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Title:

<u>Enhancing Macrocell Downlink Performance Through Femtocell User Cooperation</u>

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This thesis studies cooperative techniques that rely on femtocell user diversity to improve the downlink communication quality of macrocell users. We analytically analyze and evaluate the achievable performance of these techniques in the downlink of Rayleigh fading channels. We provide an approximation of both the bit-error rate (BER) and the data throughput that macrocell users receive with femtocell user cooperation. Using simulations, we show that under reasonable SNR values, cooperative schemes enhance the performances of macrocells by improving the BER, outage probability, and data throughput of macrocell users significantly when compared with the traditional, non-cooperative schemes.

Enhancing Macrocell Downlink Performance Through Femtocell User
Cooperation

by

Adem Mabruk Zaid

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Adem Mabruk Zaid, Author

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

DEDICATION

I dedicate this work to my parents who supported me by all means during the course of my study

Chapter 1 – INTRODUCTION

Femtocells are low-power base stations with small communication coverage designed and targeted for home and small business use [2, 13]. Due to their low cost, their ability to provide high data rates, and to their low power consumption, they have recently attracted considerable research attention in current literatures [3, 4, 9]. About 50% of phone calls and about 70% of data communication are projected to be taking place indoors in the next few years [10]. In addition to offering high data-rate services at low power usage, femtocells can potentially reduce the traffic load on traditional macro-cellular networks by servicing macrocell users that happen to be under their coverage. Femtocell deployment, however, still presents some major challenges, pertaining mainly to interference and handoff [4, 15].

The interference problem arises primarily because femtocells are often required to share the same spectrum resources among themselves as well as with the macrocell which they belong to. Solutions attempting to mitigate interference have been proposed in literature [4–6, 20]. In [20], for example, dynamic frequency reuse has been proposed to address interference in dense femtocell networks. The idea is to divide the macrocell into three sectors, where each sector is assigned a frequency band that is different from those assigned to the other two sectors. The authors in [5] propose an interference management approach that relies on frequency allocation as well, known as frequency fractional reuse (FFR), to address interference in femtocells. This approach proposes that

femtocells use frequency sub-bands that are different from those used by the macrocell, and is shown to mitigate interference, reduce outage probability, and increase overall system throughput.

User mobility and handoff have also given rise to very challenging issues when dealt with in the context of femtocells, especially when compared with traditional macrocellular networks. The challenges faced when managing mobility and handoff in femtocells (as opposed to in traditional macrocellular networks) are mainly due to the randomness nature of femtocell deployments, the low power levels at which femtocells operate, the small area sizes covered by femtocells, the asymmetrical data rates between femtocells and macrocells, and the lack of controlling entities (different femtocells are likely to have and be managed by different owners). In an effort to address some of these issues, several approaches have been proposed [8,11,15,21]. In [11], the authors propose to rely on the received signal strength at the user to trigger handoff process. That is, the user is handed off to another neighboring cell when its received signal strength from the neighboring cell plus a certain threshold is greater than that received from its current cell. This approach, however, can be inefficient when users are located within a close proximity of the macrocell base station, because in this case the signal of macrocell base station can be overwhelming. To address this issue, the authors in [21] propose to rely on the signal to noise plus interference ratio (SINR) instead of the received signal strength at the mobile user. In [15], a handoff scheme between femtocells and their underlying macrocell that relies on both velocity and signal strength is proposed, where both femtocells and the macrocell are assumed to operate at the same frequency. In [8], Moon et al. propose the RSS (Received Signal Strength)-based scheme for two-tier cellular networks, where

a large number of femtocell base stations operating at low transmit power are deployed within the coverage area of macrocell base stations. The RSS-based scheme accounts for the asymmetrical nature in the transmit power of femtocells and macrocells.

The small size nature of femtocells makes the handoff management task even more challenging. In order to reduce the number of unnecessary handovers of high-speed mobile users, Zaman et al. [21] propose that any user that enters a femtocell coverage area while being served by the macrocell base station and stays for more than a specific time will be handed over to this femtocell as long as the received SINR is higher than that of the currently serving cell.

Another major challenge also pertains to femtocells lies in the asymmetry nature of data rates offered by femtocells and macrocells. The data rates offered by femtocell base stations (e.g., offered by broadband internet access links) are many orders of magnitude higher than those offered by macrocell base stations (e.g., offered by 3G cellular links). This can be very problematic for femtocell users that, while being handed off from their femtocells to the macrocell, desire to maintain high data rates, similar to those received while in their femtocells, as well as for those macrocell users (e.g., 3G users) that also desire to receive data rates comparable to those offered by femtocells.

With this in mind, in this thesis, we propose an approach that improves overall data throughput of macrocell users. Specifically, we propose cooperative techniques that improve the received signal quality in the downlink of macrocell users[1] through user diversity, thereby increasing the overall throughput that macrocell users achieve. We

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[1]Hereafter, macrocell users will be used to refer to 1) traditional cellular users and 2) femtocell users that are handed off to the macrocellular network

analyze and evaluate the achievable downlink performances of Rayleigh fading channels by deriving approximations of both the bit-error-rate (BER) and the data throughput that macrocell users receive with and without femtocell user cooperation. Using simulations, we also show that cooperative transmission schemes significantly improve the BER, the outage probability, and the data throughput when compared with the traditional, non-cooperative scheme.

The rest of this thesis is organized as follows. Chapter 2 presents the network model and architecture. Chapter 3 derives and presents the performance of the proposed cooperative scheme for both the signal user case and the multiple users case. Chapter 4 describes the proposed relays selection approach. Chapter 5 presents the simulation results. Finally, we conclude the thesis in Chapter 6.

Chapter 2 – NETWORK MODEL AND ARCHITECTURE

In this thesis, we study the downlink communication of a macrocellular network. As depicted in Fig. 2.1, we consider a two-tier network architecture, where a number of femtocells is deployed within the communication range of a macrocell base station (MBS). Users located within the coverage range of a femtecoll base station or access point (FAP) (referred to as femtocell users) are serviced by the FAP, whereas, users that are not covered by any FAP (referred to as macrocell users) are serviced by the MBS.

In this work, we propose a technique that enhances macrocell downlink capacity through femetocell user cooperation. The idea is based on the fact that at any given time, there might exist some idle femtocell users that are not being serviced by their FAP, due to for e.g. not having any data to receive and/or the FAP is busy servicing other users. In this case, any nearby macrocell users that happen to be receiving data from the MBS can rely on these idle femtocell users to help increase its received signal quality through cooperative diversity. In other words, during their idle periods, femtocell users can play the role of relays to improve the quality of the MBS's signals intended for and received by macrocell users. To do so, those femtocell users that are willing to cooperate are then required to tune their transceivers to the macrocell frequency band whenever they are idle.

