Decentralized Femtocell Transmission Regulation in Spectrum-Sharing Macro and Femto Networks

Xiaoli Chu, Yuhua Wu, David López-Pérez
Centre for Telecommunications Research
King’s College London, London WC2R 2LS, UK
E-mail: {xiaoli.chu, yuhua.wu, david.lopez}@kcl.ac.uk

Haibo Wang
School of Electronics and Information Engineering
Beijing Jiaotong University, Beijing 100044, China
E-mail: bbwang@bjtu.edu.cn

Abstract—Due to considerations of spectrum availability and network infrastructure, existing macrocell networks may have to share the spectrum with overlaid femtocells. In spectrum-sharing macro and femto networks, different transmit powers used by macro base stations (MBSs) and femto access points, together with potentially densely deployed femtocells, may create dead spots where reliable coverage cannot be guaranteed to either macro or femto users. In this paper, we devise a decentralized strategy to regulate femtocell management of transmit power and usage of radio resources depending on its distance from the closest MBS. Simulation results for the orthogonal frequency division multiple access (OFDMA) downlink (DL) of spectrum-sharing macro and femto networks show that the proposed decentralized femtocell regulating strategy is able to guarantee reliable DL coverage over targeted macro and femto service areas while providing superior spatial spectrum reuse, for even a large number of spectrum-sharing femtocells deployed per cell site.

Keywords—Femtocell, macrocell, spectrum-sharing, OFDMA, downlink.

I. INTRODUCTION

Almost all current cellular networks are facing problems of imperfect coverage, especially indoors. One cost-effective way to improve the network coverage and capacity is the emerging femto network, where low-power miniature base stations (BS), a.k.a. femtocell access points (FAP), are overlaid on macro cellular networks. Each FAP provides high-data-rate wireless connections to user equipments (UE) in a short range using the same radio-access technology as the macro underlay. FAPs are connected to an operator’s network through local broadband connections. Due to concerns of security, backhaul capacity and customer preference, closed-access femtocells [1] that each serves only a group of authorized UEs are likely to be deployed. Indoor femtocells based on orthogonal frequency division multiple access (OFDMA) technologies are expected to deliver massive improvements in coverage and capacity for next generation mobile networks [2].

Inter-cell interference is among the most urgent challenges in femtocell deployments [1]. A centralized downlink (DL) frequency planning across OFDMA femto and macro cells was proposed in [3]. However, as plug-and-play devices, FAPs are likely to be deployed by end users, and interference in a femto network cannot be managed by centralized network planning [2]. The decentralized spectrum allocation strategy [4] for the OFDMA DL of a two-tier network avoids cross-tier 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 frequency sub-channels assigned to the femto tier.

Although operating femtocells in a dedicated spectrum can eliminate the interference between macro and femto networks, operators may still choose to deploy them in a same spectrum due to spectrum availability, cost, and network infrastructure considerations [3], [5]. In spectrum-sharing macro and femto networks, different transmit powers of macro BSs (MBS) and FAPs, in conjunction with potentially densely deployed closed access FAPs, may create dead spots where reliable coverage cannot be guaranteed to either macro or femto users in the DL. Inter-cell interference is among the most urgent challenges in femtocell deployments [1]. A centralized downlink frequency planning across OFDMA femto and macro cells was proposed in [3]. However, as plug-and-play devices, FAPs are likely to be deployed by end users, and interference in a femto network cannot be managed by centralized network planning [2]. The decentralized spectrum allocation strategy [4] for the OFDMA DL of a two-tier network avoids cross-tier 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 frequency sub-channels assigned to the femto tier.

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We have presented a thorough DL outage probability (OP) analysis for spectrum-sharing macro and femto cells in [7]. In this paper, we improve the closed-form macro and femto DL OP lower bounds derived in [7] by embracing the randomness of transmit powers employed by different FAPs, and propose a decentralized strategy to regulate femtocells’ managements of transmit powers and usages of radio resources depending on their distances from the closest MBS, so that satisfactory macro and femto DL coverage can be guaranteed over their targeted service areas for a given number of femtocells per cell site. Our work is different from [6] in that it accounts for path loss, Rayleigh fading and lognormal (LN) shadowing, and allows different DL signal-to-interference ratio (SIR) targets and OP constraints for macro and femto cells.

