Outage and Diversity-Multiplexing Trade-off Analysis of Closed and Open-Access Femtocells

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Abstract— **Femtocells promise to increase the number of users served in a given macrocell by creating indoor hotspots connected to the mobile operator network via cheap backhaul links (i.e., the Internet). However, the interference created by the femtocell transmissions may critically impair the performance of the macrocell users. This effect can be potentially alleviated via so called *open-access* home base stations. In this paper, the transmission reliability of macro (outdoor) and femto (indoor) users is studied for a quasi-static fading channel in the presence of both open and closed-access home base stations, in terms of outage probability and diversity-multiplexing trade-off. Analytical results are derived that shed light on the impact of femtocells and the advantages of open-access home base stations in different regimes of channel power gains and transmission rates.**

I. INTRODUCTION

Femtocells are often seen as an easy fix to the problem of providing increased network coverage to indoor users of cellular systems. This is mostly due to the availability of cheap backhaul connections between the home base stations (HBSs), installed by the subscribers in their premises, and the operator's network, in the form of last-mile links followed by the Internet [1]. The two basic operating modes of HBS are *open-access* (OA), whereby only the subscriber's devices are allowed to access the HBS, and closed-access (CA), for which all users have the same privileges in accessing the HBS.

Allowing more indoor users to transmit, femtocells may possibly affect the quality of service of the existing macrocell users communicating directly to the macrocell base station (BS), due to the additional interference. In this paper, we study this issue by analyzing the transmission reliability of femtocell and macrocell users in the uplink of a single macrocell overlaid with a single OA or CA HBSs, over quasi-static fading channels (see Fig. 1). Specifically, we first derive analytical expressions for the outage probability with both CA and OA for fixed transmission rates and SNR. We then address the diversity-multiplexing trade-off (DMT) [2][3] in both scenarios, thereby considering the regime of high SNR and of different transmission rate scalings (multiplexing gains).

Related analyses of the performance of cellular systems in the presence of femtocells can be found in [4] and reference therein. Especially related are [5][6]. In [5], the DMT analysis of a single-macrocell single-femtocell system is presented, by modelling the latter as a "Z-interference channel"[2]. In [6] a performance comparison of OA and CA femtocells is provided in terms of achievable throughputs, accounting for the random location of the femtocell with a cell, but not for fading. In both works, one key assumption is that the HBS decodes the signal from the femtocell user and, for OA (in [6]), also the signal of the macrocell users assigned to the HBS. In this work, instead, we do not impose this conventional restriction and allow the HBS to operate, more generally, as a relay for the macro-base station, which is the intended decoder for both femtocell and macrocell users. We mark that, using this standpoint, performance of CA and OA femtocells in multicell systems in the absence of fading is studied in [7].

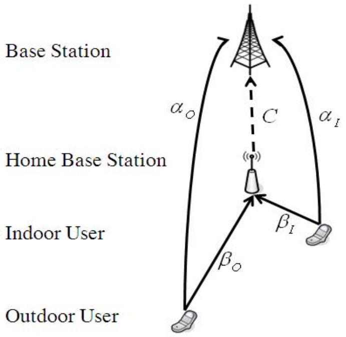

Fig. 1. A macrocell overlaid with a femtocell is modelled as a multiple access channel aided by a relay, where the destination is the BS and the relay is the HBS. An out-of-band link (e.g., last-mile link) connects the HBS to the BS.

Notation: The notation $\doteq$ is the exponential equality $f(\rho)\dot{=}\rho^d$ if $\lim_{\rho\rightarrow\infty} f(\rho)/\rho = d$, and $\dot{\leq},\dot{\geq}$ are similarly defined. $(x)^+$ denotes $\max\{x,0\}$ and $C(x) = \log_2(1+x)$.

II. SYSTEM MODEL

Consider a macrocell, served by single BS which is overlaid with a femtocell served by a HBS, as depicted in Fig. 1. For simplicity, we focus our discussion on the case of a single active indoor (i.e., femtocell) user and a single active outdoor (i.e., macrocell) user per cell. Indoor and outdoor users transmit one message per transmission block with rates

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[2] I.e., no interference is assumed between femtocell user and BS.