At any given time slot, when the MBS transmits its modulated signal to a macro-cell user (also referred to as *destination node* hereafter), the transmitted signal will be
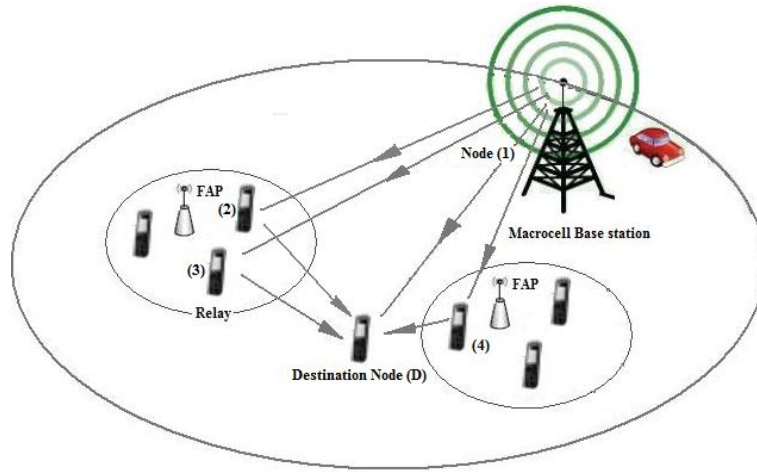
Figure 2.1: Two tier network architecture

received by the desired destination node as well as by all nearby idle femtocell users, possibly belonging to different femtocells. Depending on their distances as well as the channel conditions between them and the MBS, these idle femtocell users may receive signals with different strengths. To enable the cooperative diversity, these intermediate idle femtocell users will play the role of relays by first amplifying the signals they received, and then retransmitting them right away, one node at a time. Having each relay send its signal during a separate time slot prevents any possible data collision. Note that when the relays are forwarding the received signals to the destination node (i.e., during cooperation period), the MBS can concurrently transmit data to other macrocell user(s), avoiding then the loss of any transmission opportunities. In other words, because femtocell cooperation occurs concurrently with MBS's transmission, the overall system throughput increases, as cooperation here improves received signal strength, yet without loosing transmission opportunities.

At the destination node, multiple copies of the original message are then received over multiple time slots. These copies are then combined via a combining technique at the destination node to recover the original data. Although various signal combination techniques exist, in this work, we consider that the destination node uses the maximum ratio combining (MRC) technique [12] to combine and recover its original data. We assume that all channels are slow, flat faded, Rayleigh distributed, and mutually independent. We also assume that all relays have a perfect channel state information (CSI) estimation of their backward (source-to-relay) and forward (relay-to-destination) channels. The destination node, on the other hand, is assumed to have a perfect CSI of its backward (relay-to-destination) channel, and a perfect knowledge of all relays' forward and backward CSI values. We also assume that the modulation technique in use is the binary phase shift keying (BPSK) one.

Chapter 3 – BER ANALYSIS

In this chapter, we derive the bit-error rate (BER) performances of the proposed cooperative scheme by first considering single-user and then multiple users scenarios.

3.1 Single User Case

We begin our analysis by considering single-user case; i.e., when only one macrocell user is being serviced by the MBS. For this, we first derive the conditional bit error probability when cooperative diversity is applied as a function of the instantaneous received signal to noise ratio. Then, we derive the average bit error rate from the calculated conditional bit error probability by taking into consideration the distribution of the received signal to noise ratio (SNR) at the receiver node.

3.1.1 Conditional BER Derivation

Letting n denote the number of transmitters (i.e., the MBS plus $(n-1)$ relays referred to as node i, $i = 2, 3, \ldots, n$, as shown in Fig. 2.1), the BPSK modulated signal sent by the MBS and received at the destination D and at node i at time slot t can be written respectively as

$$y_{1D}(t) = h_{1D}\sqrt{E_b}S_1(t) + W_D(t) \tag{3.1}$$

$$y_{1i}(t) = h_{1i}\sqrt{E_b}S_1(t) + W_i(t) \tag{3.2}$$

where E_b is the bit (transmitted) energy sent by the MBS (i.e., node 1), $S_1(t) \in \{-1, +1\}$ is the BPSK bit code, $h_{1i} \sim CG(0, \Omega_{1i})$ is the complex Gaussian channel between the MBS and node i for $i = 2, 3, ..n$, $h_{1D} \sim CG(0, \Omega_{1D})$ is the complex Gaussian channel between the MBS and the destination D, $W_i(t)$ and $W_D(t) \sim G(0, \sigma_N^2)$ represent the Gaussian noise observed at node i and the destination D at time slot t.

During time slot $t + 1$, node 2 (the first relay) amplifies its received signal and then forwards it to the destination. During time slot $t + 2$, node 3 (the second relay) amplifies its received signal and then forwards it to the destination, and so does node 4 (the third relay) during time slot $t + 3$, and so forth. Therefore, node i's signal will be received at the destination D during time slot $t + i - 1$, and is given by

$$y_{iD}(t + i - 1) = \alpha_i h_{iD}\left(h_{1i}\sqrt{E_b}S_1(t) + W_1(t)\right) + W_D(t + i - 1)$$

for $i = 2, 3, ..., n$, $W_D(t + i - 1) \sim G(0, \sigma_N^2)$ represents the Gaussian noise observed at the destination D at time slot $(t + i - 1)$, and α_i represents the amplification factor of node i, which can be written as

$$\alpha_i = \sqrt{\frac{E_i}{E_b|h_{1i}|^2 + \sigma_N^2}}$$

where E_i represents the bit transmitted energy by node i for $i = 2, 3, ..., n$. At the destination node, all received signals are combined using the MRC technique. The

combined signal at time $(t + n - 1)$ can then be written as

$$y_{out}(t + n - 1) = \sum_{i=1}^{n} w_i y_{iD}(t + i - 1)$$

where w_i represents the weighting factor of the ith signal, which, in general, is equal to the complex conjugate of the square root of the signal received power divided by the noise power. Thus, the combined signal can be expressed as

$$y_{out}(t+n-1) = \frac{h_{1D}^* \sqrt{E_b}}{\sigma_N^2} y_{1D}(t) + \sum_{i=2}^{n} \frac{\alpha_i^* h_{1i}^* h_{iD}^* \sqrt{Eb}}{\sigma_N^2 (\alpha^2 |h_{iD}|^2 + 1)} y_{iD}(t+i-1) \qquad (3.3)$$

where (*) represents the complex conjugate. From Eq. (3.3), it follows that the SNR at the output of the MRC combiner is

$$\gamma = \gamma_{1D} + \sum_{i=2}^{n} \frac{\gamma_{1i} \gamma_{iD}}{\gamma_{1i} + \gamma_{iD} + 1} \qquad (3.4)$$

where γ_{1D} represents the SNR of the component received through the direct path (i.e., from MBS to D), γ_{1i} represents the SNR of the signal received at relay node i coming from D, and γ_{iD} represents the SNR of the signal at D coming from relay node i. Note that the SNR at the output of the MRC combiner is the sum of all received signals' SNRs. Therefore, the conditional bit error probability $P_b(E/\gamma)$ of the cooperative scheme can be expressed as

$$P_b(E/\gamma) = Q\left(\sqrt{\gamma_{1D} + \sum_{i=2}^{n} \frac{\gamma_{1i} \gamma_{iD}}{\gamma_{1i} + \gamma_{iD} + 1}}\right) \qquad (3.5)$$

where $\gamma_{ij} = \frac{|h_{ij}|^2 E_i}{\sigma_N^2}$, $Q(.)$ is the standard Gaussian error function, and σ_N^2 is the noise variance, i.e., the one sided noise power spectral density of the Gaussian noise observed at the receiver.