In the rest of the paper, system and channel models are introduced in Section II, improved DL OP lower bounds are presented in Section III, the decentralized femtocell regulating strategy is proposed in Section IV, simulation results and conclusions are provided in Sections V and VI, respectively.

II. SYSTEM AND CHANNEL MODELS

We consider the OFDMA DL of spectrum-sharing macro and femto networks. The basic radio resource unit that can be allocated in OFDMA transmissions is a resource block (RB) [8]. It is assumed that all subcarriers of an RB are assigned with the same power. Intra-cell interference in an OFDMA network is avoided by allowing one scheduled UE per RB in each cell [4]. The macrocell serves outdoor UEs in a disc area centered at the MBS with a radius $r_m$. Interference from its neighboring macrocells is ignored for analytical tractability. Closed-access indoor femtocells, each serving a number of authorized indoor UEs over a disc area centered at the FAP with a radius $r_f$, are randomly overlaid on the macrocell. As
locations of femtocells vary from one cell site to another, they are modeled by a homogeneous spatial Poisson point process (SPPP) $\Phi$ with a density of $\lambda_0$ on the $\mathbb{R}^2$ plane [9]. A single-antenna transceiver is assumed for each MBS, FAP and UE.

Since the bandwidth and duration of an RB are typically restricted [8], it is assumed that all subcarriers within an RB experience the same LN shadowing and Rayleigh flat fading [4], shadowing and fading coefficients remain constant within each RB but may vary from one RB to another, and Rayleigh fading results in unit-mean exponential power gains [4]. As cellular networks are typically interference limited, thermal noise is neglected for analytical tractability. Following the IMT-2000 channel model [10] for terrestrial radio propagation decays, path losses of links from an MBS to an outdoor UE, from an FAP to its indoor UEs, from an FAP to an outdoor UE, from an MBS to an indoor UE, and from an interfering FAP to an indoor UE are given respectively in Table I.

### Table I Terrestrial Radio Propagation Model [10]

<table>
<thead>
<tr>
<th>Link (Tx/Rx)</th>
<th>Fixed loss</th>
<th>Path-loss exponent</th>
<th>Partition loss</th>
<th>Path loss (PL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS/MUE</td>
<td>$\phi_0=10^{-1} \frac{f}{J}$</td>
<td>$\alpha_M$</td>
<td>N/A</td>
<td>$PL_{M} = \phi_0 d^{\alpha_M}$</td>
</tr>
<tr>
<td>Serving FAP/FUE</td>
<td>$\phi_0=10^{-1} \frac{f}{J}$</td>
<td>$\alpha_F$</td>
<td>N/A</td>
<td>$PL_{F} = \phi_0 d^{\alpha_F}$</td>
</tr>
<tr>
<td>FAP/MUE</td>
<td>$\phi_0=\phi_F$</td>
<td>$\alpha_M$</td>
<td>$\xi$</td>
<td>$PL_{M} = \phi_0 d^{\alpha_M + \xi}$</td>
</tr>
<tr>
<td>MBS/FUE</td>
<td>$\phi_0=\phi_M$</td>
<td>$\alpha_F$</td>
<td>$\xi$</td>
<td>$PL_{F} = \phi_0 d^{\alpha_F + \xi}$</td>
</tr>
<tr>
<td>Interfering FAP/FUE</td>
<td>$\phi_0=\phi_F$</td>
<td>$\alpha_F$</td>
<td>$\xi$</td>
<td>$PL_{F} = \phi_0 d^{\alpha_F + \xi}$</td>
</tr>
</tbody>
</table>

In Table I, $f$ is the carrier frequency in MHz, $d$ denotes the range of the link, and $\xi$ indicates that double-wall partition loss is assumed for all links from interfering indoor FAPs to the indoor UE of interest.

