Improving Macrocell Downlink Throughput in Rayleigh Fading Channel Environment Through Femtocell User Cooperation

Adem M. Zaid, Bechir Hamdaoui, Xiuzhen Cheng, Taieb Znati, Mohsen Guizani

***Abstract*—This paper studies cooperative techniques that rely on femtocell user diversity to improve the downlink communication quality of macrocell users. We analytically derive 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.**

***Index Terms*—Cooperation, femtocells, downlink throughout.**

I. INTRODUCTION

FEMTOCELLS are low-power base stations with small coverage targeted for home and small business uses [1, 2]. Due to their low cost, low power consumption, and to their ability to provide high data rates, they have recently attracted considerable research attention [3–5]. About 50% of phone calls and about 70% of data communication are projected to be taking place indoors in the next few years [6]. In addition to offering high data-rates at low power, femtocells can potentially reduce the traffic load on traditional macrocellular networks by servicing macrocell users that happen to be under their coverage. Femtocell deployment still, however, presents some major challenges, pertaining mainly to interference and handoff [4, 7].

The interference problem arises primarily because femtocells are often required to share the same spectrum resources with each other, and with the macrocell which they belong to. Solutions attempting to mitigate interference have been proposed in literature [4, 8–10]. In [9], 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 [10] propose an interference management approach that too relies on frequency allocation, 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. One major challenge 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/4G cellular links). This can be very problematic for femtocell users, which desire to maintain high data rates while being handed off from their femtocells to the macrocell (i.e., maintain data rates that are similar to those received while being in their femtocells).

In this paper, we propose techniques that rely on user cooperation to improve throughput of macrocell users[1] in femtocell/macrocell networks. But before delving into the details of the proposed cooperation framework, we want to mention that although user cooperation has great potential for improving network performances (as will be illustrated in this work), it also gives rise to several challenges. Users' willingness is one of them. Naturally, if a user does not see an immediate benefit and reward from its cooperation, then it will not cooperate. Other concerns, like security/privacy concerns and resource (e.g., energy, bandwidth, etc.) limitations, are also legitimate reasons that make users shy away from cooperation.

Cooperation cannot be forced on users, and therefore, it can only be promoted by giving users good incentives to do so. We want to mention that the focus of this work is not on cooperation incentives, and there are many recently proposed mechanisms that aim to provide users with good incentives to cooperate (e.g., [11–13] to say a few). For example, in [11, 12], the authors propose to treat the relaying task as a service, in which the relaying users get rewarded for their service while the source, destination, or both get charged for receiving the relaying service. The charging/rewarding policies are done by exchanging virtual currency or credit among users that can be converted later to some form of service.

Our contributions in this work are: $i)$ proposing coop-

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A. M. Zaid and B. Hamdaoui are with Oregon State University (e-mail: zaida@onid.edu, hamdaoui@eecs.orst.edu).

X. Cheng is with George Washington University (e-mail: cheng@gwu.edu).

T. Znati is with the University of Pittsburgh (e-mail: znati@cs.pitt.edu).

M. Guizani is with Qatar University (e-mail: mguizani@ieee.org).

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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.

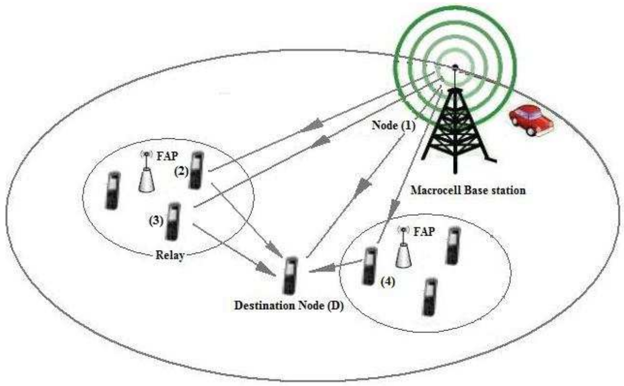

Fig. 1. Two-tier network architecture

erative techniques that improve the received signal quality in the downlink of macrocell users through user diversity, thereby increasing the overall throughput that macrocell users achieve; ii) analyzing and evaluating 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 under femtocell user cooperation; iii) proposing a relay selection mechanism that can be implemented in a distributed manner; and iv) showing via simulation that cooperative transmission schemes significantly improve the BER, the outage probability, and the data throughput when compared with non-cooperative techniques.

The rest of this paper is organized as follows. Section II presents the network model and architecture. Section III derives and presents the performance of the proposed cooperative schemes. Section IV describes the proposed relays selection approach. Section V presents the simulation results. Finally, we conclude the paper in Section VII.

II. Network Model and Architecture

In this paper, we study the downlink communication of a macrocellular network. As depicted in Fig. 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 macrocell user (also referred to as *destination node* hereafter), the transmitted signal will be received by the desired destination node as well as by all nearby idle femtocell users, possibly belonging to different femtocells. After receiving the signal, the destination node sends an ACK back to the MBS informing it whether the signal is received correctly or not. This ACK signal will also be received by all femtocell users that are located nearby the destination node, and will also be used by them to determine whether the femtocell user is close enough to play the role of a relay. Depending on their distances as well as on 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 amplifying and retransmitting the received signals, one user 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, the MBS can concurrently transmit data to other macrocell user(s), avoiding then the lost 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 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, the destination node uses the maximum ratio combining (MRC) technique [14] to combine and recover its original data. We assume that all channels are slow, flat faded, Rayleigh distributed, and mutually independent, and consider BPSK modulation technique.

In this work, we rely on the communication between the MSB and the destination to estimate the source-to-relay channel, and on the ACK sent by the destination to the MSB to estimate the relay-to-destination channel. We assume that relays extract the source-to-relay channel information from the MBS transmission during the first, direct transmission sent by the MBS. Once the destination node receives the first transmitted signal, it sends an ACK signal to the MBS. In addition to informing the MBS whether the signal was received correctly, the ACK contains the relay-to-destination channel information which the destination extracts based on the previous signal received from the relay. Relays use this ACK to estimate the relay-to-destination channel.