R_I and R_O (bits/ channel use), respectively. Assuming time synchronization, the discrete-time received signals for the BS and HBS at time $t = 1, ..., n$ are

$$\begin{aligned} y_{B,t} &= \sqrt{\alpha_I} h_{IB} x_{I,t} + \sqrt{\alpha_O} h_{OB} x_{O,t} + z_{B,t}, \quad (1) \\ y_{H,t} &= \sqrt{\beta_I} h_{IH} x_{I,t} + \sqrt{\beta_O} h_{OH} x_{O,t} + + z_{H,t}, \quad (2) \end{aligned}$$

where subscripts distinguish indoor ("I") user, outdoor ("O") user, HBS ("H") and BS ("B"); α_i, β_i are the user i-to-BS and user i-to-HBS average channel power gains respectively, $i \in \{O, I\}$; h_{iB}, h_{iH} model independent quasi-static Rayleigh fading unit-power channels (i.e., h_{iB}, h_{iH} are complex Gaussian with unit power); $x_{i,t}$ represents user i's transmitted symbol, which is assumed to satisfy the block power constraint $\frac{1}{n}\sum_{t=1}^{n} E\left[|x_{i,t}|^2\right] \leq \rho_i$,where we set $\rho_i = \rho$ since any difference in power can be captured by the average channel gains α_i, β_i; and, finally, $z_{B,t}$, $z_{H,t}$ are the independent unit-power complex Gaussian noise sequences at the BS and HBS respectively. The HBS is connected to the BS via a last-mile link (e.g., DSL or cable) followed by the Internet, which we model here as an out-of-band (i.e., orthogonal) link of capacity C bits/ channel use. The HBS receives (2) for $t = 1, ..., n$ and, based on this, decides the nC bits to be sent to the BS. The BS decodes both messages of indoor and outdoor users based on the signal (1) for $t = 1, ..., n$ and the bits received from the HBS.

We consider two different femtocell configurations [1]: (*i*) *Closed Access* (CA): In this case, we assume that the femtocell attempts to decode the indoor user's signal and treats the outdoor user's signal as noise[3]. Upon successful decoding of the indoor user's message, the femtocell dedicates a rate up to the total capacity C for transmission of such message towards the BS; (*ii*) *Open Access* (OA): Here we assume that the femtocell attempts to decode both the indoor and the outdoor users' signals. Upon successful decoding, the femtocell transmits up to γC bits/ dim for the indoor user's message and up to $(1-\gamma) C$ bits/ dim for the outdoor user's signal, where $0 \leq \gamma \leq 1$ determines the fraction of the capacity allocated for each message. We will analyze the performance of CA and OA femtocells in terms of outage probability (for fixed transmission rates) in Sec. III and DMT in Sec. IV, respectively.

III. OUTAGE ANALYSIS

In this section, we analyze the probability of outage under the assumption of fixed rates R_I and R_O, channel power gains α_i, β_i and power ρ. The outage probability is defined as the probability that *at least one* of the messages from the indoor and/or outdoor users is not successfully decoded at the BS (i.e., common outage event). Using the law of total probability, the outage probability for the OA femtocell can be computed as follows

$$\begin{aligned} P_{out}^{OA} &= P_{H,OI} P_{out|OI} + P_{H,O} P_{out|O} \quad (3) \\ &\quad + P_{H,I} P_{out|I} + P_{H,none} P_{out|none}, \end{aligned}$$

where $P_{H,OI}$, $P_{H,O}, P_{H,I}$ are the probabilities of successful decoding at the HBS of both outdoor and indoor messages ($P_{H,OI}$), of the outdoor message only ($P_{H,O}$), and of the indoor message only ($P_{H,I}$), respectively; $P_{H,none}$ is the probability of decoding no message at the HBS; and, finally, $P_{out|OI}$, $P_{out|I}$, $P_{out|O}$, $P_{out|none}$ denote the outage probability (at the BS) conditioned on the corresponding decoding events at the HBS (e.g., $P_{out|OI}$ is the outage probability conditioned on the HBS decoding both messages). The outage probability for CA femtocell can be found as

$$P_{out}^{CA} = P_{H,I} P_{out|I} + P_{H,none} P_{out|none}, \quad (4)$$

where $P_{H,I}$ and $P_{H,none}$ are similarly redefined for CA (notice that $P_{H,OI} = P_{H,O} = 0$ for CA).