III. DOWNLINK OUTAGE PROBABILITIES

A. Femtocell Downlink Outage Probability

Under the assumption that all subcarriers of an RB are assigned with the same power and see the same channel state, the SIR of an RB is equivalent to that of one of its subcarriers. For an indoor FUE located at the cell edge of its serving FAP, the received SIR of an RB is given by

$$\text{SIR}_F = \frac{P_{F} \phi_{F}^{-\alpha_F} H_{F} Q_{F}} { \sum_{i \in \Phi} P_{i} \phi_{i}^{-\alpha_i} H_{i} Q_{i} + P_{M} \phi_{M}^{-\alpha_M} H_{M} Q_{M} + P_{G} \phi_{G}^{-\alpha_G} H_{G} Q_{G} + P_{G,MB} \phi_{G,MB}^{-\alpha_G,MB} H_{G,MB} Q_{G,MB} + P_{G,MB} \phi_{G,MB}^{-\alpha_G,MB} H_{G,MB} Q_{G,MB} }$$  

where it is assumed that each FAP transmits with a power of 100%, the set $\Phi$ is used because the set of FAPs transmitting in the given RB excluding the FAP of interest has the identical spatial distribution as $\Phi$ [9]; $P_{F} = P_{F,Tx} G_{F,A,F,UE}$, with $P_{F,Tx}$ being the transmit power per subcarrier in the RB from the serving FAP, $G_{F,A,F}$ being the FAP antenna gain, and $G_{UE}$ being the UE antenna gain; $P_{M} = P_{M,Tx} G_{M,B,MB,UE}$, being $P_{M,Tx}$ the MBS transmit power per subcarrier in the RB and $G_{MB}$ the MBS antenna gain; $P_{G} = P_{G,Tx} G_{G,UE}$, being $P_{G,Tx}$ the transmit power per subcarrier in the RB of interfering FAP $i$ (i.e., $i \in \Phi$); $G_{F,MB}$, $G_{U,E}$ and $G_{M,MB}$ are assumed to be the same for all FAPs, UEs and MBSs, respectively; $D_{F,Tx}$ and $D_{F,UE}$ are distances from the MBS and interfering FAP $i$ to the FUE, respectively; $H_{F}$, $H_{M}$ and $H_{F,UE}$ are exponentially distributed unit-channel mean transmit power gains from the serving FAP, MBS and interfering FAP $i$ to the FUE of interest, respectively; $Q_{F} \sim \text{LN}(\mu_F, \xi^2 \sigma_F^2)$, $Q_{M} \sim \text{LN}(\mu_M, \xi^2 \sigma_M^2)$ and $Q_{F,UE} \sim \text{LN}(\mu_{F,UE}, \xi^2 \sigma_{F,UE}^2)$ are the LN shadowing from the home FAP, MBS and interfering FAP $i$ to the FUE, respectively, and $\xi = 0.1 \ln 10$ [4].

As output powers of most contemporary wireless systems approximately exhibit LN distributions [11], we assume that in an RB, transmit powers per subcarrier from interfering FAPs are i.i.d. RVs following a LN distribution, i.e., $P_{i,Tx} \sim \text{LN}(\mu_i, \xi^2 \sigma_i^2)$ for $i \in \Phi$, where both $\mu_i$ and $\sigma_i$ are in dBm. Hence, $(P_{F,Tx,\text{dB}})$ is normally distributed in the range of $[P_{F,Tx,\text{min}}(\text{dBm}), P_{F,Tx,\text{max}}(\text{dBm})]$, where $P_{F,Tx,\text{min}}$ and $P_{F,Tx,\text{max}}$ are the minimum and maximum powers that an FAP transmits in a subcarrier. Following the empirical rule of the normal distribution [12], we have $(P_{F,Tx,\text{min}}(\text{dBm}) \approx \mu_F - 3 \sigma_F + \mu_T - 3 \sigma_T)$, and $(P_{F,Tx,\text{max}}(\text{dBm}) \approx \mu_F + 3 \sigma_F + \mu_T + 3 \sigma_T)$.