3.1.2 Average BER Derivation

The average BER of the received signal at the output of the demodulator can be expressed as [16]

$$P_b(E) = \int_0^\infty P(E/\gamma)P_\gamma(\gamma)\,d\gamma \tag{3.6}$$

where $P_b(E/\gamma)$ is the conditional bit error probability given in Eq. (3.5), and $P_\gamma(\gamma)$ is the probability density function (pdf) of the SNR at the output of the MRC combiner.

By using the integral form of the $Q(.)$ function, the BER of the cooperative scheme can be written as

$$P_b(E) = \frac{1}{\pi} \int_0^\infty \int_0^{\pi/2} P_\gamma(\gamma)e^{-\frac{\gamma}{sin^2\theta}}\,d\gamma d\theta \tag{3.7}$$

Since the conditional BER of the cooperative scheme is a function of the total SNR (the sum of all branches' SNRs), Eq. (3.7) can be rewritten as

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \prod_{i=1}^n M_{\gamma_i}\left(-\frac{1}{sin^2\theta}\right)\,d\theta \tag{3.8}$$

where M_{γ_i} is the moment generating function.

The probability distribution of the two-hop path SNR can then be written as

$$p_\gamma(\gamma) = \frac{2\gamma e^{-\gamma(1/\bar{\gamma}_{1i}+1/\bar{\gamma}_{iD})}}{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}\left(\frac{\bar{\gamma}_{1i}+\bar{\gamma}_{iD}}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}}K_1\frac{2\gamma}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}} + 2K_0\frac{2\gamma}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}}\right)U(\gamma) \tag{3.9}$$

where $\bar{\gamma}_{1i}$ and $\bar{\gamma}_{iD}$ represent the average received SNRs at relay node i and at the destination D, respectively, K_0 and K_1 are the zeroth and first order modified Bessel function, and $U(\gamma)$ is the unit step function. Eq. (3.9) can be approximated as [1]

$$p_\gamma(\gamma) \approx \left(\frac{1}{\bar{\gamma}_{1i}} + \frac{1}{\bar{\gamma}_{iD}} \right) e^{-\left(\frac{1}{\bar{\gamma}_{1i}} + \frac{1}{\bar{\gamma}_{iD}} \right)\gamma} \tag{3.10}$$

The pdf of the one-hop path is

$$p_\gamma(\gamma) = \frac{1}{\bar{\gamma}_{1D}} e^{-\frac{1}{\bar{\gamma}_{1D}}\gamma} \tag{3.11}$$

By substituting Eqs. (3.10) and (3.11) into Eq. (3.8), the BER becomes

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\gamma}_{1D}} \right) \prod_{i=2}^{n} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\gamma}_{1iD}} \right) d\theta \tag{3.12}$$

where

$$\bar{\gamma}_{1iD} = \frac{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}{\bar{\gamma}_{1i} + \bar{\gamma}_{iD}}$$

For comparison purposes and completeness, we include the expression of the BER of the non-cooperative (traditional) scheme, in which the MBS sends its signal directly to the destination node; no cooperation from the femtocell users. The pdf of the one-hop path (source-to-destination) SNR is expressed as in Eq. (3.11), which, after being substituted in Eq. (3.6), it gives a BER that is equal to

$$P_b(E) = \frac{1}{2} \sqrt{\frac{\bar{\gamma}_{1D}}{\bar{\gamma}_{1D} + 1}}$$

3.2 Multiple-Users Case

In this section, we study the performance of cooperative diversity in multiple users environment, in which multiple macrocell users and femtocell users can all be active in the network. Here, we assume that these active macrocell users and femtocell users share the same frequency band. This sharing assumption of the frequency resources will incur extra interference, in addition to that caused by neighboring MBSs. Similar to what was done in Section 3.1, we first derive the conditional bit error probability under cooperative diversity as a function of the instantaneous received signal to interference and noise ratio (SINR). Then, we derive the average BER from the calculated conditional bit error probability by taking into consideration the distribution of the received SINR at the destination node.

3.2.1 Conditional BER Derivation

When considering multiple users setting, the received signals at relay node i and at the destination node D, given by Eqs. (3.1) and (3.2) in the case of single user only, become

$$y_{1D}(t) = h_{1D}\sqrt{E_b}S_1(t) + \sum_{j \in \mathcal{I}_{D_1}} h_{jD}\sqrt{E_j}S_j(t) + W_D(t) \qquad (3.13)$$

$$y_{1i}(t) = h_{1i}\sqrt{E_b}S_1(t) + \sum_{j \in \mathcal{I}_i} h_{ji}\sqrt{E_j}S_j(t) + W_i(t) \qquad (3.14)$$

where $\mathcal{I}_{D_1}$ and $\mathcal{I}_i$ represent the sets of users whose transmitted signals interfere with the reception at the destination D and the relay node i during time slot t, respectively.

Once the relay nodes receive the signal transmitted by the MBS, each relay amplifies its received signal and forwards it to the destination node in a timely fashion as described previously, one at a time. The two-hop path signal received at destination D at time slot $t + i - 1$ can then be written as

$$
\begin{aligned}
y_{iD}(t+i-1) = \ & \alpha_i h_{iD} \{ h_{1i} \sqrt{E_b} S_1(t) + \sum_{j \in \mathcal{I}_i} h_{ji} \sqrt{E_j} S_j(t) + W_i(t) \} \\
& + \sum_{j \in \mathcal{I}_{D_i}} h_{jD} \sqrt{E_j} S_j(t+i-1) + W_D(t+i-1)
\end{aligned} \tag{3.15}
$$

where $\mathcal{I}_{D_i}$ represent the set of users whose transmitted signals interfere with the reception at the destination D during $(t + i - 1)$ time slot.

At the destination node, multiple copies of the same signal will be received at different time slots, which will then be combined using the MRC technique as done in the single user case.

The BER analysis from Eqs. (3.13) and (3.15) is complicated, because it requires the statistical properties of each interference component. In order to simplify the analysis of the BER when cooperative diversity is applied, we suggest the use of the central limit theorem (CLT). For a large number of interferers, using CLT, the sum of all interference components can be approximated as a Gaussian random variable with mean and variance equal to the sum of the means and variances of these interference components. Using this approximation, Eqs. (3.13) and (3.14) can be approximated as

$$
y_{1D}(t) \approx h_{1D} \sqrt{E_b} S_1(t) + X_{1D}
$$

$$y_{1i}(t) \approx h_{1i}\sqrt{E_b}S_1(t) + X_i$$

where $X_{1D} \approx \sum_{j \in \mathcal{I}_{D_1}} h_{jD}\sqrt{E_j}S_j(t) + W_D(t)$ is a Gaussian random variable representing the approximation of the sum of the interference components and the white Gaussian noise at the destination node during the direct transmission. X_{1D} has a zero mean and a variance equals the sum of the Gaussian noise variance, σ_N^2, and the variance of the interference components. Similarly, $X_i \approx \sum_{j \in \mathcal{I}_i} h_{ji}\sqrt{E_j}S_j(t) + W_i(t)$ is a Gaussian random variable representing the sum of the noise and the interference at relay node i during the first transmission.

