Outage Probability Analysis for Collocated Spectrum-Sharing Macrocell and Femtocells

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Abstract—Femtocells have been considered by the wireless industry as a promising solution not only to improve indoor coverage, but also to unload traffic from already overburdened macrocells. In spite of potentially excessive interference caused by densely deployed femtocells, macrocells may have to share the same spectrum with femtocells, due to spectrum availability and network infrastructure considerations. In this paper, we derive closed-form expressions for downlink outage probabilities (OP) of collocated spectrum-sharing macrocell and femtocells, based on the stochastic geometry theory. Orthogonal frequency division multiple access (OFDMA) is considered in the downlink of both macro- and femto-cells. Simulation results show that the derived OP expressions are able to predict OP performance of collocated spectrum-sharing macro- and femto-cells, and provide insights on the effects of different system and channel parameters on co-channel femtocell deployments.

Keywords—Femtocell, macrocell, OFDMA, outage probability.

I. INTRODUCTION

Almost all current cellular networks are facing issues arising from imperfect coverage, especially indoors. One cost-effective solution for mobile operators to improve coverage is the emerging femtocell network, where femtocell access points (FAP) [1] are overlaid on an existing macrocell and provide high-data-rate connections to user equipments (UE) within a short range using the same radio-access technology as the macro underlay. Indoor femtocells are expected to solve the problem of weak macro signals inside buildings and offload a large amount of traffic from macrocells. For next generation wireless networks, orthogonal frequency division multiple access (OFDMA) based femtocells are widely anticipated to deliver massive improvements in coverage and capacity [1].

Given that most femtocells will be deployed within coverage of macrocells, inter-cell interference is among the most urgent challenges that must be tackled for successful deployments of femtocells. As plug-and-play devices, FAPs are likely to be deployed by end users. The number and locations of active FAPs will be hardly known to operators. Hence, interference caused by femtocells cannot be managed using conventional network planning methods. The spectrum allocation policy in [2] avoids femto-to-macro interference by assigning orthogonal spectra to the macro and femto tiers, and mitigates femto-to-femto interference by allowing each femtocell to access only a random subset of the spectrum resources assigned to the femto tier. However, femtocells may have to operate in the same spectrum with macrocells, because of spectrum availability and infrastructure considerations [3]. It is technically challenging to achieve the high areal spectral efficiency promised by spectrum sharing between colocated macro- and femto-cells, due to the near-far effect. It has been shown in [4] that the maximum allowable spatial intensity of simultaneous co-channel femto transmissions subject to constraints on macro and femto outage probabilities (OP) varies with the location w.r.t. the central macro base station (MBS). Nevertheless, the analysis in [4] accounts for path loss and Rayleigh fading only, without considering the effect of shadowing, and mainly focuses on the enhanced robustness against inter-cell interference offered by multiple antennas employed at the MBS and FAPs.

In this paper, we provide an analysis of downlink (DL) OP for colocated spectrum-sharing macro- and femto-cells, based on the stochastic geometry theory [5]. Closed-form macro and femto OP expressions are derived as functions of the location w.r.t. the MBS, the spatial intensity of simultaneous co-channel femto transmissions, the FAP transmit power, the macro and femto target signal-to-interference ratios (SIR), etc. Our OP analysis accounts for path loss, wall-penetration loss, Rayleigh fading and lognormal shadowing. Simulation results verify the accuracy of these closed-form OP expressions and demonstrate that our analytical results permit explicit studies of the impact of different system and channel parameters on the deployments of colocated spectrum-sharing macro- and femto-cells.

The rest of the paper is organized as follows. System and channel models are introduced in Section II. DL OP analysis is presented in Section III. Simulation results are provided in Section IV. Conclusions are drawn in Section V.

II. SYSTEM AND CHANNEL MODELS

A. System Model

The basic radio resource unit that is addressable for OFDMA transmissions is a resource block (RB) [6], which is defined in time and frequency domains. Intra-cell interference in OFDMA networks is avoided by maintaining orthogonality among co-cell UEs [2], [7], i.e., one scheduled UE per RB in each cell.