As a quality-of-service (QoS) requirement, SIR$_F$ to be no less than a target SIR $\gamma_F$. Denoting $S_F = P_{F,Tx}^{-\alpha_F} H_{F} Q_{F}$ and $I_M = P_{M,Tx}^{-\alpha_M} H_{M} Q_{M}$, and assuming identical channel statistics across all RBs, the DL OP of an FUE is given by

$$\text{Pr}(\text{SIR}_F < \gamma_F) = \text{Pr}\left( \frac{S_F}{I_M} < \frac{\gamma_F}{\gamma_M} \right) + \text{Pr}\left( \frac{S_F}{I_M} = \frac{\gamma_F}{\gamma_M} \right)$$  

where $\text{Pr}(S_F/I_M < \gamma_F)$ is the probability of the macro-to-femto interference alone being strong enough to cause a femto DL outage, and $\text{Pr}(S_F/I_M \geq \gamma_F)$ is the probability of the femto-to-femto interference together with the not-strong-enough macro-to-femto interference causing an FUE outage.

For an indoor FUE at a distance $d$ from the MBS, the first probability on the right side of (2) is calculated in [7] to be

$$\text{Pr}\left( \frac{S_F}{I_M} = \frac{\gamma_F}{\gamma_M} \right) = \frac{1}{4} P_{\gamma_F} \left[ 2 \pi \alpha_F + 2 \pi \alpha_M + 2 \pi \alpha_G + 2 \pi \alpha_{GB} \right]$$  

where $N$, $\alpha_F$, $\alpha_M$, $\alpha_G$ and $\alpha_{GB}$ are respectively the order, weight factors and abscissas of the Gauss-Hermite integration [13, Table 25.9], $M$, $\text{nu}$ and $b_n$ (m = 1, ..., M) are respectively the order, weight factors and abscissas of the Gauss-Hermite integration [13, Table 25.10], $\lambda_0$ is the spatial intensity of the set $\Phi$, $\mu_F = \mu_M = \mu_{GB} = \mu_{GB} = \mu_{GB}$ and $\gamma_M = \gamma_M = \gamma_M = \gamma_M = \gamma_M$, and $\nu_0 = \nu_0 = \nu_0 = \nu_0 = \nu_0$.

Thus, $\text{Pr}(S_F/I_M < \gamma_M)$ is lower bounded by the sum of (3) and (4). This lower bound is better than that in [7] because it considers different transmit powers used by different FAPs.

B. Macrocell Downlink Outage Probability

For an MUE at a random distance $D_M$ from the MBS, the
received SIR of an RB is given by

\[
\text{SIR}_M = \frac{P_{M,Tx}G_M \phi_M d_{M,F}^{\alpha_M}}{\sum_{i=0}^{M} P_{i,Tx}G_i \phi_i d_{i,F}^{\alpha_i} + H_M Q_M}
\]

(5)

where \(D_M\) (\(i \in \Phi\)) is the distance from interferring FAP \(i\) to the MUE, \(H_M\) and \(H_M\) are the exponentially distributed unit-mean channel power gains from the MBS and interfering FAP \(i\) to the MUE, respectively, and \(Q_M \sim \text{LN}(\zeta_M, \zeta^2\sigma^2_M)\) denote the LN shadowing from the MBS and interfering FAP \(i\) to the MUE, respectively.

As a basic QoS requirement, \(\gamma_M\) needs to be less than a target SIR \(\gamma_F\). For an outdoor MUE at a distance \(d\) from the MBS, a lower bound of the DL OP relative to \(\gamma_M\) is given by the probability of at least one dominant interfering FAP being able to individually cause a macro DL outage. Following derivations similar to those in Section III-B of [7], we have

\[
\text{Pr}(\text{SIR}_M < \gamma_M | D_M = d) \geq e^{-d^2 \sigma^2_M} \sum_{n=0}^{\infty} \frac{\left(d^2 \sigma^2_M \right)^n}{n!}
\]

(6)

where \(d = \sqrt{d_{\text{MAC}} d_{\text{FAP}} d_{\text{BS}} d_{\text{MAC}}} + \sigma_M^2 + 5.57^2 \) dB, \(\beta_M = \sqrt{d_{\text{MAC}}^2} \) dB.