Following the same approach, the two-hop received signal given by Eq. (3.15) can be approximated as

$$y_{iD}(t + i - 1) \approx \alpha_i h_{iD}\left(h_{1i}\sqrt{E_b}S_1(t) + X_i\right) + X_{iD}$$

where $X_{iD} \approx \sum_{j \in \mathcal{I}_{D_i}} h_{ji}\sqrt{E_j}S_j(t + i - 1) + W_D(t + i - 1)$ is a Gaussian random variable which represents the approximation of the sum of the interference at the destination and the white Gaussian noise during the $(t + i - 1)$ time slot.

The signal at the output of the MRC becomes then

$$y_{out}(t + n - 1) \approx \frac{h_{1D}^*\sqrt{E_b}}{\sigma_{1D}^2}y_{1D}(t) + \sum_{i=2}^{n}\frac{\alpha_i^*h_{1i}^*h_{iD}^*\sqrt{Eb}}{\sigma_i^2\alpha^2|h_{iD}|^2 + \sigma_{iD}^2}y_{iD}(t + i - 1)$$

and the received SINR, ρ, is expressed as

$$\rho = \rho_{1D} + \sum_{i=2}^{n}\frac{\rho_{1i}\rho_{iD}}{\rho_{1i} + \rho_{iD} + 1} \tag{3.16}$$

where ρ_{1D} represents the SINR of the direct signal from the MBS to the destination node D. ρ_{1i} represents the SINR of the signal sent by the MBS and received at relay node i, and ρ_{iD} represents the SINR of the signal sent by relay node i and received at the destination D. Note that the total SINR (ρ) at the output of the MRC has a similar form of the received SNR given in Eq. (3.4). Therefore, the conditional bit error probability is

$$P(E/\rho) = Q\left(\sqrt{\rho_{1D} + \sum_{i=2}^{n} \frac{\rho_{1i}\rho_{iD}}{\rho_{1i} + \rho_{iD} + 1}}\right)$$

3.2.2 Average BER Derivation

Because the interference at the receiving nodes is approximated as a Gaussian random variable, the SINR distributions of the one-hop signal and the two-hop signal have similar forms to those given in Eqs. (3.11) and (3.10), respectively. As a result, the average BER, $P_b(E)$, has a similar form to the average BER given in Eq. (3.12), and is given by

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\rho}_{1D}}\right) \prod_{i=2}^{n} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\rho}_{1iD}}\right) d\theta$$

where

$$\bar{\rho}_{1iD} = \frac{\bar{\rho}_{1i}\bar{\rho}_{iD}}{\bar{\rho}_{1i} + \bar{\rho}_{iD}}$$

Chapter 4 – RELAY SELECTION APPROACH

In this section, we propose an approach for selecting the set of idle femtocell users that will play the role of relaying the MBS's transmitted signal to the destination node. As mentioned in Chapter 2, when the signal is sent by the MBS, a number of idle femtocell users will receive it as well. Among these idle femtocell users, only a small set of nodes will relay it to the destination node[1]. Intuitively, for an efficient implementation of cooperative diversity, the nodes selected for relaying should be the ones that can provide the best possible performance. Besides, the selection process should be smooth, short and with a small overhead involved.

In the traditional cooperative diversity literature, one can find several different protocols for relays selection, all aiming at a common objective of trying to ease up the selection process and to make it efficient. In [17], for instance, the first relay, selected among a set of idle users, $C = \{1, 2, \ldots, n\}$, corresponds to the one that provides the highest possible performance, which is determined by

$$\max_{i \in C}\{\min(\rho_{1i}, \rho_{iD})\}$$

This selection process is carried out at the destination node [17]. However, in order for the destination node to perform this process, some feedback among source node (i.e., the MBS), candidate relays, and the destination node is needed. This feedback should

---

[1]The destination node is what determines the number of needed relays.

enable each candidate relay to have knowledge of its forward and backward channel values, which as the authors described in [17] can be validated through three main steps: 1) The source node sends a sequence to allow the relays to know their backward channel values, 2) the relays each sends a sequence to the destination node to allow the destination node to know its channel values toward the relays, and 3) the relays broadcast the information they obtained during the first step to both the source and the destination nodes. However, the question of how does each relay use the feedback channel to send its sequence to the destination node so that it can estimate the $min\{\rho_{1i}, \rho_{iD}\}$ value needed for the selection decision has not been addressed. Does it happen in a timely fashion such that one relay at a time sends its sequence to the destination or does it happen in a heuristic matter? However, it is expected that reaching such an optimal decision incurs more transmissions/overhead. Unlike in [17], the authors in [18] propose that relay selection be made by the relays themselves, not by the destination node. They suggest that after candidate relays finish evaluating their forward and backward channels values, candidate relays broadcast their channels values to each other. Therefore, each candidate relay can compare its values with others' values until the optimum decision is made. Like in [17], the authors here did not explain how relays inform each other about their channels values. In addition, this approach is based on the assumption that candidate relays can hear each other, which may not always be true in practice. If candidate relays can not hear each other, two or more relay nodes might start forwarding their signals to the destination at the same time, which may result in a collision.

For our cooperative diversity technique, we propose a deterministic relay selection approach that is fast and incurs minimum overhead. The approach is described as fol-

lows:

Relay selection. First, given that the two-hop (MBS-relay-destination) SINR at the destination is expressed as

$$\rho_{eq} = \frac{\rho_{1i}\rho_{iD}}{\rho_{1i} + \rho_{iD} + 1},$$

we require that the idle femtocell users that can be considered as candidate relays for a particular macrocell user be those whose two-hop SINRs meet the minimum required SINR threshold; i.e.,

$$\rho_{th_{min}} \leq \rho_{eq} \leq \rho_{th_{max}} \tag{4.1}$$

where $\rho_{th_{min}}$ and $\rho_{th_{max}}$ are the min and the max SINR thresholds that are to be chosen/decided on by the destination. Among all the relays whose SINRs satisfy the above inequality, only $n - 1$ relays will be selected by the destination node to serve as relays.

The verification of the inequality given in (4.1) is carried out by the idle femtocell users themselves. But in order to enable each idle relay node to calculate its corresponding instantaneous ρ_{eq} value, each node is required to have knowledge of its backward channel, its forward channel, its experienced interference level, and the interference level experienced at the destination node. For this, we assume that relays can extract their backward channels values from the MBS transmission during the first, direct transmission sent by the MBS. Once the destination node correctly receives the first packet, it sends an ACK signal to the MBS to inform it that the packet was received correctly. In this work, we assume that the ACK signal has three extra roles in addition to informing the MBS about the successful reception: 1) it informs the MBS and idle femtocell users about whether the destination node opts for the cooperative diversity scheme, as a better

signal quality may be needed at the destination node, $2)$ it informs idle femtocell users about the interference level at the destination node, and $3)$ it is used by idle femtocell users to evaluate their forward channels values. Therefore, after these two transmissions, all idle femtocell users can determine their ρ_{eq} values.