We consider the OFDMA DL of colocated spectrum-sharing macro- and femto-cells. The macrocell covers a disc of radius \( R \) with the MBS in the center. Locations of outdoor UEs at a point in time form a stationary Poisson point process (SPPP) on \( \mathbb{R}^2 \) [5]. For analytical tractability, co-channel interference from neighboring macrocells is ignored. Closed-access femtocells, each serving its authorized UEs only [8], are overlaid on the macrocell. Locations of simultaneously transmitting co-channel...
FAPs at a point in time form a marked SPPP on $R^2$ [5], with a spatial intensity of $\lambda_0 \rho$, where $\lambda_0$ is the spatial density of FAPs and $\rho (0 < \rho \leq 1)$ is the probability of each FAP transmitting in an RB. Each femtocell covers a disc of radius $r_f$ and serves $U_f$ indoor UEs. The average number of FAPs within the macrocell coverage is $N_e$. Without loss of generality, we assume that each MBS/FAP assigns equal transmission power to all RBs for a given transmission time interval (TTI) [2]. A single-antenna transceiver is assumed for all MBS, FAPs and UEs. Since cellular networks are mostly interference limited, thermal noise at the receiver is neglected for simplicity.

### B. Channel Model

In the DL channel, temporal variations of each subchannel are modeled by lognormal (LN) shadowing and frequency-flat Rayleigh fading, the latter resulting in exponentially distributed power gains. Shadowing and fading coefficients are constant within each TTI, but may vary from one TTI to the next.

Terrestrial propagation decays follow the IMT-2000 channel model [9]. The path loss from the MBS to an outdoor UE is

$$PL_{Y} = \phi_d d_{Y}^{-\alpha_d} = 10^{-7.3} f_c^{-3},$$

where $d$ denotes the distance of the link, $\phi_d = 10^{-7.3} f_c^3$ and $\alpha_d$ are the fixed loss and path loss exponent of outdoor channel, respectively, and $f_c$ is the carrier frequency in MHz.

The path loss from an FAP to its indoor UE is given by

$$PL_{F} = \phi_f d_{Y}^{-\alpha_f},$$

where $\phi_f = 10^{-7.3}$ and $\alpha_f$ denote the fixed loss and the path loss exponent of indoor propagation, respectively.

The path loss from an FAP to an outdoor UE is given by

$$PL_{MF} = \phi_{MF} d_{MF}^{-\alpha_{MF}} = \phi_f \zeta_{MF} d_{MF}^{-\alpha_{MF}},$$

where $\phi_{MF} = \phi_f \zeta$ and $\alpha_{MF}$ denote the fixed loss and the path loss exponent on the link from an indoor FAP to an outdoor UE, respectively, and $\zeta$ denotes the wall-penetration loss.

The path loss from the MBS to an indoor UE is given by

$$PL_{FM} = \phi_{FM} d_{FM}^{-\alpha_{FM}} = \phi_f \zeta_{FM} d_{FM}^{-\alpha_{FM}},$$

where $\phi_{FM} = \phi_f \zeta$ and $\alpha_{FM}$ represent the fixed loss and the path loss exponent from the MBS to an indoor UE, respectively.

The path loss from the link of an interfering FAP to an indoor UE is given by

$$PL_{FF} = \phi_f d_{FF}^{-\alpha_{FF}} = \phi_f \zeta_{FF}^2 d_{FF}^{-\alpha_{FF}},$$

where $\phi_f = \phi_f \zeta$ and $\alpha_{FF}$ denote the fixed loss and the path loss exponent of the link from an interfering FAP to an indoor UE, respectively, and $\zeta_{FF}^2$ indicates double wall-penetration losses.

### III. DOWNLINK OUTAGE PROBABILITIES

#### A. Femtocell Downlink Outage Probability

For a given RB, the received SIR of an indoor femto UE (FUE) at the cell edge of its home FAP is given by

$$SIR_F = \frac{P_T \phi_f^{-1} H_{Y} Q_{Y} r_{Y}^{-\alpha_f}}{P_{M,Tx}^{-1} H_{M,Tx} Q_{M,Tx} D_{M,Tx}^{-\alpha_{M,Tx}} + \sum_{i=\Phi} P_T \phi_f^{-1} H_{Y} Q_{Y} r_{Y}^{-\alpha_f}},$$