III. BER Analysis

In this section, we derive the BER performance of the proposed cooperative scheme by first considering single-user and then multiple-user scenarios.

A. Single-User Case

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

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

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

$$y_{1i}(t) = h_{1i}\sqrt{E_b}S_1(t) + W_i(t) \tag{2}$$

where E_b is the bit 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. Ω_{1i}, Ω_{1D}, and σ_N^2 are the corresponding variances.

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 $i = 2, 3, ..., n$, where $W_D(t+i-1) \sim G(0, \sigma_N^2)$ 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 is the bit energy sent by node i. At the destination node, all received signals are combined (using the MRC technique) at time $(t+n-1)$, and can be written as

$$y_{out}(t+n-1) = \sum_{i=1}^{n} w_i y_{iD}(t+i-1) \tag{3}$$

where w_i represents the weighting factor of the i^{th} 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

$$y_{out}(t+n-1) = \frac{h_{1D}^*\sqrt{E_b}}{\sigma_N^2}y_{1D}(t) + \sum_{i=2}^{n}\frac{\alpha_i^* h_{1i}^* h_{iD}^*\sqrt{Eb}}{\sigma_N^2(\alpha^2|h_{iD}|^2+1)}y_{iD}(t+i-1) \tag{4}$$

where (*) represents the complex conjugate. From Eq. (4), it follows that the SNR, γ, at the output of the MRC combiner is

$$\gamma = \gamma_{1D} + \sum_{i=2}^{n}\frac{\gamma_{1i}\gamma_{iD}}{\gamma_{1i} + \gamma_{iD} + 1} \tag{5}$$

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 [15].

$$P_b(E/\gamma) = Q\left(\sqrt{\gamma_{1D} + \sum_{i=2}^{n}\frac{\gamma_{1i}\gamma_{iD}}{\gamma_{1i} + \gamma_{iD} + 1}}\right) \tag{6}$$

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.

2) Average BER Derivation: The average BER of the received signal at the output of the demodulator can be expressed as [16]

$$P_b(E) = \int_0^\infty P_b(E/\gamma)P_\gamma(\gamma)\,d\gamma \tag{7}$$

where $P_b(E/\gamma)$ is the conditional bit error probability given in Eq. (6), and $P_\gamma(\gamma)$ is the probability density function (pdf) of the SNR at the output of the MRC combiner [16].

By using the integral form of the $Q(.)$ function [15], it follows that the BER of the cooperative scheme can be written as

$$P_b(E) = \frac{1}{\pi}\int_0^\infty\int_0^{\pi/2} P_\gamma(\gamma)e^{-\frac{\gamma}{sin^2\theta}}\,d\gamma d\theta \tag{8}$$

Since the conditional BER of the cooperative scheme is a function of the total SNR (the sum of all branches' SNRs), Eq. (8) can be rewritten as

$$P_b(E) = \frac{1}{\pi}\int_0^{\pi/2}\prod_{i=1}^{n} M_{\gamma_i}\left(-\frac{1}{sin^2\theta}\right)d\theta \tag{9}$$

where M_{γ_i} is the moment generating function. It then follows that the probability distribution of the two-hop path SNR can be written as

$$p_\gamma(\gamma) = \frac{2\gamma e^{-\gamma(1/\bar{\gamma}_{1i}+1/\bar{\gamma}_{iD})}}{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}\left(\frac{\bar{\gamma}_{1i}+\bar{\gamma}_{iD}}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}}K_1\frac{2\gamma}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}} + 2K_0\frac{2\gamma}{\sqrt{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}}\right)U(\gamma) \tag{10}$$

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. (10) can be approximated as [17]

$$p_\gamma(\gamma) \approx \left(\frac{1}{\bar{\gamma}_{1i}} + \frac{1}{\bar{\gamma}_{iD}}\right)e^{-\left(\frac{1}{\bar{\gamma}_{1i}}+\frac{1}{\bar{\gamma}_{iD}}\right)\gamma} \tag{11}$$

The pdf of the one-hop path SNR, on the other hand, is

$$p_\gamma(\gamma) = \frac{1}{\bar{\gamma}_{1D}}e^{-\frac{1}{\bar{\gamma}_{1D}}\gamma} \tag{12}$$

By substituting Eqs. (11) and (12) into Eq. (9), the BER becomes

$$P_b(E)=\frac{1}{\pi}\int_0^{\pi/2}\Bigg(\frac{sin^2\theta}{sin^2\theta+\bar{\gamma}_{1D}}\Bigg)\prod_{i=2}^{n}\Bigg(\frac{sin^2\theta}{sin^2\theta+\bar{\gamma}_{1iD}}\Bigg)d\theta \quad (13)$$

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; i.e., there is no cooperation from the femtocell users. The pdf of the one-hop path (source-to-destination) SNR is expressed as in Eq. (12), which, after being substituted in Eq. (7), yields a BER that is equal to

$$P_b(E)=\frac{1}{2}\sqrt{\frac{\bar{\gamma}_{1D}}{\bar{\gamma}_{1D}+1}} \quad (14)$$

B. Multiple-User Case

We now study the performance of cooperative diversity in a multiple-user environment, where multiple macrocell users and femtocell users can all be active in the network. Recall that the system being considered in this work is two-tier femtocell/macrocell networks, where femtocells and macrocells are assumed to communicate over two different frequencies. Since each FAP serves multiple femtocell users, each FAP relies then on a multiple access technique (e.g., TDMA) to allow multiple users to share and use the same frequency. Now when a femtocell user chooses to cooperate, it does so through the macrocell frequency so as to $1)$ avoid interference with other femtocell users and $2)$ can communicate with the macrocell user which will be tuned on the macrocell frequency.

Similar to what was done in Section III-A, 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.