Relaying order. Now, we describe the order through which selected relays, if ever needed, should amplify and forward their signal. Intuitively, we want the relays to be ordered according to their SINR values; i.e., the relay with the highest SINR to start first, the relay with the second highest SINR to start second, etc. For this, we propose that each selected relay (i.e, each idle femtocell users whose SINR satisfies the Inequality (4.1)) sets a back-off counter as soon as it receives the ACK signal from the destination node. Each selected relay sets its back-off counter to a value that is a decreasing function of Δ given by

$$\Delta = \frac{\rho_{eq} - \rho_{th_{min}}}{\rho_{th_{max}} - \rho_{th_{min}}} \tag{4.2}$$

For each idle time slot, each selected relay decrements its counter by 1, and when the counter reaches zero, the selected relay starts relaying the signal to the destination. The idea here is that the higher the Δ value; i.e., the greater the SINR value, the sooner the selected relay starts relaying the signal. This allows relays with higher SINRs to start relaying first. Through Eq. (4.2), it can be guaranteed that the candidate relays that have the highest γ_{eq} values will start transmission before others. Once the first relay (n=2) starts forwarding its signal to the destination node, other candidate relays must freeze their back-off counters until the first relay finishes its transmission. Once done and

the forwarded packet is received correctly at the destination node, the destination node sends an ACK signal to the first relay and to all nodes in the network to inform: 1) the first relay that the destination node has received the forwarded message correctly, and 2) all other candidate relays and the MBS about whether more relays are needed or not. If more relays are needed, then other candidate relays activate their back-off counters once again, but this time on a value that is equivalent to the difference of their counters values during the first phase and the first chosen relay counter value; i.e., if the first relay counter value was c_1 and the second relay (candidate relay that has the second highest Δ value) counter value is c_2, then this relay will wait only for a period of length $c_2 - c_1$ before it starts transmitting. As soon as the second relay (n=3) starts transmission, other candidate relays freeze their counter values once again and then they set them back on if more relays are requested by the destination node, which can be known through the destination node transmission of the ACK signal. If more relays are needed, then the third relay (candidate relay that has the third highest Δ value) waits only for a period of length $c_3 - c_2$ before it starts transmitting. Similarly, the fourth relay (n=5) will wait $c_4 - c_3$ the next round, and so forth.

It is important to mention that this relay selection approach does not incur extra transmissions. In addition, it is clear that the destination node is the one that decides whether cooperative diversity should be applied. This decision is based on the needed signal quality at the destination node. If a higher signal quality is needed, the destination node can request femtocell users' cooperation. When cooperative diversity is applied, the destination node can also decide on how many relay nodes should be used. If even a better service is needed, then it can request for more relays to be involved in the

transmission. The more the relays, the better the quality as will be shown later.

Chapter 5 – PERFORMANCE EVALUATION

In this chapter, we use MATLAB simulations to evaluate the effectiveness of the proposed techniques. We evaluate and analyze the performance of cooperative diversity first for the single user case and then for the multiple users case. The studied performance metrics are the bit-error rate, outage probability, and network throughput.

5.1 Single User Case

We now focus on the single user case, and evaluate the performance in terms of achievable BER and data throughput of both the cooperative and the non-cooperative schemes. We consider studying the impact of the number of relays as well as the impact of the source-to-destination and the relay-to-destination SNRs on the achievable performances. In this simulation study, we assume that all relays backward channels and the source-to-destination channel experience similar conditions, meaning that $\bar{\gamma}_{1D} = \bar{\gamma}_{12} = ... = \bar{\gamma}_{1n}$, and that all relays forward channels also experience similar conditions, meaning that $\bar{\gamma}_{2D} = \bar{\gamma}_{3D} = ... = \bar{\gamma}_{nD}$. This assumption is reasonable, since relays are located within, roughly, an equal distance from the destination node (e.g., the destination node can choose relays that are an equal distance apart from it), and then so are the relays from the MBS.
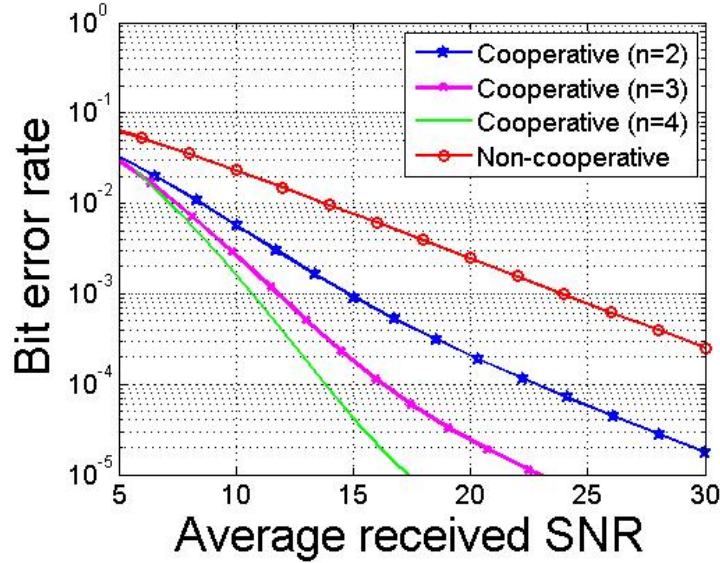
Figure 5.1: BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=10dBs for different values of the number of relays.

5.1.1 BER Analysis

Fig. 5.1 shows the BER performance as a function of the average received SNR (which is the measured SNR at the destination) when the relay-to-destination SNR value is 10dBs for various values of the number of relays (note: the number n shown in the figure represents the number of transmitting nodes; i.e., $(n-1)$ relays plus the MBS). The figure shows that as the received SNR increases, the BER decreases for all schemes, but the decrease is more pronounced under the cooperative scheme. We also observe that for different SNR values, the greater the number of relays, the lower the BER. The BER when $n = 3$, for example, is smaller than that obtained when $n = 2$, and the BER obtained when $n = 4$ is smaller than that obtained when $n = 3$. For completeness, we present in Fig. 5.2 these same results but when the relay-to-destination SNR value
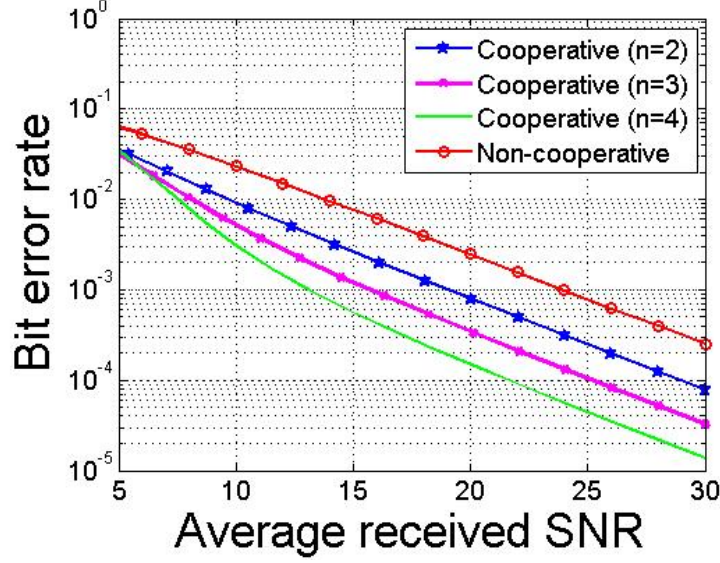
Figure 5.2: BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=2dBs for different values of the number of relays.

is 2dBs. We observe similar performance behaviors also when the relay-to-destination SNR is reduced to 2dBs. The gap in BER between that of the cooperative and that of the non-cooperative is smaller though.

5.1.2 Throughput Analysis

In this section, we evaluate and compare the data throughput achievable under the co-operative and the non-cooperative schemes. For this, we consider that the MBS has an infinite stream of packets each of length L bits that it desires to send to the destination node. We define the throughput as the ratio of the total number of successfully transmitted packets (expressed in bits) to the total time needed to deliver those packets.