Calculation of the decoding probability at the HBS will be detailed below for CA and OA. As for the evaluation of the conditional outage probabilities at the BS, the following quantity turns out to be useful. Denote as $P_{out}(R_I, R_O)$, the probability of outage for a BS decoder based only on the received signal (1) for $t = 1, ..., n$ (i.e., without accounting for the bits received from the HBS). The set of rates that can be reliably decoded by such decoder is given by the capacity of the multiple access channel (1), which is $\mathcal{R}_B$=$\{(R_O, R_I)$: $R_O \leq C(\alpha_O g_{OB} \rho)$, $R_I \leq C(\alpha_I g_{IB} \rho)$, $R_O + R_I \leq C((\alpha_I g_{IB} + \alpha_O g_{OB})\rho)\}$, with $g_{ij} = |h_{ij}|^2$, and is sketched in Fig. 2-(a). Accordingly, by extending the analysis in [9] to multiple access channels with unequal channel gains, we obtain $P_{out}(R_I, R_O) = \Pr[(R_O, R_I) \notin \mathcal{R}_B]$ as

$$\begin{aligned} P_{out}(R_I, R_O) &= P_{B,I}(R_I, R_O) + P_{B,O}(R_I, R_O) \\ &\quad + P_{B,none}(R_I, R_O), \quad (5) \end{aligned}$$

where $P_{B,I}(R_I, R_O)$, $P_{B,O}(R_I, R_O)$, and $P_{B,none}(R_I, R_O)$ are the outage probabilities at the BS due to not decoding O, not decoding I, and not decoding any of the messages, respectively, and are defined as

$$\begin{aligned} P_{B,I}(R_I, R_O) &= G_{IB} \exp\left[(-K_{B,I})\right. \\ &\quad \left. - \exp\left(-\left(\frac{K_{B,O}}{G_{IB}} + K_{B,I}\right)\right)\right], \quad (6) \end{aligned}$$

and (7) with definitions $G_{ij} = ((2^{R_i} - 1)\zeta_j + 1)^{-1}, K_{B,i} = (2^{R_i} - 1)/(\alpha_i \rho)$ with $i \in \{I, O\}$, $j \in \{B, H\}$ and $\zeta_B = \alpha_O / \alpha_I$. $P_{out,O}(R_I, R_O)$ is the same as $P_{out,I}(R_I, R_O)$ with switched subscripts "I" and "O".

Remark 1: For the special case of the symmetric channel gains, i.e., $\zeta_B = 1$, the above probabilities reduce to eq. (15)-(17) of [9].

A. Closed-Access Femtocells

In this section we evaluate the outage probability (4) for CA femtocells. Recall that, with CA, the HBS decodes the indoor user's message and treats the outdoor user's message as (Gaussian) noise of power $\beta_O \rho$.

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[3] However, no outage is declared if decoding is not successful, unlike [5].

$$P_{B,none}(R_I,R_O)=1-\exp\left(-K_{B,O}\right)+\frac{\exp\left(-\frac{2^{R_O+R_I}-1}{\rho}\right)\left(\exp\left(-K_{B,O}\left(\alpha_O-1\right)\right)-\exp\left(-2^{R_I}K_{B,O}\alpha_O\left(\alpha_O-1\right)\right)\right)}{\alpha_O-1}$$
$$+\frac{\exp\left(\frac{1}{\alpha_O\rho}\right)\left(\exp\left(-\left(\frac{\zeta_B}{\alpha_O\rho}-K_{B,O}\right)\right)-\exp\left(-2^{R_O}\left(\frac{\zeta_B}{\rho}-K_{B,O}\alpha_O\right)\right)\right)}{\left(2^{R_O}-1\right)^{-1}\left(2^{R_O}-1+\zeta_B\right)}+\exp\left(-K_{B,I}\right)\left(\exp\left(\frac{K_{B,O}}{G_{IB}}\right)G_{IB}\right), \quad (7)$$

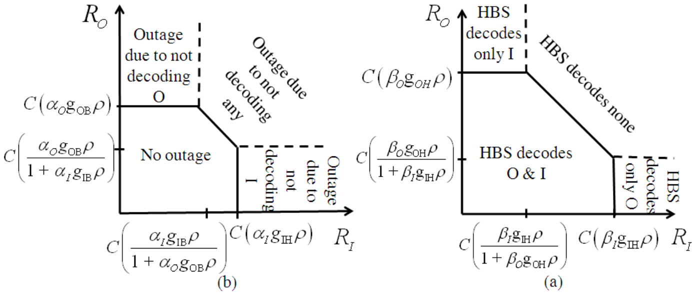

Fig. 2. Illustration of the achievable regions and corresponding outage events for (a) HBS of a CA femtocell and (b) BS.