where the interference is summed over transmissions from the MBS and the set $\Phi$ of FAPs that transmit in the given RB; $P_{M,Tx}$ being the MBS transmit power in each RB, $G_{MBS}$ being the MBS antenna gain and $G_{UE}$ being the UE antenna gain; $P_T$ being the FAP transmit power in each RB (which is assumed for all FAPs) and $G_{FAP}$ being the FAP antenna gain; $r_f$ is used for the worst case that all indoor UEs locate on the edge of their home femtocells; $D_{M,Tx}$ and $D_{F,Tx}$ are random distances from the MBS and interfering FAP $i$ to the indoor UE, respectively; $H_{M,Tx}$ and $H_{F,Tx}$ denote exponentially distributed unit-mean power gains on the links from the home FAP, MBS and interfering FAP $i$ to the indoor UE, respectively; $Q_{Y} \sim LN(\zeta Y, \sigma_{YY})$, $Q_{M} \sim LN(\zeta_{YM}, \sigma_{Y_{M}})$ and $Q_{M,Tx} \sim LN(\zeta_{YM}, \sigma_{Y_{M}})$ denote the lognormal shadowing on the links from the home FAP, MBS and interfering FAP $i$ to the indoor UE, respectively, with $\zeta = 0.11n10 [2]$. Random variables (RV) $H_{M,Tx}$, $H_{F,Tx}$, $Q_{M,Tx}$, $D_{M,Tx}$, $D_{F,Tx}$, $\{Q_{M,Tx}\}$ and $\{D_{M,Tx}\}$ are mutually independent.

For successful decoding of messages intended for the indoor UE, SIR$_F$ has to be no less than the SIR target $\gamma_Y$, which represents a minimum quality of service (QoS) requirement. Assuming identical statistics across all RBs, the OP of an indoor FUE is given by

$$P(SIR_F < \gamma_Y) = P\left\{\frac{S_F}{I_{FM}} + \sum_{i=\Phi} P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}} < \gamma_Y\right\}$$

$$= P\left(\frac{S_F}{I_{FM}} < \gamma_Y\right) + P\left(SIR_F < \gamma_Y: \frac{S_F}{I_{FM}} \geq \gamma_Y\right)$$

where $S_F = P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}$ is the received signal power from the home FAP, and $I_{FM} = P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}$ denotes the received interference power from the MBS.

For an indoor FUE at a distance $d_{Y}\text{m}$ from the MBS, the first probability in the second line of (7) is given by

$$P\left(\frac{S_F}{I_{FM}} < \gamma_Y\right) D_{FM} = d_{FM} = P\left(\frac{H_{YY} Q_{YM} r_{YM}^{-\alpha_{YM}}}{H_{YY} Q_{YM} r_{YM}^{-\alpha_{YM}}} < \frac{P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}}{P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}} : \gamma_Y\right).$$

According to [10], the product of an exponential RV and a lognormal RV can be approximated as a lognormal RV. For the values of $\sigma_{YY}^2$ and $\sigma_{YM}^2$ considered in this paper (Table 1), we approximately have $H_{YY} \sim LN\left(\mu_{YY}, \sigma_{YY}^2\right)$, with $\mu_{YY} = (\zeta_{YM} - 2.5)$ dB, $\sigma_{YY}^2 = \zeta_{YM}^2 + 5.5^2$ dB, and $H_{YY} Q_{YY} \sim LN\left(\mu_{YY}, \sigma_{YY}^2\right)$, with $\mu_{YY} = (\zeta_{YM} - 2.5)$ dB, $\sigma_{YY}^2 = \zeta_{YM}^2 + 5.5^2$ dB. Let $\vartheta = H_{YY} Q_{YY}$, it is easy to show that $\vartheta \sim LN\left(\tilde{\mu}_Y - \tilde{\mu}_{YM}, \tilde{\vartheta}_Y^2 + \tilde{\vartheta}_M^2\right)$. Thus, (8) can be calculated using the LN cumulative distribution function (CDF) of $\vartheta$, i.e.,

$$P\left(\frac{S_F}{I_{FM}} < \gamma_Y D_{FM} = d_{FM}\right) = F_{\vartheta}\left(\frac{P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}}{P_T \phi_f^{-1} H_{YY} Q_{YY} r_{YY}^{-\alpha_{YY}}} : \gamma_Y\right)$$

where $F_{\vartheta}(x; \tilde{\mu}_Y - \tilde{\mu}_{YM}, \tilde{\vartheta}_Y^2 + \tilde{\vartheta}_M^2) = P(\vartheta < x)$ is the CDF of the lognormal RV $\vartheta$.