B. Minimum Distance of an FAP from an MBS

According to (3), \(\text{Pr}(S/F_M \gamma_M | D_M = d)\) is a monotonically decreasing function of \(d\) for given \(P_{M,Tx}\) and \(P_{F,Tx}\). If the value of \(d\) is too small, i.e., if an FUE gets too close to the MBS, it is likely \(\text{Pr}(S/F_M \gamma_M | D_M = d) > \phi_F\) and \(\text{Pr}(S/F_M \gamma_M | D_M = d) > \phi_F\). Thus, assuming all FUEs served by an FAP experience identical path loss from an MBS [6], a necessary condition for a femtocell to provide \(\text{Pr}(\text{SIR}_F \gamma_F) \leq \phi_F\) is to be at least \(d_{\text{F,min}}\) in distance from the MBS, where \(d_{\text{F,min}}\) is given by solving \(\text{Pr}(S/F_M \gamma_M | D_M = d, P_{F,Tx} = P_{F,Tx,max}) = \phi_F\) for \(d\), i.e.,

\[
d_{F,\text{min}} = \frac{P_{M,Tx}G_M \phi_M d_{M,F}^{\alpha_M}}{P_{F,Tx,max}G_F \phi_F d_{F,M}^{\alpha_F} \left(\epsilon_F, \mu_F - \beta_M, \sqrt{\sigma_F^2 + \sigma_M^2}\right)}
\]

(8)

No FAP needs to be deployed in a range less than \(d_{\text{F,min}}\) from an MBS, where all UEs should be connected to the MBS.

C. Decentralized Distance-Dependent Femtocell Regulation

According to (1), for given \(P_{M,Tx}, \phi_F, P_{F,Tx,min}, P_{F,Tx,max}\) and \(D_M\), SIR \(S/F_M\) monotonically increases with \(P_{F,Tx}\). Hence, there is a lower bound (LB) on \(P_{F,Tx}\) required for an UE at a distance \(d\) from the MBS to meet \(\text{Pr}(\text{SIR}_F < \gamma_F | D_M = d) = \phi_F\). This lower bound, namely \(P_{F,Tx}^{(LB)}(d)\), is obtained by solving \(\text{Pr}(S/F_M \gamma_M | D_M = d) = \phi_F\) for \(P_{F,Tx}\). This non-linear equation in \(P_{F,Tx}\) can be readily solved numerically by using standard functions such as \text{solve} in MATLAB\textsuperscript{b} and \text{NSolve} in Mathematica\textsuperscript{c}.

Following previous subsections, \(P_{F,Tx}^{(LB)}(d)\) would also mainly be determined by macro-to-femto interference and could be approximated by solving \(\text{Pr}(S/F_M \gamma_M | D_M = d) = \phi_F\) for \(P_{F,Tx}\), i.e.,

\[
P_{F,Tx}^{(LB)}(d) = \frac{P_{M,Tx}G_M \phi_M d_{M,F}^{\alpha_M}}{P_{F,Tx,max}G_F \phi_F d_{F,M}^{\alpha_F} \left(\epsilon_F, \mu_F - \beta_M, \sqrt{\sigma_F^2 + \sigma_M^2}\right)}
\]

(9)

which shows that \(P_{F,Tx}^{(LB)}(d)\) is approximately a monotonically decreasing function of \(d\) for given \(P_{M,Tx}\). Hence, if \(d_{F,\text{min}} \leq d \leq r_M\), then \(P_{F,Tx}(d_M) = P_{F,Tx}^{(LB)}(d_M)\), where \(P_{F,Tx}^{(LB)}(d_M) = P_{F,Tx,\text{min}}\) as in (7), and \(P_{F,Tx}^{(UB)}(d_M) = P_{F,Tx,\text{max}}\) as in (8).

