor user is minor. Therefore, we suggest the switched-beam antenna to further improve the link reliability. In this example, for the omnidirectional antenna system at $\rho = 0.075$, the link reliability of outdoor user with the OSG method is mere 6% higher than that with the CSG method. Compared to the omnidirectional antenna system in the OSG method, the switched-beam antenna can further improve the link reliability by 17%.

Figure 6 shows the femtocell capacity against the subcarrier usage ratio ρ. In the figure, the femtocell capacity increases as the number of used subcarriers increases. The switched-beam antenna can achieve higher femtocell capacity than the

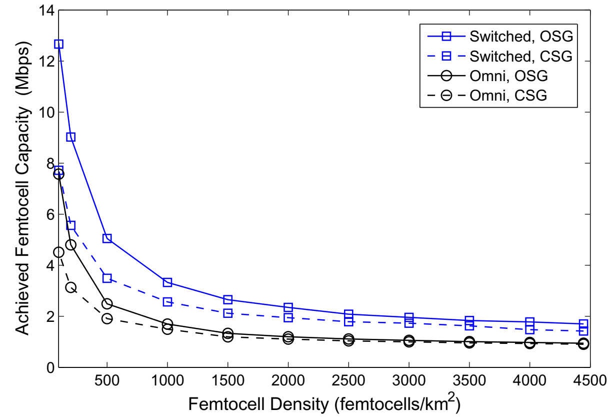

Fig. 7. Achieved femtocell capacity versus the femtocell density with the link reliability requirement $P_{rel} \geq 90\%$ for indoor femtocell user and the outdoor user.

omnidirectional antenna. Figure 6 also shows that the OSG access method can achieve higher femtocell capacity than the CSG method. From Figs. 4 and 5, in the omnidirectional antenna system with the link reliability requirement $P_{rel} \geq 90\%$ of the indoor and outdoor users, the maximum allowable subcarrier usage ratio can be $\rho = 0.056$ for the CSG method, and $\rho = 0.061$ for the OSG method. We can observe from Fig. 6 that in the omnidirectional antenna system, the achieved capacity of the OSG method is 7% higher than that of the CSG method. The switched-beam antenna can further improve the capacity. For example, if we use the switched-beam antenna in the OSG method, the maximum allowable subcarrier usage ratio can increase from $\rho = 0.061$ to $\rho = 0.1$. Compared to the omnidirectional antenna system in the OSG method, the switched-beam antenna can further improve the capacity by 87%.

B. Impact of Femtocell Density

Figure 7 illustrates the achieved femtocell capacity against the femtocell density, where the link reliability $P_{rel} \geq 90\%$ of indoor femtocell user and the outdoor user are ensured. In this figure, due to the increasing interference from the neighboring femtocells, the achieved femtocell capacity decreases as the femtocell density increases. It is also shown that with the link reliability requirement $P_{rel} \geq 90\%$ for all users, the OSG method using the switched-beam antenna can improve femtocell capacity over that using the omnidirectional antenna.

Noteworthily, the CSG method using the switched-beam antenna can yield a higher femtocell capacity than the OSG method using the omnidirectional antenna. The OSG method can select the base station with a higher signal strength and thus improves the femtocell capacity. However, in the omnidirectional antenna system, the OSG method only slightly improves the capacity at a high femtocell density because the transmissions of neighboring femtocells cause considerable interference to the considered user. Even in the CSG method, using the switched-beam antenna can significantly improve the femtocell capacity. For example, at the femtocell density of 2500 $\mathrm{femtocells/km^2}$ (the corresponding separation distance between two femtocells $d_{sf} \approx 20$ m), compared to the CSG method in the omnidirectional antenna system, the OSG method can improve the femtocell capacity by only 7%. If we adopt the switched-beam antenna instead of the omnidirectional antenna in the CSG method, the femtocell capacity can be remarkably improved by 72%. Therefore, in the femtocell systems where the privacy and security are the most important concerns, the CSG method using the switched-beam antenna can be a good option to achieve high-capacity femtocells.

V. CONCLUSIONS

In this paper, at the two-tier interference environment, we investigated the effects of access methods and switched-beam directional antenna on link reliability and femtocell capacity of OFDMA-based femtocell systems. The simulation results show that the OSG method using the switched-beam antenna can achieve higher femtocell capacity than that using the omnidirectional antenna. Besides, using the switched-beam antenna is more effective to reduce the interference and improve the femtocell capacity than employing the OSG access method only. In the environment where the security is the major concern, using the switched-beam antenna is a good option.

Many interesting issues are worthwhile for further investigation from this work. For example, the simulation results show that even if the OSG access method and the switched-beam antenna are used to reduce the interference, the link reliability of outdoor user is still much less than that of indoor user. Therefore, the femtocell systems still need other techniques (e.g., power allocation and channel selection) to achieve the tradeoff between the link reliability of indoor user and that of outdoor user and to improve the overall femtocell capacity.

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