The second probability in the last line of (7) is given by
CDFs of femto interferers and its complementary set, i.e., substituting the lognormal PDF of given by the probability that at least one dominant femto

last line of (11) for simplification of expression, we define

Accordingly, the lower bound of (10) can be written as

where

According to (7), the OP w.r.t. the SIR target γ of an indoor FUE at a distance \( d_{FM} \) from the MBS, is given approximately by the summation of (9) and (13).

B. Macrocell Downlink Outage Probability

For a given RB, the SIR of an outdoor macro UE is given by

where

For successful decoding of the DL signal intended for the outdoor UE, SIRm has to be no less than the SIR target \( \gamma_m \). Assuming identical statistics across all RBs, the OP of an outdoor macro UE is given by

As in the analysis of femtocell DL OP, a lower bound of (15) is given by the probability that at least one dominant femto interferer causes a macro outage w.r.t. \( \gamma_m \). Following similar steps to those leading to (11), we obtain
where \( F_{S_M}(w) = P(S_M \leq w) \) is the CDF of \( S_M \). we approximate
\( H_{MBS} H_{MBS,M} = \ln(\tilde{\mu}_M, \tilde{\sigma}_M^2) \), with \( \tilde{\mu}_M = \tilde{\gamma}(h_{MBS} - 2.5) \) dB and
\( \tilde{\sigma}_M = \frac{\sqrt{\sigma^2_M + 5.57^2}}{10} \) dB [10], and define
\[
K_M = \pi \left( \frac{P_{c,Tx} \tilde{\gamma}_M}{\tilde{\sigma}_M^2} \right)^{\frac{1}{2}} \exp \left( \frac{2 \tilde{\mu}_M}{\tilde{\sigma}_M^2} + \frac{2 \tilde{\sigma}_M^2}{\tilde{\sigma}_M^2} \right).
\]

For an outdoor UE at a distance \( d_M \) from the MBS, the received signal power from the MBS is given by \( S_M(d_M) = P_{M,Tx} H_{MBS,M} d_M^{\alpha_M} \). Since \( H_{MBS,M} \sim LN(\tilde{\mu}_M, \tilde{\sigma}_M^2) \), with \( \tilde{\mu}_M = \tilde{\gamma}(h_{MBS} - 2.5) \) dB and \( \tilde{\sigma}_M = \frac{\sqrt{\sigma^2_M + 5.57^2}}{10} \) dB [10] for the value of \( \tilde{\sigma}_M^2 \) given in Table I, it is easy to show that \( S_M(d_M) \sim LN(\tilde{\mu}_M, \tilde{\sigma}_M^2) \), with \( \tilde{\mu}_M = \tilde{\mu}_M + \ln(P_{M,Tx}) - \ln(d_M^{\alpha_M}) \). By substituting the lognormal PDF of \( S_M(d_M) \) into (16) and using the Gauss-Hermite series expansion [11], we calculate the OP for an outdoor UE at a distance \( d_M \) from the MBS as follows
\[
P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) = \sum_{n=0}^{\infty} \frac{(-1)^n}{\sqrt{n!}} \left[ \tilde{\mu}_M^{n} \right]^n \left( \tilde{\sigma}_M^2 \right)^n \left( \frac{1}{\tilde{\gamma}} \right)^n \exp \left( \frac{-\tilde{\gamma}^n}{\tilde{\sigma}_M^2} \right) \left( \prod_{i=1}^{n} \left( \frac{2 \tilde{\mu}_M}{\tilde{\sigma}_M^2} \right)^n \right).
\]

C. Interpretations

The collocated spectrum-sharing macrocell and femtocells to meet their respective DL SIR outage constraints. For instance, such QoS constraints may stipulate that \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \) be \( \leq \varepsilon_i \) and \( \leq \varepsilon_i \), respectively.

According to (9), \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \) is a monotonically decreasing function of \( d_M \) for given \( P_{M,Tx} \) and \( P_{F,Tx} \). If an FUE to meet the QoS requirements \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \leq \varepsilon_i \) is to be at least \( d_{F,Tx,min} \) in distance away from the MBS, with
\[
d_{F,Tx,min} = \left( \frac{P_{c,Tx} \tilde{\gamma}_M}{\tilde{\sigma}_M^2} \right)^{\frac{1}{2}} \left( \frac{1}{\tilde{\gamma}} \right)^n \left( \prod_{i=1}^{n} \left( \frac{2 \tilde{\mu}_M}{\tilde{\sigma}_M^2} \right)^n \right)
\]
where \( F_{M,Tx}^{-1}(\varepsilon_i|\tilde{\sigma}_M^2) \) is the inverse CDF of \( \tilde{\gamma} \) evaluated at \( \varepsilon_i \), and \( d_{F,Tx,min} \) is equivalent to the no-coverage femtocell radius in [4].