On the other hand, according to (6), for given \(d\), \(\phi_F\) and \(P_{M,Tx}\), \(\text{Pr}(\text{SIR}_M < \gamma_M | D_M = d)\) monotonically increases with \(P_{F,Tx}\) and \(\sigma_F\) to the distance \(d\) \(\epsilon_F, \mu_F - \beta_M, \sqrt{\sigma_F^2 + \sigma_M^2}\) as discussed in Section III-A. If \(P_{F,Tx,\text{min}}\) is fixed as in (7) while \(P_{F,Tx,\text{max}}\) is considered as a variable, then in order to maintain the successful DL reception of an MUE at a distance \(d\) from the MBS, \(P_{F,Tx,\text{max}}\) needs to be upper bounded (UB) by \(P_{F,Tx,\text{max}}^{(UB)}(d)\), which is given by solving \(\text{Pr}(\text{SIR}_M < \gamma_M | D_M = d) = \phi_F\) for \(P_{F,Tx,\text{max}}\) and \(P_{F,Tx,\text{min}}^{(UB)}(d)\) is a monotonically decreasing function of \(d\).

These discussions show that there are distance-dependent upper and lower bounds on the FAP transmission power for ensuring reliable macro and femto DL coverage at a certain location with respect to the MBS. Also note that in co-channel deployments of macro and femto cells, macrocells are likely to be given higher priority to access the spectrum than femtocells [14], because macrocells provide infrastructural networks to most outdoor mobile UEs. In this case, under the assumption that each FAP is able to infer its distance from the closest MBS, e.g., by using GPS or measuring the received power from the MBS with prior calibration [6], we propose a decentralized strategy to regulate femtocell management of transmit power and usage of radio resources according to its
distance \( d (d_{M,\text{min}} \leq d \leq d_M) \) from the closest MBS:

- **a)** For a given RB, if \( P_{\text{F,Tx,max}} (d) \leq \min \{ P_{\text{F,Tx,max}}^{(\text{UB})} (d), \bar{P}_{\text{F,Tx,max}} \} \), then the FAP can transmit in the RB with a power per subcarrier in the range \( \{ P_{\text{F,Tx,min}}^{(\text{UB})} (d), \bar{P}_{\text{F,Tx,max}} \} \).
- **b)** For a given RB, if \( P_{\text{F,Tx,max}} (d) \leq \min \{ P_{\text{F,Tx,max}}^{(\text{UB})} (d), \bar{P}_{\text{F,Tx,max}} \} \), in which case \( P_{\text{F,Tx,min}} (d) \leq P_{\text{F,Tx,min}}^{(\text{UB})} (d) \leq \bar{P}_{\text{F,Tx,max}} \) because in (9) \( P_{\text{F,Tx,min}} (d) \leq \bar{P}_{\text{F,Tx,max}} \) for \( d \geq d_{M,\text{min}} \), then the FAP can only transmit in the RB with a reduced probability \( \rho (0 < \rho \leq 1) \) with the power per subcarrier \( P_{\text{F,Tx,min}}^{(\text{UB})} (d) \). The probability \( \rho \) is calculated based on (6) to be

\[
\rho = \exp \left[ - \frac{\zeta (\beta_{\text{FF},M}, P_{\text{M,Tx}}^{(\text{UB})} (r_M))^{\alpha_{\text{FF}}} - \zeta (\beta_{\text{MF},M}, P_{\text{M,Tx}}^{(\text{UB})} (r_M))^{\alpha_{\text{MF}}}}{\gamma_{\text{MF}}} \right]
\]

where \( P_{\text{F,Tx,min}}^{(\text{UB})} (r_M) \) is the upper bound on the maximum transmission power per subcarrier of all FAPs in order for the MBS to provide DL coverage over a disc area of radius \( r_M \). Since \( P_{\text{F,Tx,max}}^{(\text{UB})} (r_M) \) is a function of the spatial density \( \lambda_F \) of spectrum-sharing femtocells, \( \rho \) also varies with \( \lambda_F \).