Proposition 1: The outage probability with a CA femtocell is given by (4), where

$$P_{H,none} = 1-G_{IH}\exp\left(-K_{H,I}\right), \quad (8)$$
$$P_{out|I} = P_{out}((R_I-C)^+, R_O), \quad (9)$$
$$\text{and } P_{out|none} = P_{out}\left(R_I,R_O\right), \quad (10)$$

with $G_{IH} = \left(\left(2^{R_I}-1\right)\zeta_H+1\right)^{-1}$, $K_{H,i} = \left(2^{R_i}-1\right)/\left(\beta_i\rho\right)$, $\zeta_H=\beta_O/\beta_I$ and $P_{H,I}=1-P_{H,none}$.

Proof: Probability $P_{H,none}$ is given by $P_{H,none} = \Pr\left[R_I > C\left(\frac{\beta_I g_{IH}\rho}{1+\beta_O g_{OH}\rho}\right)\right]$, which can be easily calculated using the fact that g_{OH} and g_{IH} are exponentially distributed. Moreover, the outage probability $P_{out|I}$ at the BS, conditioned on the HBS decoding the indoor user message, is given by $P_{out}((R_I-C)^+, R_O)$. This is because the HBS provides up to C bits to the BS regarding the message of the indoor user on the HBS-BS link, upon decoding. These bits reduce the effective rate of the indoor message to be decoded at the BS to $(R_I-C)^+$ (see, e.g., [8]). □

B. Open-Access Femtocells

With OA femtocells, the HBS attempts to decode both the messages of indoor and outdoor users.

Proposition 2: The outage probability with a OA femtocell is given by (3), where $P_{H,I}$, $P_{H,O}$ and $P_{H,none}$ are the same as $P_{B,I}(R_I,R_O)$, $P_{B,O}(R_I,R_O)$, and $P_{B,none}(R_I,R_O)$ with α_O, α_I, ζ_B and $K_{B,i}$ replaced with β_O, β_I, ζ_H, and $K_{H,i}$ respectively, and $P_{H,OI}=1-P_{H,I}-P_{H,O}-P_{H,none}$. Moreover, we have

$$P_{out|OI} = P_{out}((R_I-(1-\gamma)C)^+, (R_O-\gamma C)^+) \quad (11a)$$
$$P_{out|O} = P_{out}(R_I, (R_O-C)^+), \quad (11b)$$
$$P_{out|I} = P_{out}((R_I-C)^+, R_O), \quad (11c)$$
$$P_{out|none} = P_{out}(R_I,R_O). \quad (11d)$$

for some $0\leq\gamma\leq 1$.

Proof: The probabilities of successful decoding at the HBS can be evaluated from Fig. 2-(b) similarly to [9]. For instance, the probability of decoding only the indoor user is given by $P_{H,I} = \Pr\left[R_O > C\left(\beta_O g_{OH}\rho\right),\ R_I \leq C\left(\frac{\beta_I g_{IH}\rho}{1+\beta_O g_{OH}\rho}\right)\right]$. The outage probability (11a) follows from the fact that the HBS, upon decoding both messages, reduces the effective rates to be decoded at the BS to $\left(R_I-(1-\gamma)C\right)^+$ and $\left(R_O-\gamma C\right)^+$. The other terms in (11) are obtained similarly. □

IV. DMT ANALYSIS

Here, we address the DMT analysis of the scenarios with OA and CA femtocells. When evaluating the DMT, one assumes asymptotically large power (or signal-to-noise ratio, SNR) ρ and a collection of transmission schemes, one for each ρ, with rates $R_O=r_O\log_2\rho$ and $R_I=r_I\log_2\rho$, with (r_O,r_I) being the corresponding multiplexing gains. We set $r_O=r_I=r$, with r being the *per-user multiplexing gain* and assume that the capacity of the HBS-BS link scales as $C=c\log_2\rho$ for some $c\geq 0$. Moreover, we write the channel power gains α_i,β_i, $i\in\{O,I\}$ as

$$\alpha_i=\rho^{\bar{\alpha}_i-1} \text{ and } \beta_i=\rho^{\bar{\beta}_i-1}, \quad (12)$$

so that $\bar{\alpha}_i$ and $\bar{\beta}_i$ define the scaling of $\alpha_i\rho$ and $\beta_i\rho$ in dB versus the power ρ (see, e.g., [10]). Notice that varying $\bar{\alpha}_i,\bar{\beta}_i$ allows to account for differences in the power gains as measured in dB. This is especially important in the scenario at hand, where indoor and outdoor channels may have significantly different powers. Given the system parameters above, a diversity gain $d(r)$ is achievable if the probability of outage ((3) for OA and (4) for CA) satisfies $P_{out}\dot{\leq}\rho^{-d(r)}$.