According to (9) and (13), for given \( d_{F,M}, u_T \) and \( P_{M,Tx} \), \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \) is a monotonically decreasing function of \( P_{F,Tx} \). The minimum \( P_{F,Tx} \) required for meeting \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \leq \varepsilon_i \), namely \( P_{F,Tx,min}(d_M) \), can be obtained by solving \( \frac{P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \leq \varepsilon_i \} \) for \( P_{F,Tx} \). According to (17), for given \( d_M, u_T \) and \( P_{M,Tx} \), \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \) is a monotonically increasing function of \( P_{F,Tx} \) and the maximum \( P_{F,Tx} \) that satisfies \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \leq \varepsilon_i \), namely, \( P_{F,Tx,max}(d_M) \), can be obtained by solving \( P(\text{SIR}_M < \gamma_M|\tilde{D}_M = d_M) \) for \( P_{F,Tx} \). These non-linear equations in \( P_{F,Tx} \) can be solved using standard functions such as \( \text{fsolve} \) in MATLAB® and \( \text{NSolve} \) in Mathematica®.

At a distance \( d \in (d_{F,Tx,min}, r_M) \) from the MBS, if \( P_{F,Tx,min}(d) \leq P_{F,Tx,max}(d) \), then \( P_{F,Tx}(d) \) can be set in the range \( [P_{F,Tx,min}(d), P_{F,Tx,max}(d)] \), for simultaneously meeting the constraints on both macro and femto DL OPs; otherwise, we have to reduce \( u_T \) to make the femtocell deployment feasible. Given \( \delta_i, u_T \) can be reduced by decreasing \( \rho \), e.g., as in the F-ALOHA strategy [2].

IV. SIMULATION RESULTS

In this section, we present simulation results to evaluate the derived closed-form femto and macro OP expressions. In the simulations, spatial distributions of outdoor UEs and FAPs on the \( R^2 \) plane follow independent SPPPs. All indoor UEs locate on the edge of their home femtocells. Rayleigh fading has a unit average power. Values of other major system and channel parameters used in the simulations are given in Table I.

<p>| Table I. Parameters Used in the Simulations |</p>
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>( \xi )</td>
<td>5 dB, 10 dB</td>
<td>( P_{M,Tx} )</td>
<td>43 dBm</td>
</tr>
<tr>
<td>( u_M, u_F )</td>
<td>4</td>
<td>( P_{F,Tx} )</td>
<td>( \leq 23 ) dB</td>
</tr>
<tr>
<td>( d_F )</td>
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<td>( \sigma_M )</td>
<td>15 dB</td>
</tr>
<tr>
<td>( \sigma_F, \sigma_M )</td>
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<td>( \sigma_{FF} )</td>
<td>2 dB</td>
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<td>( \sigma_F )</td>
<td>8 dB</td>
<td>( \sigma_{FF} )</td>
<td>12 dB</td>
</tr>
<tr>
<td>( \sigma_{FF}, \sigma_{MF} )</td>
<td>10 dB</td>
<td>( \rho )</td>
<td>0 dB</td>
</tr>
<tr>
<td>( \sigma_{MF}, r_M )</td>
<td>10 dB</td>
<td>( \rho )</td>
<td>2</td>
</tr>
<tr>
<td>( f_c )</td>
<td>2000 MHz</td>
<td>( \gamma_M )</td>
<td>3 dB</td>
</tr>
<tr>
<td>( \varepsilon_M, \varepsilon_F )</td>
<td>0.1</td>
<td>( \varepsilon_F )</td>
<td>5 dB</td>
</tr>
</tbody>
</table>