By substituting \( \rho \lambda_F \) in place of \( \lambda_F \) into (6), we can see that \( \rho \lambda_F \) is the maximum spatial density of femtocells transmitting in a same RB with \( P_{\text{F,Tx,max}} = \bar{P}_{\text{F,Tx,max}} \), in order to maintain the successful DL reception of an MUE at the macrocell edge. In other words, if the spatial density of femtocells transmitting in a same RB is effectively reduced from \( \lambda_F \) to \( \rho \lambda_F \), then \( \Pr (\text{SIR}_M < \gamma_M \mid D_M = \rho \lambda_F, P_{\text{F,Tx,max}} = \bar{P}_{\text{F,Tx,max}}) = \delta_M \). The probability \( \rho \) can be controlled in a way similar to the Frequency ALOHA strategy [4]. The decentralized femtocell regulating strategy requires an estimate of an FAP’s distance from the closest MBS and infrequent updates of the MBS transmit power, channel statistics and a local spatial intensity of spectrum-sharing femtocells, which can be provided, e.g., by the mobile operator through the backhaul connection.

### V. Simulation and Numerical Results

In this section, we present simulation and numerical results to evaluate the closed-form femto and macro DL OP lower bounds, and the decentralized femtocell regulating strategy. Each simulation consists of 1000 random drops of femtocells following a homogeneous SPPP, with an average of \( N_F = (\rho \lambda_F \sigma_f^{2} \xi) \) FAPs distributed in the disc area centered at the MBS with a radius \( r_M \), and with 1000 trials per drop to simulate random fading and shadowing. All femtocells are indoor and closed-access. It is assumed that each FAP knows its distance from the MBS. Each FUE is \( r_T \) away from its serving FAP. Based on the 3GPP LTE Release 8 [8], we use a bandwidth of 20 MHz to provide 100 RBs in each DL time slot, and each RB contains 12 subcarriers. DL OPs are evaluated on a per RB basis and depend on transmit powers per subcarrier in an RB, but in favor of easy interpretation, simulation and numerical results are presented in terms of the total transmit power of an MBS or an FAP, which is given by multiplying the used transmit power per subcarrier in an RB by 12 and adding the transmit powers of all available 100 RBs together. Table II lists the values of major system and channel parameters used.

#### Table II System and Channel Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \xi )</td>
<td>10 dB (and 15 dB in Fig. 4)</td>
<td>MBS transmit power</td>
<td>43 dBm</td>
</tr>
<tr>
<td>Number of FUEs per femtocell</td>
<td>2</td>
<td>FAP transmit power</td>
<td>( \leq 23 ) dBm</td>
</tr>
<tr>
<td>( \sigma_F )</td>
<td>4</td>
<td>( \sigma_{\text{U,MBS}} )</td>
<td>15 dB</td>
</tr>
<tr>
<td>( \sigma_{\text{U,FAP}} )</td>
<td>3</td>
<td>( \sigma_{\text{F}} )</td>
<td>2 dB</td>
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<td>( \sigma_{\text{U}} )</td>
<td>8 dB</td>
<td>( \sigma_{\text{UB}} )</td>
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<tr>
<td>( r_F )</td>
<td>4 dB</td>
<td>( r_M )</td>
<td>1000 m</td>
</tr>
<tr>
<td>( r_T )</td>
<td>12 dB</td>
<td>( r_P )</td>
<td>30 m</td>
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<td>( \alpha_{\text{FF}} )</td>
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<td>( \alpha_{\text{MBS}} )</td>
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<td>( \alpha_{\text{MBS}} )</td>
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Fig. 1 shows the DL OPs obtained from simulations and the lower bounds versus the distance from the MBS, for \( N_F = 30, 100 \). The FAP of interest transmits at a power of 23 dBm. Transmit powers per subcarrier in an RB of interfering FAPs are generated as i.i.d. RVs lognormally distributed in \( [P_{\text{F,Tx,min}}^{(\text{UB})}, \bar{P}_{\text{F,Tx,max}}] \), where \( P_{\text{F,Tx,min}} \) is given by (7) and \( \bar{P}_{\text{F,Tx,max}} \) is \( -7.79 \) dBm corresponding to a power of 23 dBm equally distributed among 1200 subcarriers. We can see that the femto DL OP lower bound is very tight, but there is a gap between the formula and simulation curves of macro DL OP for \( N_F = 100 \). This is because the DL OP lower bounds consider strong femto interferers only, which may contribute only a part of the total femto-to-macro interference when the number of femtocells per cell site is large. While at reasonably small OP values that we are usually more interested in, e.g., 0.1 and less, the macro DL OP lower bound is in close agreement with the simulation results. For a given \( N_F \), as the distance from the MBS increases, macro DL OP increases, while femto DL OP decreases. At a given distance, when \( N_F \) increases from 30 to 100, macro DL OP becomes much higher, but femto DL OP increases only slightly, indicating that the effect of femto-to-macro interference is much more significant than femto-to-femto interference. This supports our discussion in Section IV.