Lemma 1: Setting $R_O=r_O\log\rho$ and $R_I=r_I\log\rho$, we have

$$P_{out}\left(R_O,R_I\right)\dot{\leq}\rho^{-d_{out}(r_O,r_I)},$$

with

$$d_{out}\left(r_O,r_I\right) = \min\Big(\left(\bar{\alpha}_I+\bar{\alpha}_O-2\left(r_O+r_I\right)\right)^+, \left(\bar{\alpha}_O-r_O\right)^+, \left(\bar{\alpha}_I-r_I\right)^+\Big). \quad (13)$$

Proof: Using the conventional definition $g_{iB}=\rho^{-a_i}$ and $g_{iH}=\rho^{-b_i}$, where a_i and b_i are random variables representing the exponential order of g_{iB} and g_{iH}, it can be proved that the probability density function of a_i,b_i can be written as [2][3]

$$f_{a_i}(x)=f_{b_i}(x)\dot{=}\begin{cases}\rho^{-\infty}=0, & \text{for } x<0\\ \rho^{-x}, & \text{for } x\geq 0.\end{cases} \quad (14)$$

Using the union bound, we easily obtain

$$\begin{aligned} & P_{out}\left(R_O, R_I\right) \dot{\leq} \\ & \Pr\left[\left(r_O + r_I\right) > \max\left(\left(\bar{\alpha}_I - a_I\right)^+, \left(\bar{\alpha}_O - a_O\right)^+\right)\right] \\ & + \Pr\left[r_O > \left(\bar{\alpha}_O - a_O\right)^+\right] + \Pr\left[r_I > \left(\bar{\alpha}_I - a_I\right)^+\right] \end{aligned} \quad (15)$$

and the result follows from the standard application of Laplace's principle using (14) [2][3].□

A. Closed-Access Femtocells

Proposition 3: The following DMT is achievable for a femtocell with CA

$$d^{CA}\left(r\right) = \min\left\{d_{out|I},\ d_{H,none} + d_{out|none}\right\}, \quad (16)$$

where

$$\begin{aligned} d_{out|I} &= d_{out}(r, (r-c))^+, & (17) \\ d_{H,none} &= (\bar{\beta}_I - \bar{\beta}_O - r)^+, & (18) \\ \text{and } d_{out|none} &= d_{out}\left(r, r\right). & (19) \end{aligned}$$

with definition (13).

Proof: We need to evaluate (4) in the given setting. To this end, we bound $P_{out}^{CA} \leq P_{out|I} + P_{H,none}P_{out|none}$ (using $P_{H,I} \leq 1$) and then find exponential inequalities for the three terms at hand. For instance, the probability of outage at the HBS $P_{H,none}$ satisfies the exponential inequality

$$P_{H,none} \dot{\leq} \Pr\left[r > \left((\bar{\beta}_I - b_I)^+ - (\bar{\beta}_O - b_O)^+\right)^+\right]$$

which leads to $P_{H,none} \dot{\leq} \rho^{-d_{H,none}}$ with (18) using the Laplace principle and (14). The other terms $P_{out|I}$ and $P_{out|none}$ can be treated similarly by using Lemma 1 and recalling that, upon detection of the indoor user, the HBS communicates (up to) $C = c\log\rho$ bits/ channel regarding the indoor message.□