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. (1) and (2) in the case of single user only, become

$$y_{1D}(t)=h_{1D}\sqrt{E_b}S_1(t)+\sum_{j\in\mathcal{I}_{D_1}}h_{jD}\sqrt{E_j}S_j(t)+W_D(t) \quad (15)$$

$$y_{1i}(t)=h_{1i}\sqrt{E_b}S_1(t)+\sum_{j\in\mathcal{I}_i}h_{ji}\sqrt{E_j}S_j(t)+W_i(t) \quad (16)$$

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

$$\begin{aligned}y_{iD}(t+i-1)= \;& \alpha_i h_{iD}\{h_{1i}\sqrt{E_b}S_1(t)+\sum_{j\in\mathcal{I}_i}h_{ji}\sqrt{E_j}S_j(t)\\ &+W_i(t)\}+\sum_{j\in\mathcal{I}_{D_i}}h_{jD}\sqrt{E_j}S_j(t+i-1)\\ &+W_D(t+i-1)\end{aligned} \quad (17)$$

where $\mathcal{I}_{D_i}$ represent the set of users whose transmitted signals interfere with the reception at the destination D during time slot $(t+i-1)$. 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 derivation in the multiple user/interferer case is very challenging, as it requires the statistical properties of each interference component. In order to simplify the BER analysis when cooperative diversity is applied, we propose the use of the central limit theorem (CLT) instead. 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 components. Using this approximation, Eqs. (15) and (16) can be approximated as

$$y_{1D}(t)\approx h_{1D}\sqrt{E_b}S_1(t)+X_{1D} \quad (18)$$

$$y_{1i}(t)\approx h_{1i}\sqrt{E_b}S_1(t)+X_i \quad (19)$$

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 equaling 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. (17) can be approximated as

$$y_{iD}(t+i-1)\approx\alpha_i h_{iD}\left(h_{1i}\sqrt{E_b}S_1(t)+X_i\right)+X_{iD} \quad (20)$$

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 time slot $(t+i-1)$.

The signal at the output of the MRC becomes then

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

and the received SINR, ρ, is expressed as

$$\rho=\rho_{1D}+\sum_{i=2}^{n}\frac{\rho_{1i}\rho_{iD}}{\rho_{1i}+\rho_{iD}+1} \quad (21)$$

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. (5). Therefore, the conditional bit error probability is

$$P_b(E/\rho) = Q\left(\sqrt{\rho_{1D} + \sum_{i=2}^{n} \frac{\rho_{1i}\rho_{iD}}{\rho_{1i} + \rho_{iD} + 1}}\right) \qquad (22)$$

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. (12) and (11), respectively. As a result, the average BER, $P_b(E)$, has a similar form to the average BER given in Eq. (13), which can be written as (after some algebraic manipulations)

$$P_b(E) = \frac{1}{\pi}\int_0^{\pi/2} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\rho}_{1D}}\right) \prod_{i=2}^{n} \left(\frac{sin^2\theta}{sin^2\theta + \bar{\rho}_{1iD}}\right) d\theta \qquad (23)$$

where

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

IV. 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 Section II, 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. This set is to be determined by the destination node as will be explained later. Intuitively, for an efficient implementation of cooperative diversity, the nodes to be selected for relaying should be the ones that can provide the best possible performance, and the selection process should be smooth and should incur no (or minimum) overhead.

In the traditional cooperative diversity literature, one can find several different protocols for relays selection [18–21]. In [18], for instance, the relay providing the highest min SINR among all possible relays is selected. This selection process is performed by the destination node, and requires feedback exchange among the source node (i.e., the MBS), the candidate relays, and the destination node. This feedback provides each candidate relay with knowledge about its forward and backward channel values, which is done in three exchange steps: $1)$ the source node sends a sequence to the relays to allow them to determine their backward channel values, $2)$ each relay sends a sequence to the destination node to allow it to determine its channel value towards the relay, and $3)$ the relays broadcast the information they obtained during the first step to both the source and the destination nodes. The question of how each relay uses 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, however, been addressed, and reaching such an optimal decision is likely to incur more transmissions/overhead. Unlike in [18], the authors in [19] propose that relay selection be made by the relays themselves, not by the destination node. They suggest that after determining their forward and backward channels values, the candidate relays broadcast and share their channels values among themselves, so that to allow each relay to compare its channel values with other relays' values until the optimum decision is made. This approach, however, assumes that candidate relays can hear each other, which may not be true in practice. If relays can not hear one another, two or more relay nodes' transmissions might collide while forwarding the signal to the destination. In [21], the authors propose a MAC protocol with distributed relay selection. The idea is that when the channel/link between the source and the destination nodes is poor, a relay is selected in the vicinity of both nodes via distributed contention process to replace the link by a two-hop path with a better channel condition.

Approaches that rely on Q-learning [22] and Genetic Algorithms [20] to provide a solution approximation have also been proposed. These techniques do not require coordination, as they try to estimate the relay solution in a distributed manner. There have also been proposed relay selection approaches for other channel models, such Nakagami [23] and MIMO [18, 24]. Our work focuses on the Rayleigh channel model, and proposes a deterministic relay selection approach for Rayleigh channels that is fast and incurs very little overhead. The approach is described as follows:

Relay selection. The first step consists of filtering out the relays whose cooperation is likely not to be beneficial to the destination. For this, we use the two-hop (MBS-relay-destination) SINR metric as the basis for deciding whether a relay is beneficial to the destination, where the two-hop SINR at the destination is again (previously derived in Eq. (21))

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

We then require that all candidate relays whose two-hop SINRs fall below a minimum required SINR threshold be filtered out and not considered as relays. More precisely, the idle femtocell users that can be considered as candidate relays for a particular macrocell user are those whose two-hop SINRs satisfy