We assume that a packet is successfully transmitted when all of its L bits are received successfully at the destination. The throughput η of both the cooperative and the non-cooperative schemes is $C(1 - P_b)^L$ where C is the capacity of the channel in bits per second.

Figs. 5.3 and 5.4 show the normalized[1] throughput obtained under the studied schemes as function of the average received SNR for two values of the relay-to-destination SNR: 10dBs and 2dBs. In the simulation, we assume $L = 1000$ bits. It can be seen that when the relay-to-destination channel SNR is 10dBs, the throughput obtained using co-operative diversity is higher than that obtained under the non-cooperative scheme. The throughput gain (between the cooperative and the non-cooperative) is significantly high, especially when the received SNR values are medium to high. For example, when the average received SNR equals 20dBs, the non-cooperative scheme achieves about 10% of the maximum throughput, whereas, the cooperative scheme achieves up to 99% (when $n = 4$). Also, observe that the throughput gain increases with the number of relays, and decreases as the average received SNR increases. This is because when the received SNR values are high, both schemes do well, and hence, both achieve similar amounts of throughput. On the other hand, as the relay-to-destination channel worsens (e.g., when the relay-to-destination channel SNR is 2dBs as shown in Fig. 5.4), the throughput gain is slightly less substantial.

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[1]Normalized with respect to the channel capacity; i.e., the achievable throughput corresponding to when $P_b = 0$.
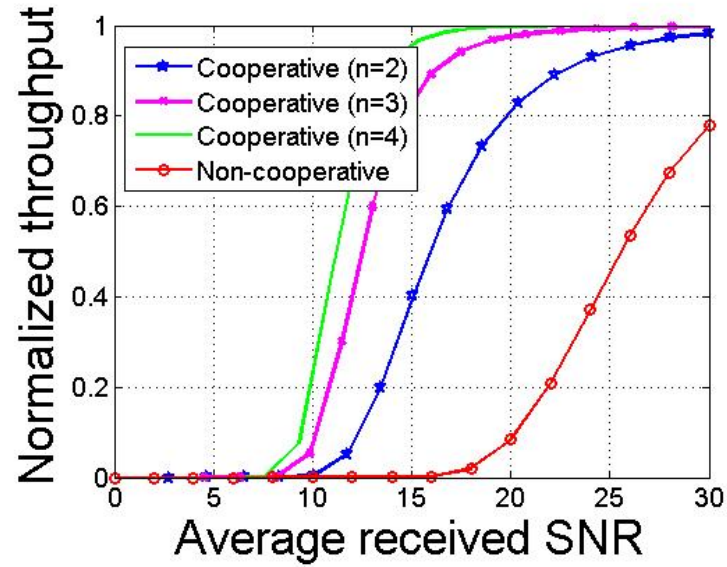
Figure 5.3: Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=10dBs
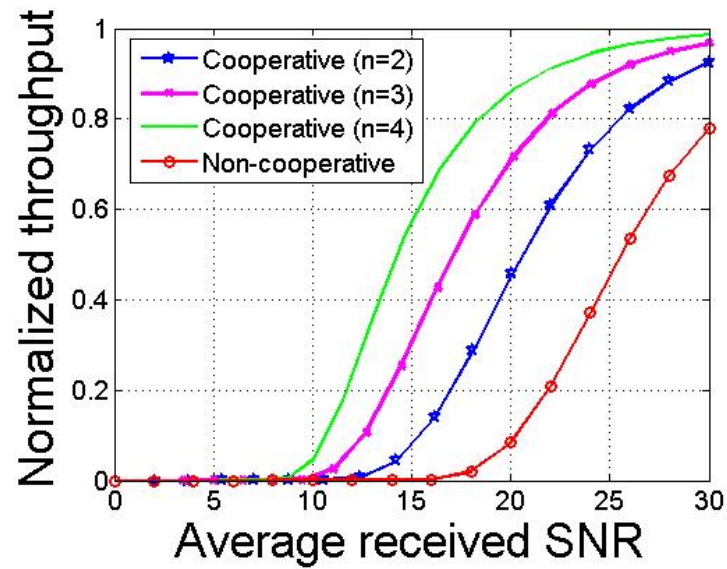

Figure 5.4: Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=2dBs
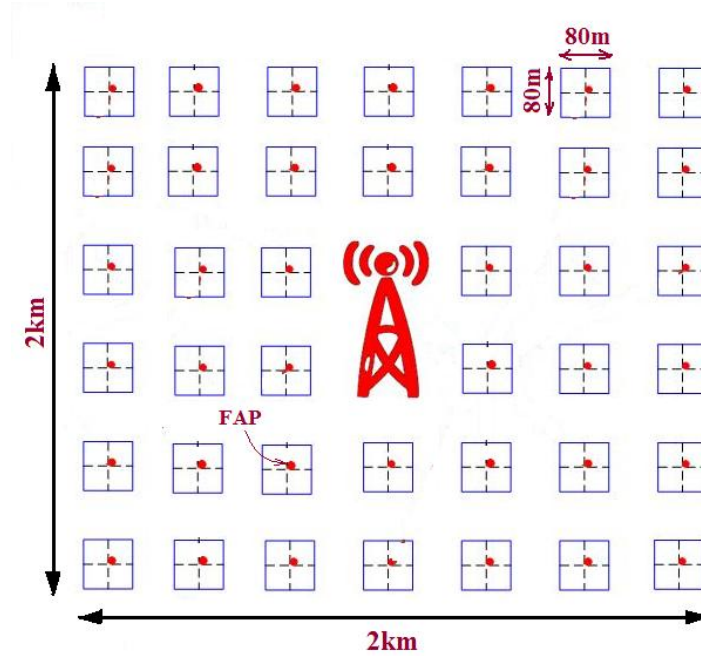
Figure 5.5: OFDMA network under study.

5.2 Multiple Users Case

In this section, we consider studying and evaluating the performance of the cooperative techniques in the presence of multiple users. We evaluate and assess the performance improvements in terms of outage probability, and data throughput in the macrocell downlink communication due to femtocell user cooperation, and study the impact of cooperation level on these performances. We also evaluate the throughput that macrocell users can obtain under cooperative diversity as a function of the percentage of femtocell coverage ratio.

In this simulation, we study a $4km^2$ area having multiple, uniformly placed houses

as shown in Fig.5.5. Each individual house has an area of $80 \times 80m^2$ in which a FAP is located at the center. We assume that there are 3400 users uniformly distributed in the network, some of which are considered to be active while the others are considered to be idle. Also, some of the users are assumed to be placed indoor (inside the houses), which will then be serviced through the FAP that belongs to the house the user is located in. Users that are not situated indoor are, on the other hand, assumed to be outdoor, which will then be serviced by the MBS located at the center of the $4km^2$ area. All active users within the network are assumed to have an infinite number of packets to send. In this work, we also assume that femtocell users and macrocell users all share the same frequency resources. However, at any time slot, we assume that macrocell users cannot have access to more than half of the frequency band. Femtocell users, on the other hand, have full access to the whole frequency band at all time. This resource allocation may not be the best in terms of its ability to eliminate/avoid interference in two tier networks, but it serves the purpose of this work, because our goal here is to demonstrate the performance improvement that macrocell users can gain as a result of femtocell user cooperation. We consider an OFDMA access scheme in our simulation, because it is known to perform better than other access schemes when it comes to the ability to suppress interference in two tier networks [19]. This is because of the orthogonality nature of OFDMA subcarriers, which make it more robust in combating interference. In this simulation, we assume each user will be assigned only one subcarrier to carry out its communication. The network parameters used in this simulation are summarized and listed in Table 5.1.