Fig. 1 shows the OP versus the number of simultaneously transmitting co-channel femtocells (i.e., \( \rho_{F,Tx} \)), for \( P_{M,Tx} = 43 \) dBm, \( P_{F,Tx} = 23 \) dBm, \( \xi = 10 \) dB, \( \rho = 1 \), and at a distance of 300 m or 600 m away from the MBS. The OP curves provided by our closed-form OP expressions are in close agreement with simulation results. As \( \rho_{F,Tx} \) increases from 1 to 100, the macro OP increases significantly, while the femto OP remains almost constant. For a given distance and any \( \rho_{F,Tx} > 10 \), the macro OP is much higher than the femto OP, indicating that the femto-to-macro interference is much more significant than the femto-to-femto interference. This is mainly due to the double-wall separation between neighboring femtocells (as in (5)). At a longer distance from the MBS, the macro OP becomes much higher, while the femto OP gets slightly lower.
Fig. 2 plots the minimum MBS-to-FUE distance ($d_{FM\text{min}}$) versus $P_{F,Tx}$, for $P_{M,Tx} = 43$ dBm, $\xi = 5$ dB or 10 dB, and to keep the femto DL OP below 0.1. The curves obtained using (18) match closely with simulation results. For either value of $\xi$ considered, $d_{FM\text{min}}$ decreases with $P_{F,Tx}$. For a given $P_{F,Tx}$, $d_{FM\text{min}}$ is much reduced for $\xi = 10$ dB, i.e., a relatively high-attenuation channel, as compared with the case for $\xi = 5$ dB.

Fig. 2 $d_{FM\text{min}}$ vs. $P_{F,Tx}$, for $P_{M,Tx} = 43$ dBm, $\rho = 0.1$, and $\xi = 5$ dB or 10 dB.

Fig. 3 shows the maximum and minimum FAP transmit powers, i.e., $P_{F,Tx,max}(d)$ and $P_{F,Tx,\text{min}}(d)$, versus the distance $d$ from the MBS, for $P_{M,Tx} = 43$ dBm, $N_F = 100$, $\xi = 5$ dB, and $\rho = 1$ or 0.1. Both $P_{F,Tx,max}(d)$ and $P_{F,Tx,\text{min}}(d)$ decrease with $d$. At any given $d$, we find that $P_{F,Tx,max}(d) < P_{F,Tx,\text{min}}(d)$ for $\rho = 1$. In this case, it is not feasible to overlay 100 femtocells on the macrocell. As $\rho$ is reduced to 0.1, $P_{F,Tx,\text{min}}(d)$ decreases slightly while $P_{F,Tx,max}(d)$ increases significantly, making it possible to deploy 100 femtocells within the macro coverage. Since $\rho$ is the probability of each FAP transmitting in an RB, a reduced $\rho$ translates into less femtocells transmitting in each RB, thereby mitigating interference caused by femtocells.

Fig. 4 plots $P_{F,Tx,max}(d)$ and $P_{F,Tx,\text{min}}(d)$ versus $d$ under the same condition as Fig. 3, except for $\xi = 10$ dB. In this case, $P_{F,Tx,max}(d) > P_{F,Tx,\text{min}}(d)$ even for $\rho = 1$. By comparing Fig. 4 with Fig. 3, we can observe that as $\xi$ increases, $P_{F,Tx,\text{min}}(d)$ decreases while $P_{F,Tx,max}(d)$ increases, indicating that a higher-attenuation environment favors a higher spatial density of simultaneous co-channel femtocell transmissions.

Fig. 3 $P_{F,Tx,max}(d)$ and $P_{F,Tx,\text{min}}(d)$ vs. the distance $d$ from the MBS, for $P_{M,Tx} = 43$ dBm, $N_F = 100$, $\xi = 5$ dB, and $\rho = 1$ or 0.1.

Fig. 4 $P_{F,Tx,max}(d)$ and $P_{F,Tx,\text{min}}(d)$ vs. $d$, for $P_{M,Tx} = 43$ dBm, $N_F = 100$, $\xi = 10$ dB, and $\rho = 1$ or 0.1.

V. CONCLUSIONS

In this paper, we have derived closed-form expressions of DL OPs for collocated spectrum-sharing macro- and femtocells, taking into account outdoor and indoor radio propagation characteristics. Simulation results have verified the accuracy of our analytical results. In order to meet the DL OP constraint for both macrocell and femtocells, the interference caused by femtocells has to be limited by adjusting the FAP transmit power w.r.t. its distance to the MBS or by reducing the spatial density of simultaneous co-channel femtocell transmissions.

REFERENCES