$$\rho_{th_{min}} \leq \rho_{eq} \qquad (24)$$

where $\rho_{th_{min}}$ is the min SINR threshold that is to be chosen by the destination. The verification of the inequality given in (24) is carried out by the idle femtocell users themselves. But in order to enable each idle femtocell user to calculate its corresponding instantaneous ρ_{eq} value, each user/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 transmitted signal, it sends an ACK signal to the MBS to inform it that the signal/packet was received correctly. In this work, we assume that the ACK signal has three extra roles besides informing the MBS about the signal's successful reception: $1)$ it informs the MBS and idle femtocell users about whether the destination node opts for the cooperative diversity scheme (this decision is made by the destination node, and is purely based on the signal quality that it receives from the MBS), 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 (i.e., MBS's first transmitted signal and the destination node's ACK signal), 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 to the destination node. Intuitively, we want the relays to be ordered according to their SINR values; i.e., the relay with the highest SINR is to start first, the relay with the second highest SINR is to start second, and so on. For this, we propose that each selected relay (i.e, each idle femtocell user whose SINR satisfies Inequality (24)) sets a back-off counter as soon as it receives the ACK signal from the destination node. The back-off counter is set to a value that is a decreasing function of $\Delta = \rho_{eq} - \rho_{th_{min}}$. Once all back-off counters are set, each selected relay decrements its back-off counter by 1 for every idle time slot, and when the counter reaches zero, the selected relay starts relaying the signal to the destination. The idea here is that because the higher the Δ value; i.e., the greater the SINR value, the sooner the selected relay starts relaying the signal, candidate relays with higher SINRs start relaying first. When 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 relaying is needed. In the event when more relaying is needed, then the second relay is to be chosen on the same back-off process basis. That is, the relay whose back-off counter reaches zero first becomes the second relay, which starts forwarding the signal as soon as its counter reaches zero. This process repeats so long as the destination node calls for more relaying. Like in most back-off mechanisms that aim at resolving medium access contention, when collision happens here, that collided signal is ignored by the destination node. Note that although the number of relays is to be determined by the signal quality threshold set by the destination itself, it can also be determined by the delay, and when the delay is judged high, the destination can limit the number of relays to a small number.

The destination node also implements and relies on a timeout mechanism to resolve the case when no more relays are available. That is, when the destination node receives no relaying signal within a timeout period, it then assumes that no relays are available, and hence, it recovers its signal based on the signals it received so far.

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 the cooperation of femtocell users as described above, and when cooperation is requested, the destination node can also decide on how many relay nodes should be used.

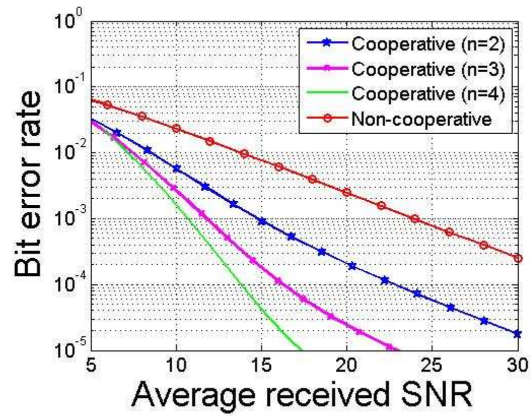

Fig. 2. BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=10dBs for different values of the number of relays.

V. Performance Evaluation

In this section, 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.

A. Single-User Case

We now focus on the single user case, and evaluate the performance in terms of the achievable BER and data throughput under 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 $\bar{\gamma}_{1D} = \bar{\gamma}_{12} = ... = \bar{\gamma}_{1n}$. We also assume that all relays' forward channels experience similar conditions, meaning that $\bar{\gamma}_{2D} = \bar{\gamma}_{3D} = ... = \bar{\gamma}_{nD}$. This assumption is reasonable, since candidate/selected relays are likely to be located within, roughly, an equal distance from the MBS and from the destination node.

1) BER Analysis: Fig. 2 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 numbers 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. 3 these same results but when

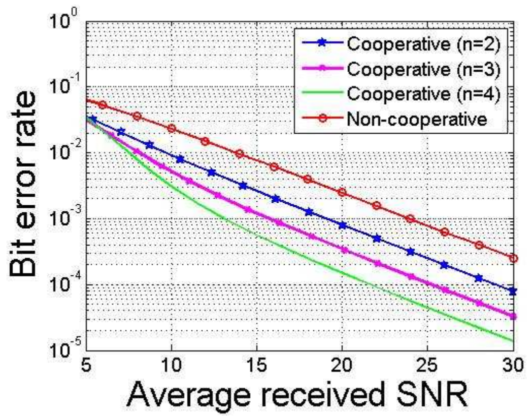

Fig. 3. BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=2dBs for different values of the number of relays.

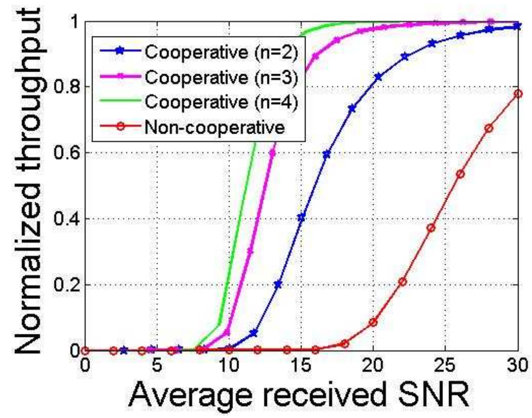

Fig. 4. Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=10dBs

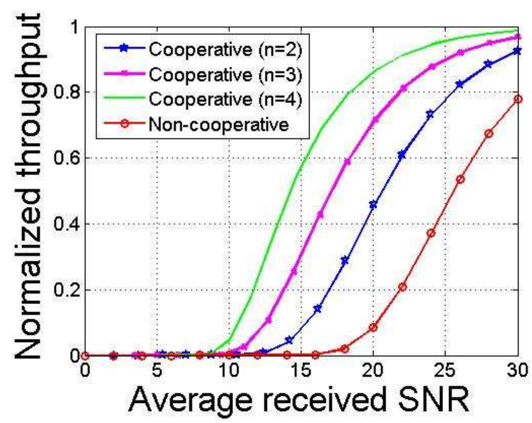

Fig. 5. Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=2dBs

the relay-to-destination SNR value is 2dBs. We observe similar performance behaviors also when the relay-to-destination SNR is reduced to 2dBs. Though expected, the gap in BER between that obtained under the cooperative scheme and that obtained under the non-cooperative scheme gets smaller as the relay-to-destination channel quality degrades.

2) Throughput Analysis: We also evaluate and compare the data throughput achievable under the cooperative 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, and P_b is already derived in Section III (Eq. (13) for the cooperative scheme and Eq. (14) for the non-cooperative scheme).