Before the downlink communication starts, each macrocell user will be assigned the

Table 5.1: Simulation Parameters

Specification	MBS	FAP	Relay node
Transmit Power	50W	90mW	150mW
Channel Bandwidth		20MHz	
FFTs		512	
Subcarrier Spacing		15kHz	
Nbr of Occubied Subcarrier		300	
White Noise Power Density		-174dBm/Hz	
Relay $\rho_{th_{min}}$			5dBs
Relay $\rho_{th_{max}}$			100dBs
Path Loss Model			
1. Indoor		$PL(dB) = 28.5 + 30log_{10}(d) + 15$	
2. Outdoor		$PL(dB) = 28.5 + 30log_{10}(d)$	

subchannel with the least interference level. Subchannels are selected by scanning all band subcarriers. The selected subchannel will also be used by the selected relay nodes. While these relays are busy forwarding their received signal to the destination (one relay at a time), the MBS can concurrently service other macrocell user(s), avoiding then the loss of any communication opportunities and thus increasing the overall network throughput.

Feomtocell downlink communications also happen in almost the same fashion. Given that each FAP manages 300 subcarriers, each femtocell user is assigned a subchannel using the same opportunistic frequency allocation mentioned above. This resource allocation allows femtocell users to reuse the same frequency channel, thus increasing the frequency resource utilization. This frequency reuse is made possible because the FAP power level is typically much lower than the MBS power level. The results presented in the next sections are averages over 12 runs.

5.2.1   Outage Probability

Outage probability can be defined as the probability that the SINR of a certain user goes below a certain threshold. In this work, we are not looking at the user's outage probability, but we are rather interested in the network outage probability, which is defined as the ratio of the number of macrocell users who are in outage to the total number of serviced macrocell users. In this simulation, we measure the received SINR, ρ, at each macrocell user, which is given by (also derived in Eq. (3.16)).

$$\rho = \rho_{1D} + \sum_{i=2}^{n} \frac{\rho_{1i}\rho_{iD}}{\rho_{1i} + \rho_{iD} + 1}$$

where ρ_{xy} can be written as

$$\rho_{xy} = \frac{P_x G_{x,y}}{\sigma_N^2 \Delta f + \sum_{m=1}^{M} P_m G_{m,y}}$$

where P_x represents node x's transmitted power, $G_{x,y}$ represents the channel gain between node x and node y, and can be defined as $G_{x,y} = 10^{PL(dB)/10}|h_{xy}|^2$, Δf represents the subcarrier spacing in Hz, σ_N^2 represents the noise variance, i.e., the one sided noise power spectral density.

Fig. 5.6 shows the outage probability of both the non-cooperative and the cooperative schemes for various numbers of relay nodes as a function of the threshold SINR. In this experiment, the femtocell coverage ratio is set to 0.6. The figure shows that as the threshold value of the received SINR increases, the outage probability also increases regardless of which scheme is used. Observe that at low SINR threshold values, the per-

formance of the non-cooperative scheme, though acceptable, is worse than that of the cooperative schemes. However, the non-cooperative scheme cannot keep up with this good performance at high threshold values. The outage probability of the cooperative scheme, on the other hand, is always lower than that of the non-cooperative scheme, and this gap becomes even greater when the number of relay nodes in the network increases. For instance, when threshold SINR=25dBs, the outage probability of the cooperative diversity when two relays ($n = 3$) are used is about 0.45, whereas that of the non-cooperative scheme is about 0.68. This means that out of 300 macrocell users being serviced by the MBS, 204 of them will be in outage when the non-cooperative scheme is used, while only about 135 macrocell users will be in outage when the cooperative scheme (with 2 relays) is used. This shows the significant improvement that can be obtained when cooperative diversity is used. Also, observe that at low SINR thresholds, the performance of the cooperative scheme when one relay is used is similar to that when two relays are used. However, as the threshold increases, the benefit of adding more relays becomes more significant. We then conclude that for high SINR threshold values, the greater the number of relays, the lower the outage probability, and hence, the destination node should accommodate higher numbers of relay nodes when the SINR threshold is high.

Figs. 5.7 and 5.8 show the outage probability for both schemes as a function of the received SINR threshold when femtocell coverage ratio is equal to 0.5 and 0.3, respectively. Clearly, a decrease in femtocell coverage ratio results in a reduction in the outage probability. This is because as the number of FAPs in the network decreases, some of the active femtocell users become idle macrocell users since the MBS is servicing at
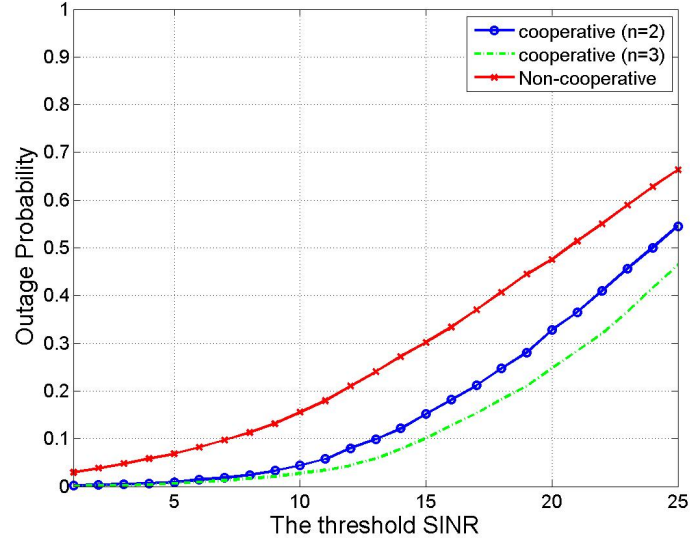
Figure 5.6: Outage probability of the non-cooperative and cooperative schemes when femtocell coverage ratio is 0.6.
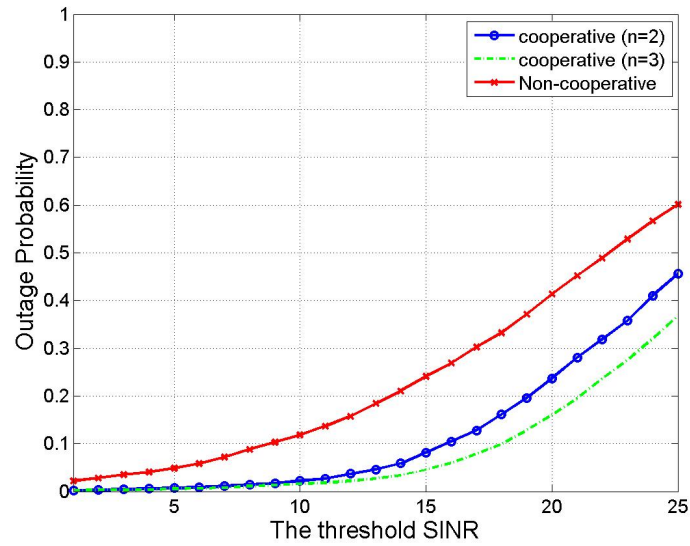