![Fig. 1 DL OP vs. the distance from the MBS, for \( N_F = 30 \) and 100, \( \xi = 10 \) dB.](image-url)
over the targeted macrocell service area even for $N_F = 100$. The associated FAP transmission power and transmission probability $\rho$ in an RB decided by the femtocell regulating strategy are plotted against the distance from the MBS in Fig. 3. The decentralized strategy reduces transmit powers of FAPs that are further away from the MBS. At a given distance from the MBS, when $N_F$ increases from 30 to 100, the femtocell regulating strategy decreases the FAP transmit power and reduces the transmission probability $\rho$ from 1 to 0.15. With a total of 100 RBs per DL time slot, $\rho = 0.15$ means that a femtocell can access 15 RBs at a time, which should be manageable by a femtocell that typically serves only 2 to 6 UEs [2].

Fig. 2 Simulated DL OPs with the decentralized femtocell regulating strategy.

Fig. 3 Simulated FAP transmit power and transmission probability ($\rho$) in a RB decided by the proposed decentralized femtocell regulating strategy.

Fig. 4 Simulated ASE with the decentralized femtocell regulating strategy.

Fig. 4 shows the simulated area spectral efficiency (ASE) (in b/s/Hz/m²) versus $N_F$, when the femtocell regulating strategy is used at each FAP, for $\xi = 10$ dB, 15 dB. The ASE is defined as the network-wide spatially averaged product of the density of successful transmissions subject to a target SIR and the corresponding spectral efficiency [15]. The femto, macro, and overall ASEs are respectively expressed as

$$\text{ASE}_F = E[\rho N_F \log_2(1 + \gamma_F)], \quad \text{ASE}_M = E[\lambda M \log_2(1 + \gamma_M)], \quad \text{ASE} = \text{ASE}_F + \text{ASE}_M,$$

where $\text{OP}_F = P (SIR_F < \gamma_F)$, $\text{OP}_M = P (SIR_M < \gamma_M)$, $\lambda M$ is the spatial density of co-channel MUEs on the $\mathbb{R}^2$ plane, and the expectations are taken with respect to spatial distributions of UEs and FAPs. Fig. 4 shows that the proposed femto regulating strategy is able to keep the macro ASE almost unaffected by even a large number of overlaid spectrum-sharing FAPs per cell site. For $\xi = 15$ dB, the overall ASE and femto ASE increase with $N_F$, indicating that spatial reuse can be improved by deploying more spectrum-sharing indoor femtocells if they are insulated by high wall-partition losses. For $\xi = 10$ dB, the overall ASE and femto ASE start to decrease with $N_F$ when $N_F$ goes beyond a certain value, indicating that if indoor femtocells are not well insulated by surrounding walls, deploying too many spectrum-sharing femtocells per cell site may even degrade spatial reuse.

VI. CONCLUSIONS

In this paper, we have proposed a decentralized strategy to regulate FAPs’ transmit powers and usages of OFDMA RBs depending on their locations within the underlying macrocell. Simulation results have shown that the decentralized femtocell regulating strategy is able to ensure satisfactory DL coverage in targeted macro and femto service areas and provide superior spatial reuse, for even a large number of femtocells deployed per cell site. Since it has been assumed that each FAP knows its distance from the MBS, presented performance of the femtocell decentralized regulating strategy serves as a benchmark.

REFERENCES