B. Open-Access Femtocells

Proposition 4: The following DMT is achievable for a femtocell with OA

$$\begin{aligned} d^{OA}\left(r\right) = \max_{0 \leq \gamma \leq 1} \min\big\{ & d_{out|OI},\ d_{H,O} + d_{out|O}, \\ & d_{H,I} + d_{out|I}, d_{H,none} + d_{out|none}\big\}, \end{aligned} \quad (20)$$

where

$$\begin{aligned} d_{out|OI} &= d_{out}\left(\left(r - \gamma c\right)^+, \left(r - \left(1-\gamma\right)c\right)^+\right) & (21a) \\ d_{out|O} &= d_{out}\left(\left(r - c\right)^+, r\right), & (21b) \\ d_{out|I} &= d_{out}\left(r, \left(r - c\right)^+\right), & (21c) \\ d_{out|none} &= d_{out}\left(r, r\right). & (21d) \end{aligned}$$

and

$$\begin{aligned} d_{H,O} &= \left(\bar{\beta}_I - r\right)^+, & (22a) \\ d_{H,I} &= \left(\bar{\beta}_O - r\right)^+, & (22b) \\ d_{H,none} &= \max\Big\{\left(\bar{\beta}_I + \bar{\beta}_O - 4r\right)^+, & (22c) \\ & \left(\bar{\beta}_I + \bar{\beta}_O - r\right)^+ + \left(\bar{\beta}_O - \bar{\beta}_I - r\right)^+\Big\} \end{aligned}$$

Proof: We bound to the outage probability (3) as

$$\begin{aligned} P_{out}^{OA} \ \dot{\leq}\ & \rho^{-d_{out|OI}} + \rho^{-\left(d_{H,O} + d_{out|O}\right)} \\ & + \rho^{-\left(d_{H,I} + d_{out|I}\right)} + \rho^{-\left(d_{H,none} + d_{out|none}\right)} \end{aligned} \quad (23)$$

where we have used $P_{H,OI} \leq 1$ and defined achievable diversity orders for the remaining individual probabilities in (3) as $P_{out|OI} \dot{\leq} \rho^{-d_{out|OI}}$ and similarly for $d_{out|O}, d_{out|I}, d_{out|none}$. These diversity orders can be obtained by using Lemma 1 and the Laplace principle.□

V. NUMERICAL RESULTS

In this section, we present some numerical results to substantiate the analysis above. We start by considering the probability of outage P_{out} for a system with fixed rates $R_O = R_I = 1$ (bits/channel use) and link capacity $C = 0$ or $C = 1$ (bits/channel use) versus the SNR ρ in Fig. 3. We set channel power gains as $\alpha_O = -10dB, \alpha_I = -20dB, \beta_O = 10dB$ and $\beta_I = 20dB$, so that the indoor user-HBS channel is $30dB$ better than the indoor user-BS channel [1]. We compare the outage performance in the presence of CA (Proposition 1) and OA (Proposition 2) with the performance of a scenario, referred to as *"No Femtocell" (NF)*, where *only the outdoor user* is present (i.e., $R_I = 0$). It is noted that in the latter case and for $C = 0$, clearly, CA and OA have the same performance.

From Fig. 3, it is seen that allowing the indoor user to transmit with $C = 0$ (no HBS) increases the outage probability with respect to the NF case[4]. However, exploiting the HBS-BS backhaul link ($C > 0$), with either CA or OA, enables a significant performance improvement. In fact, for $C \geq 1$, CA performs as good as NF due to the possibility to cancel the indoor user's interference at the BS thanks to relaying by the HBS. Moreover, for OA the performance can even be improved with respect to the NF case, since both indoor and outdoor users benefit from the presence of the HBS. Most notably, for $C > R_I + R_O = 2$, we have an increased diversity order with respect to NF, since outage is in this case prevented as long as either HBS or BS decodes.

We then consider the DMT analysis. Fig. 4 shows the DMT for the OA femtocell (Proposition 4) for $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1$, and $c = 1$, compared to the case where the femtocell is turned off ($c = 0$) and to the NF case. Similar to the discussion above, allowing transmission of the indoor user with $c = 0$ is seen to reduce the achievable diversity for sufficiently large multiplexing gain r with respect to the NF case. In particular, no multiplexing gains $r \geq 0.5$ are achievable at non-zero diversity if $c = 0$. This is well known from the analysis in [2], since when $c = 0$ the scenario at hand boils down to a multiple access channel. Our analysis reveals that on OA HBS with $c = 1$ enables a diversity gain of 1 to be achieved for all multiplexing gains $r \leq 3/8$. This

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[4] Recall that we consider the common outage probability. The individual outage probability for the outdoor user increases as well, albeit less than the common outage probability (not shown here).