Figs. 4 and 5 show the normalized[2] 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 cooperative 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, Fig. 4 shows that 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), the throughput gain is slightly less substantial. It is then worth mentioning that whether or not the cooperative scheme outperforms the non-cooperative one depends on the quality of the relay-to-destination channel when compared with that of the source-to-destination channel. That is, if the source-to-destination channel has a good quality when compared with that of the relay-to-destination channel, the non-cooperative scheme may outperform the cooperative scheme. Hence, cooperation may not be beneficial in some cases, and if this is the case, one can choose not to use cooperation.

[2]Normalized with respect to the channel capacity; i.e., the achievable throughput corresponding to when $P_b = 0$.

B. Multiple-User 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 the cooperation level on these performances. We also evaluate the throughput that macrocell users can obtain under cooperative diversity as a function of the femtocell coverage ratio.

In this simulation, we consider a $4km^2$ area with multiple,

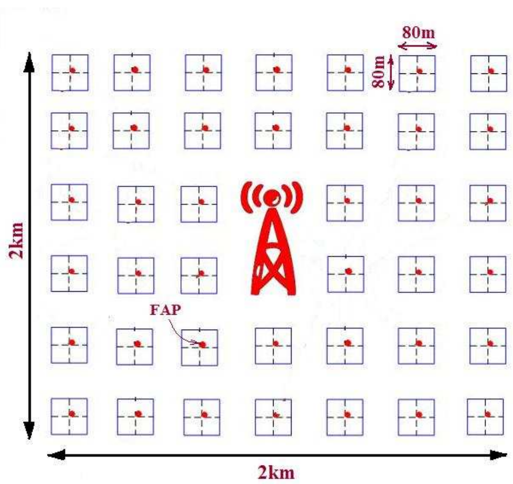

Fig. 6. Femtocell network.

uniformly placed femtocells (e.g., houses) as shown in Fig. 6. Each individual femtocell/house contains a FAP covering an area of $80 \times 80m^2$. We consider 3400 users uniformly distributed in the entire network. Some of the users are assumed to be placed indoor (inside the houses), which are then serviced by the FAP belonging to the house the user is situated in. Users that are not situated indoor are, on the other hand, assumed to be outdoor, which are then 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; i.e., frequency sub-bands. Specifically, we assume that macrocell users are only allowed access to half of the frequency sub-bands, whereas, femtocell users, on the other hand, have access to all sub-bands 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 [25]. This is because of the orthogonality nature of OFDMA sub-carriers/channels, which make it more robust in combating interference. In this simulation, we assume each user is assigned only one subcarrier to carry out its communication. The network parameters used in this simulation are summarized and listed in Table I.

In order to carry its downlink communication, each macrocell user is assigned the sub-channel with the least interference level. Sub-channels are selected by scanning all sub-carriers. These selected sub-channels are also to 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 lost of any communication opportunities and thus increasing the overall network throughput.

TABLE I
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
Path Loss Model			
1. Indoor	$PL(dB) = 28.5 + 30log_{10}(d) + 15$		
2. Outdoor	$PL(dB) = 28.5 + 30log_{10}(d)$		

Feomtocell downlink communications also happen in the same fashion. Given that each FAP manages multiple subcarriers (300 in the simulation), each femtocell user is assigned a sub-channel 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.

C. Outage Probability

From a user's viewpoint, the outage probability can be defined as the probability that the user's SINR goes below a certain threshold. From a system's viewpoint, the network outage probability is defined as the ratio of the number of macrocell users that are in outage to the total number of serviced macrocell users. In this simulation, the received SINR, ρ, at each macrocell user (i.e., the destination node) is measured using the following expression (already derived in Section III-B and given in Eq. (21)):

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

where ρ_{mn} can be written as

$$\rho_{mn} = \frac{P_m G_{m,n}}{\sigma_N^2 \Delta f + \sum_{k=1}^{M} P_k G_{k,n}}$$

where P_m represents node m's transmitted power, $G_{m,n} = 10^{PL(dB)/10}|h_{mn}|^2$ represents the channel gain between node m and node n, Δf represents the subcarrier spacing in Hz, and σ_N^2 represents the noise variance.

Fig. 7 shows the network 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 performance 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

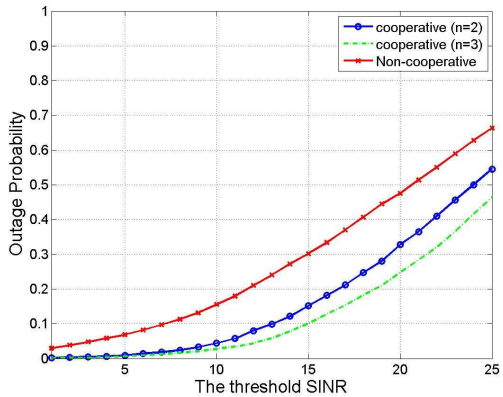

Fig. 7. Outage probability of the non-cooperative and cooperative schemes when femtocell coverage ratio is 0.6.

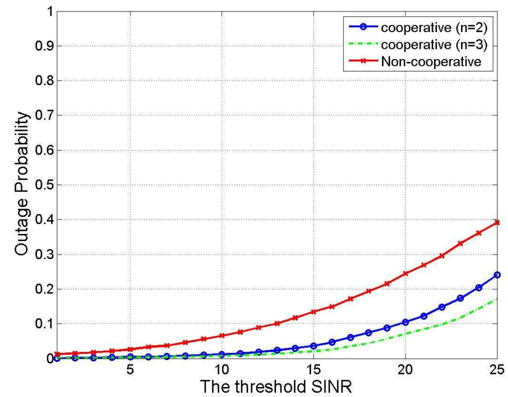

Fig. 9. Outage probability of the non-cooperative and cooperative schemes when femtocells coverage ratio is 0.3.