Figure 5.7: Outage probability of the non-cooperative and cooperative schemes when femtocell coverage ratio is 0.5.
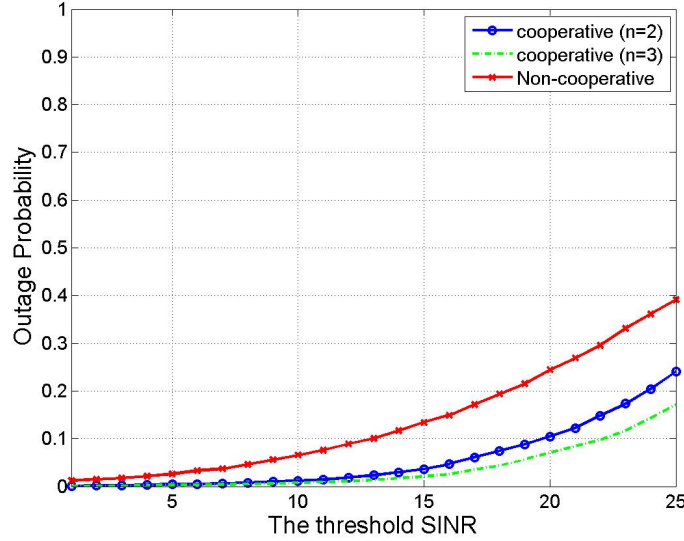
Figure 5.8: Outage probability of the non-cooperative and cooperative schemes when femtocells coverage ratio is 0.3.

full load case. This means that subcarriers reuse in the network is reduced, and consequently the interference introduced to the network becomes less. From both figures, we can make similar observations to those we made when femtocell coverage ratio is 0.60; the performance of the cooperative scheme is better than the non-cooperative scheme and as the number of relay nodes increases, the performance gets even better.

Fig. 5.9 shows the outage probability as a function of femtocell coverage ratio. The threshold SINR in this case was set to 25dBs. This figure summarizes the observations described previously. As the femtocell coverage ratio increases, the outage probability for both the cooperative and the non-cooperative case increases because of the increased two tier interference in the network. In addition, as femtocell coverage ratio increases, the difference between the outage probability of the non-cooperative scheme and the
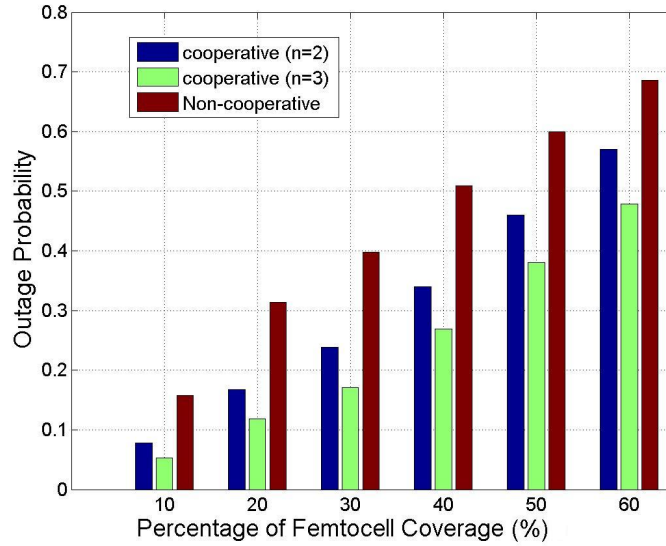
Figure 5.9: Outage probability of the non-cooperative and cooperative schemes for various femtocell coverage ratios.

outage probability of the cooperative scheme increases. The reason is because of the resulted increase in the number of idle femtocell users in the network when compared to low femtocell coverage ratio values. At low femtocell coverage ratio values, some users might be forced to send directly to the destination node without any cooperation because of the limited number of idle femtocell users. Therefore, when the femtocell coverage ratio increases, then so does the benefit of cooperation.

5.2.2   Macrocell Network Throughput

On the contrary to the per-user throughput analysis conducted in Section 5.1, we here analyze the network throughput when considering multiple users in the network. Net-
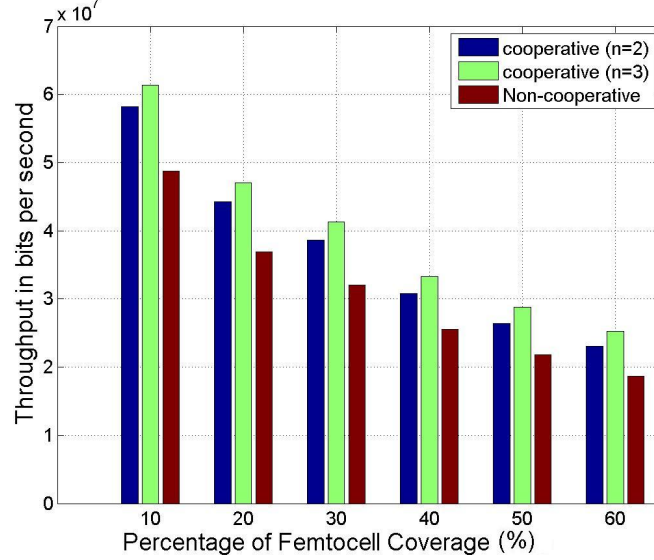
Figure 5.10: Overall network throughput for the non-cooperative and cooperative schemes as a function of femtocell coverage ratios.

work throughput is here defined as the total sum of macrocell users' capacities [7, 14]; i.e., throughput $= \sum_i \sum_j \beta_{i,j} C_{i,j}$, where $C_{i,j} = B log_2 \left(1 + \alpha SINR_{i,j}\right)$ where $\beta_{i,j} = 1$ if user j is using subcarrier i and zero otherwise, B is the bandwidth of a subcarrier, $1/\alpha$ is known as the SNR gap and is equal to $1/\alpha = -\left(2BER\right)/1.5$ [7, 14]. Here we set $BER = 10^{-6}$.

Fig. 5.10 shows the network throughput as a function of the femtocell coverage ratio. Observe that the network throughput achievable under the cooperative scheme is greater than that obtained under the non-cooperative one, especially when more relays are used. The other observation we make form the figure is that as the femtocell coverage ratio increases, the network throughput decreases regardless whether the cooperative or the non-cooperative scheme is used. This is because of the level of interference

increases as more femtocells are added to the network; i.e, some of the idle macrocell users become active femtocell users as the number of femtocells increases.

Chapter 6 – CONCLUSION

This thesis studies the cooperative transmission techniques when applied in the context of femtocells. Both the bit-error rate (BER) and user throughput performances of the downlink macrocell network were analyzed with and without femtocell user cooperation. We considered two cases: The first case studies the single user scenario; i.e., without interference consideration. The second case studies cooperation while considering the presence of multiple users; i.e., with interference consideration. We show that femtocell user cooperation in the downlink communication can substantially improve the BER, the outage probability, and the data throughput achievable by macrocell users. Using simulations, we show that under reasonable SNR values, cooperative schemes enhance the downlink performances of macrocells by improving the BER, outage probability, and data throughput of macrocell users significantly when compared with the traditional, non-cooperative schemes.

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