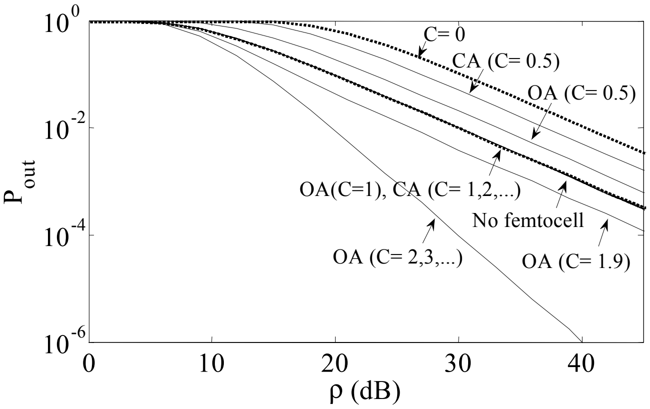

Fig. 3. P_{out} versus ρ for fixed user rates $R_O = R_I = 1$ and different values of link capacity C for CA and OA femtocells $(\alpha_o = -10dB, \alpha_I = -20dB, \beta_o = 10dB, \beta_I = 20dB)$.

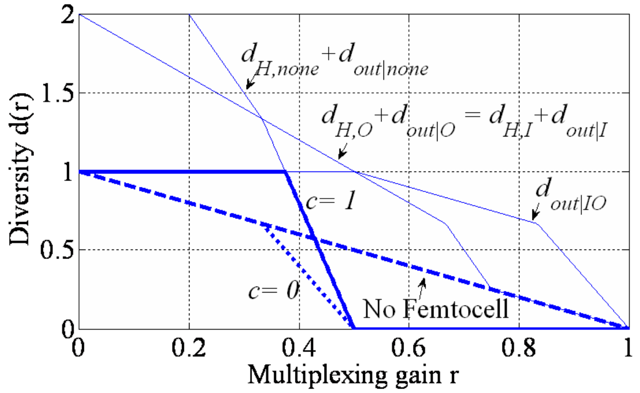

Fig. 4. DMT of the MARC with OA femtocells $(\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1, r_O = r_I = r)$.

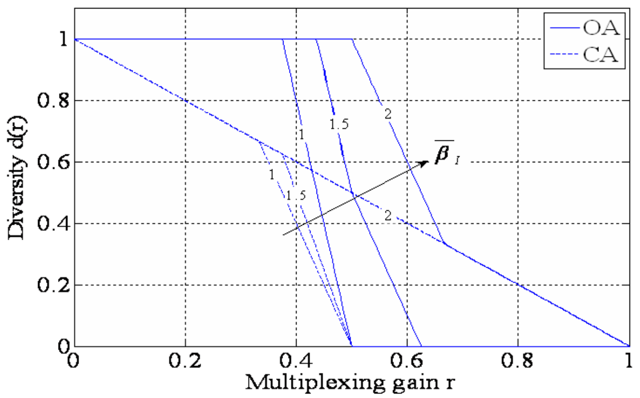

Fig. 5. Comparison between the DMT of the MARC with CA OA femtocells $(\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = \bar{\beta}_I = 1, 1.5, 2, r_O = r_I = r)$.

confirms that, with OA, the overall performance of the system, including outdoor users, can be improved.

Fig. 4 also shows the impact of the different error events on the DMT (20) for OA femtocells. In particular, it is seen that for small multiplexing gains r the dominating error event corresponds to the case where the HBS decodes both messages, whereas for larger r the dominating error events is when the HBS decodes no message.

Finally, Fig. 5 compares the performance of OA and CA in terms of DMT for $\bar{\alpha}_O = \bar{\alpha}_I = \bar{\beta}_O = 1$, $c = 1$ and different indoor user-to-HBS gain $\bar{\beta}_I$. It is seen that OA outperforms CA unless the multiplexing gain and $\bar{\beta}_I$ are large: In this case, the dominating error event corresponds to decoding no messages at the HBS, which, due to large $\bar{\beta}_I$, turns out to have the same asymptotic probability for both CA and OA. Also notice that with $\bar{\beta}_I = 2$, CA has the same DMT as NF, since correct decoding of the indoor user at the HBS happens with high probability.

VI. CONCLUDING REMARKS

The results of this paper confirm that both closed- and open access femtocells have the potential to enable additional indoor transmissions without affecting the quality of service of existing macrocell users. Notably, with the open-access approach, especially in regimes of low multiplexing gains or sufficiently large outdoor user-HBS channel power gains, femtocells are able to improve the overall system transmission reliability while accommodating also indoor users.

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