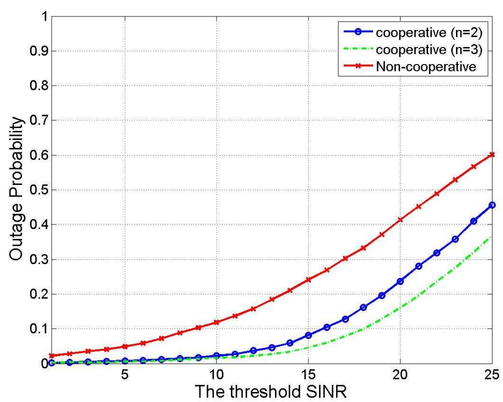

Fig. 8. Outage probability of the non-cooperative and cooperative schemes when femtocell coverage ratio is 0.5.

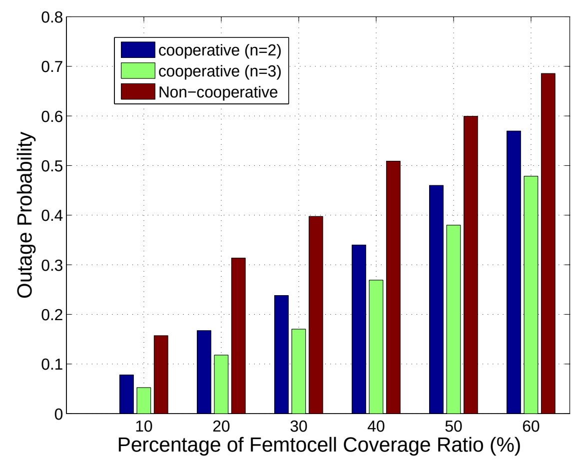

Fig. 10. Outage probability of the non-cooperative and cooperative schemes for various femtocell coverage ratios.

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 when SINR threshold values are high, the destination node is recommended to accommodate more numbers of relay nodes, because the greater the number of relays, the lower the outage probability. This is not so much needed when SINR values are low.

Figs. 8 and 9 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, thereby reducing the overall interference level. Apart from the noticed interference reduction, all other performance trends observed when femtocell coverage ratio equals 0.6 are also observed when the ratio is equal to 0.5 or 0.3.

For completeness, we show in Fig. 10 the outage probability as a function of the femtocell coverage ratio; here the threshold SINR is set to 25dBs. As the femtocell coverage ratio increases, the outage probability for both the cooperative and the non-cooperative schemes increases, due again to the increased interference level in the network. In addition, as the coverage ratio increases, the difference gap between the outage probabilities (non-cooperative versus cooperative) 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 ratios. At low femtocell coverage ratios, 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, the higher the femtocell coverage ratio, the greater the benefits of femtocell user cooperation.

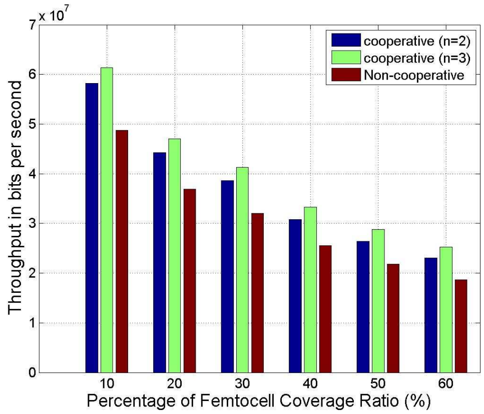

Fig. 11. Overall network throughput for the non-cooperative and cooperative schemes as a function of femtocell coverage ratios.

D. *Macrocell Network Throughput*

On the contrary to the per-user throughput analysis conducted in Section V-A, we here analyze the network throughput when considering multiple users in the network. We use the same network throughput definition given in [26, 27], where network throughput is defined as the total sum of macrocell users' capacities; that is, throughput $= \sum_i \sum_j \beta_{i,j} C_{i,j}$, where $C_{i,j} = Blog_2 (1 + \alpha SINR_{i,j})$, $\beta_{i,j} = 1$ 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 $-(2BER)/1.5$ [26, 27]. Here we set $BER = 10^{-6}$.

Fig. 11 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 of 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.

VI. User Cooperation–Potentials and Challenges

Using user cooperation to improve performance of wireless systems traces its roots back to the work of van der Meulen in 1968, where relaying (or user cooperation) is used to combat fading via channel diversity. Multiple users each equipped with a single antenna can then cooperate to create virtual multi-antenna systems, thereby mimicking transmit diversity without requiring users to have multiple antennas. Cooperation can also be viewed as a means for mobile users to simply forward or relay each other's data instead of improving channel quality via diversity.

User cooperation can improve system performance in terms energy consumption as well. The total amount of energy needed to send a user's data directly to the base station may be much greater than that to be needed with cooperation. In terms of energy savings, cooperation can also be beneficial when a user's battery is running low, where in this case, a user can rely on cooperation to help transmit its data traffic by having nearby user(s) with enough battery resources relay its traffic.

In essence, user cooperation has great potentials for reducing energy consumption and/or improving data throughput. However, it also gives rise to several unique challenges. One key challenge that needs to be overcome in order to promote user cooperation is users' willingness. There are multiple legitimate reasons for why users may not be willing to help out. One, users may not see an immediate benefit/reward of their cooperation. Two, users may be concerned about security, privacy, and/or maliciousness. Three, users may have limited resources (e.g., energy, computing, bandwidth, etc.) that make them shy away from cooperation. In spite of these difficulties, researchers have proposed strategies and approaches that can overcome these barriers, thereby encouraging cooperation among users.

There are two architectural components that wireless systems need to support in order to promote user cooperation: incentive mechanisms and enforcement strategies. Cooperation cannot be forced on users, and therefore, it can only be promoted by giving users good incentives to do so. Incentive mechanisms that aim to provide users with good incentives to encourage them to cooperate have already been proposed in the literature, and [11–13] are just a few. One approach [11] proposes to treat the relaying/forwarding task as a service that the relaying user/node offers the source and/or destination users. In this case, the relaying user gets paid for its service by the source and the destination users (or one of them). The charging/rewarding policies are done by exchanging virtual currency or credit among users that can, for e.g., be converted later to some form of service that the relying user can receive for free.

Incentive mechanisms are necessary but not sufficient to promote cooperation. Selfish user behaviors must also be penalized and prevented, where selfishness here occurs when, for e.g., users seek and receive relaying service from other users, but refrain from offering theirs to others. As a result, enforcement strategies have been developed and adopted in cooperative systems to address selfishness and maliciousness. A common strategy used to enforce user cooperation is to rely on reputation to identify selfish users in the network [13]. That is, users having low reputation values are considered as malicious, and as a result, need to be isolated and deprived from offering and/or receiving relaying services. With this strategy, a user's reputation value increases when it carries out the forwarding service properly and as expected, and decreases otherwise. This continues until the value reaches a predefined threshold, after which the user's relaying service privilege will be removed.

VII. Conclusion

This paper 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 investigated two cases. The first case studies the single user scenario; i.e., without interference consideration, whereas 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.

VIII. Acknowledgment

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References

[1] A. Schroder, H. Lundqvist, G. Nunzi, and M. Brunner, "User-assisted coverage and interference optimization for broadband femtocells," in *Proc. 2009 IFIP/IEEE Int'l Symposium on Integrated Network Management*.

[2] I. Ashraf, H. Claussen, and L. Ho, "Distributed radio coverage optimization in enterprise femtocell networks," in *Proc. 2010 IEEE Int'l Conference on Communications*.

[3] O. Namgeol, S. Han, and H. Kim, "System capacity and coverage analysis of femtocell networks," in *Proc. 2010 IEEE Wireless Communications and Networking Conference*.

[4] K. Sundaresan and S. Rangarajan, "Mitigation of inter-femtocell interference with adaptive fractional frequency reuse," in *Proc. 2010 IEEE Int'l Conference on Communications*.

[5] K. Sundaresan and S. Rangarajan, "Efficient resource management in ofdma femto cells," in *Proc. 2009 ACM Int'l Symposium on Mobile Ad Hoc Networking and Computing*.

[6] D. Perez and A. Valcarce, "OFDMA femtocells: a roadmap on interference avoidance," *IEEE Commun. Mag.*, Sept. 2009.

[7] W. Shaohong, Z. Xin, Z. Ruiming, Y. Zhiwei, F. Yinglong, and Y. Dacheng, "Handover study concerning mobility in the two-hierarchy network," in *Proc. 2009 IEEE Vehicular Technology Conference*.

[8] T. Lee, H. Kim, J. Park, and J. Shin, "An efficient resource allocation in ofdma femtocells networks," in *Proc. 2010 IEEE Vehicular Technology Conference*.

[9] M. Zaman, Y. Jang, and Z. Haas, "Interference mitigation using dynamic frquency re-use for dense femtocell network architectures," in *Proc. 2010 Ubiquitous and Future Networks*.

[10] P. Lee, T. Lee, J. Jeong, and J. Shin, "Interference management in LTE femtocell systems using fractional frequency reuse," in *Proc. 2010 Int'l Conference on Advanced Communication Technology*.

[11] J. Hu and M. Burmester, *Guide to Wireless Ad Hoc Networks*, Springer, 2009.

[12] M. Mahmoud and X. Shen, "Fescim: Fair, efficient, and secure cooperation incentive mechanism for multihop cellular networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 5, pp. 1536–1233, May 2012.

[13] G. Bella, G. Costantino, , and S. Riccobene, "Evaluating the device reputation through full observation in manets," *Journal of Information Assurance and Security*, vol. 4, no. 5, pp. 458–465, Mar. 2009.

[14] K. Sankar, "Maximal ratio combining," www.dsplog.com/2008/09/28/maximal-ratio-combining/.

[15] T. S. Rappaport, *Wireless Communications: Principles and Practice*, Prentice Hall, 2002.

[16] M. Simon and M. Alouini, *Digital communication over fading channels: a unified approach to performance Analysis*, Wiley-Interscience Publication, 2000.

[17] J. Adeane, M. Rodrigues, and I. Wassell, "Characterisation fo the performance of cooperative networks in ricean fading channels," in *Proc. 2005 Int'l Conference on Telecommunications*.

[18] L. Sun and M.R. McKay, "Opportunistic relaying for mimo wireless communication: relay selection and capacity scaling laws," *IEEE Trans. Wireless Commun.*, vol. 10, no. 6, pp. 1786–1797, June 2011.

[19] T. Villa, R. Merz, and P. Vidales, "Performance analysis of two-hop cooperative mimo transmission with relay selection in rayleigh fading channel," in *Proc. 2008 Int'l Conference on Wireless Communications, Networking and Mobile Computing*.

[20] J. Xu, H. Zhang, D. Yuan, and M. Jiang, "A new multiple relay selection scheme in dual-hop amplify-and-forward cooperative network based on genetic algorithm," in *Proc. 2011 Int'l Conference on Communcation Technolgy*.

[21] H. Slimani, B. Escrig, R. Dhaou, and A.-L. Beylot, "Cooperative MAC protocol with distributed relay selection and physical rate adaptation," in *Proc. 2013 IEEE Consumer Communications and Networking Conference*.

[22] H. Jung, K. Kim, J. Kim, O.-S. shin, and Y. Shin, "A relay selection scheme using q-learning algorithm in cooperative wireless communications," in *Proc. 2012 Asia-Pacific Conference on Communications*.

[23] B. Ji, K. Song an Y. Huang, and L. Yang, *Wireless Personal Communications*, 2012.

[24] X.N. Tran, V.H. Nguyen, T.T. Bui, C. Dinh, and Y. Karasawa, "Distributed relay selection for mimo-sdm cooperative networks," *IEICE Trans. Commun.*, vol. E95.B, no. 4, pp. 1170–1179, Apr. 2012.

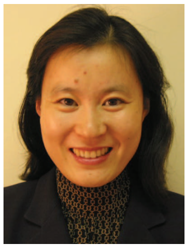
[25] T. Villa, R. Merz, and P. Vidales, "Performance evaluation of ofdma femtocells link-layers in uncontrolled deployments," in *Proc. 2010 European Wireless Conference*.

[26] H. Seo and B. Lee, "PA proportional-fair power allocation scheme for fair and efficient multiuser ofdm systems," in *Proc. 2004 IEEE Global Telecommunications Conference*.

[27] H. Lei, L. Zhang, X. Zhang, and D. Yang, "A novel multi-cell ofdma system structure using fractional frequency reuse," in *Proc. 2007 IEEE Int'l Symposium on Personal, Indoor and Mobile Radio Communications*.

Adem Zaid received the BS degree in electrical and electronic engineering from Tripoli University, Libya, in 2008, and the MS degree in electrical and computer engineering from Oregon State University in 2011, and is currently working toward finishing the master of business administration (MBA) degree at Oregon State University. His current focus is on clean technology commercialization.

Bechir Hamdaoui (S'02-M'05-SM'12) received the Diploma of Graduate Engineer (1997) from the National School of Engineers at Tunis, Tunisia. He also received M.S. degrees in both Electrical and Computer Engineering (2002) and Computer Sciences (2004), and the Ph.D. degree in Computer Engineering (2005) all from the University of Wisconsin at Madison. In September of 2005, he joined the RTCL Lab at the University of Michigan at Ann Arbor as a postdoctoral researcher. Since September of 2007, Dr. Hamdaoui has been a faculty member in the School of EECS at Oregon State University where is presently an associate professor. His research focus is on cross-layer design, distributed optimization, resource & service management, parallel computing, cooperative & cognitive networking, cloud computing, and distributed mobile sensing. He has won the NSF CAREER Award (2009), and is presently an Associate Editor for IEEE Transactions on Vehicular Technology (2009-present), IEEE Transactions on Wireless Communications (2013-present), and Wireless Communications and Computing Journal (2009-present). He also served as an Associate Editor for Journal of Computer Systems, Networks, and Communications (2007-2009). He served as the chair for the 2011 ACM MobiCom's Student Research Competition (SRC), and as the program chair/co-chair of the Pervasive Wireless Networking Workshop (PERCOM 2009), the WiMAX/WiBro Services and QoS Management Symposium (IWCMC 2009), the Broadband Wireless Access Symposium (IWCMC 2010), the Cooperative and Cognitive Networks Workshop (IWCMC 2011 & 2012), the Internet of Things, Machine to Machine, and Smart Services Applications Workshop (CTS 2012), the International Conference on Communications (ICC 2014), and several others. He also served on technical program committees of many IEEE/ACM conferences, including INFOCOM, ICC, GLOBECOM, and PIMRC. He is a senior member of IEEE, IEEE Computer Society, IEEE Communications Society, and IEEE Vehicular Technology Society.



Xiuzhen Cheng received her MS and Ph.D. degrees in computer science from the University of Minnesota - Twin Cities, in 2000 and 2002, respectively. She is a full professor at the Department of Computer Science, The George Washington University, Washington DC. Her current research interests focus on cognitive radio networks, mobile handset networking systems (mobile health and safety), wireless and mobile computing, sensor networking, wireless and mobile security, and algorithm design and analysis. She has served on the editorial boards of several technical journals and the technical program committees of various professional conferences/workshops. She also has chaired several international conferences. She worked as a program director for the US National Science Foundation (NSF) from April to October in 2006 (full time), and from April 2008 to May 2010 (part time). She received the NSF CAREER Award in 2004. She is a senior member of IEEE and a member of ACM.

Taieb Znati received a Ph.D. degree in Computer Science from Michigan State University in 1988, and a M.S. degree in Computer Science from Purdue University, in 1984. He is a Professor in the Department of Computer Science, with a joint appointment in Computer Engineering at the School of Engineering. Dr. Znati served as the Director of the Computer and Network Systems Division at the National Science Foundation. He also served as a Senior Program Director for networking research at the National Science Foundation. In this capacity, Dr. Znati led the Information Technology Research (ITR) Initiative, a cross-directorate research program, and served as the Committee Chair of the NSF Information Technology Research Initiative. Dr. Znati's main research interests are in the design and analysis of evolvable, secure and resilient network architectures and protocols for wired and wireless communication networks, and the design of new fault-tolerant mechanisms for energy-aware resiliency in data-intensive computing. He is also interested in bio-inspired approaches to address complex computing and communications design issues that arise in large-scale heterogeneous wired and wireless networks. Dr. Znati has served as the General Chair of several main conferences, including GlobeCom 2010, IEEE INFOCOM 2005, SECON 2004, the first IEEE conference on Sensor and Ad Hoc Communications and Networks, the Annual Simulation Symposium, and the Communication Networks and Distributed Systems Modeling and Simulation Conference. He also served or currently serves as a member of Editorial Boards of a number of networking, distributed system and security journals and transactions.

Mohsen Guizani (S'85-M'89-SM'99-F'09) is currently a Professor and the Associate Vice President for Graduate Studies at Qatar University, Doha, Qatar. He was the Chair of the Computer Science Department at Western Michigan University from 2002 to 2006 and Chair of the Computer Science Department at University of West Florida from 1999 to 2002. He also served in academic positions at the University of Missouri-Kansas City, University of Colorado-Boulder, Syracuse University and Kuwait University. He received his B.S. (with distinction) and M.S. degrees in Electrical Engineering; M.S. and Ph.D. degrees in Computer Engineering in 1984, 1986, 1987, and 1990, respectively, from Syracuse University, Syracuse, New York. His research interests include Computer Networks, Wireless Communications and Mobile Computing, and Optical Networking. He currently serves on the editorial boards of six technical Journals and the Founder and EIC of *Wireless Communications and Mobile Computing* journal published by John Wiley (http://www.interscience.wiley.com/jpages/1530-8669/). He is the author of eight books and more than 300 publications in refereed journals and conferences. He guest edited a number of special issues in IEEE Journals and Magazines. He also served as member, Chair, and General Chair of a number of conferences. Dr. Guizani served as the Chair of IEEE Communications Society Wireless Technical Committee (WTC) and Chair of TAOS Technical Committee. He was an IEEE Computer Society Distinguished Lecturer from 2003 to 2005. Dr. Guizani is an IEEE Fellow and a Senior member of ACM.