Enhancing Macrocell Downlink Performance Through Femtocell User Cooperation

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Abstract. This paper 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 and without femtocell user cooperation. Using simulations, we show that under reasonable SNR values, cooperative schemes improve both the BER and the data throughput of macrocell users significantly when compared with the traditional, non-cooperative scheme.

1 Introduction

Femtocells are low-power base stations with small communication coverage designed and targeted for home and small business use [2, 12]. 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 at both academic and industry [3, 4, 8]. About 50% of phone calls and about 70% of data communication are projected to be taking place indoors in the next few years [9]. In addition to offering high data-rate services at low power usage, femtocells can potentially reduce the traffic load on traditional macrocellular networks by servicing macrocell users which happen to be under their coverage. Femtocell deployment, however, still presents some major challenges, pertaining mainly to interference and handoff [4, 13].

The interference problem arises primarily because femtocells are often required to share the same spectrum resources among themselves as well as with the macrocell they belong to. Solutions attempting to mitigate interference have been proposed in literature [4–6, 15]. In [15], 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 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, especially when compared with traditional macrocelluar 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 [7, 10, 13, 16]. In [10], 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 [16] propose to rely on the signal to noise plus interference ratio (SINR) instead of the received signal strength at the mobile user. In [13], 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 [7], 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. [16] 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 so 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 1) to femtocell users that, while being handed off from their femtocells to the macrocell, they desire to maintain high data rates, similar to those received while in their femtocells, and 2) to 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 paper, 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 analytically analyze and evaluate the achievable performance in the downlink of Rayleigh fading channels under both the cooperative and the non-cooperative schemes. We provide an approximation of both the bit-error-rate and the data throughput that macrocell users receive with and without femtocell user cooperation. Using simulations, we show that under reasonable SNR values, the cooperative transmission schemes improve both the bit-error rate and the data throughput significantly when compared with the traditional, non-cooperative scheme.

The rest of this paper is organized as follows. Section 2 presents the network architecture. Section 3 derives and presents the performance of the proposed cooperative scheme. Section 4 presents the results. Finally, we conclude the paper in Section 5.

2 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. We want to mention that, in this work, we are not proposing an interference management scheme, and instead, we propose to use the Frequency Fractional Reuse (FFR) approach proposed in [5] to resolve the interference problem. FFR is illustrated well through Fig. 2, where four frequency bands (A, B, C, and D) are reused rotatively

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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

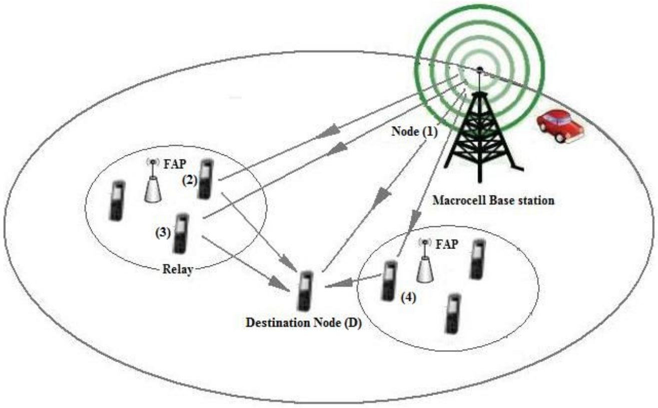

Fig. 1. Two tier network architecture

to reduce interference among the femtocells themselves as well as between the femtocells and the macrocell. Depending on the location of the femtocells vis-a-vis of the MBS, different frequency combinations are used by femtocells and the macrocell to avoid/reduce interference. Readers are referred to [5] for more details on this approach.

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. Recall that femtocell users when communicating with their FAP use a frequency band that is different that used by the macrocell.

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. 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 play the role of relays by first amplifying their received signals, and then retransmitting them right away, one node at a time. Letting each relay send its signal in 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), thus no transmission opportunities are lost. 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 assume that the destination node uses the Maximum Ratio Combining (MRC) technique [11] to combine and recover its original data.

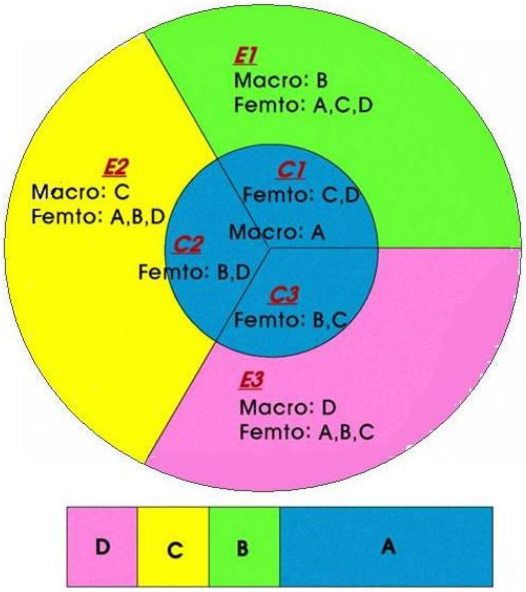

Fig. 2. Interference management using FFR [5]

In this study, we consider Rayleigh fading channels, and assume that destination nodes have full knowledge of the source-destination as well as the relay-destination channels. We also assumed that the modulation technique in use is the binary phase shift keying (BPSK) one.

3 Cooperative Diversity

Letting n denote the number of transmitters (i.e., the number of relays plus the MBS), the BPSK modulated signal received at the destination and at the relay can be represented mathematically as [1]

$$y_{1i}(t) = h_{1i}\sqrt{\frac{E_b}{n}}S_k(t) + W_i(t) \tag{1}$$

where E_b is the bit transmitted energy, $S_k(t) \in \{-1, +1\}$ is the BPSK bit code for $k = 1, 2$, h_{1i} is the fading coefficient magnitude between the MBS and the receiver i for $i = 2, ...n, D$, and $W_i(t)$ represents the Gaussian noise observed at the relay node during the first time slot. Note that in Equation (1), the bit energy is divided by n, and the reason for this is to maintain the same amount of per-bit consumed energy in the non-cooperative as well as in the cooperative scheme (this is so as to have a fair comparison). During the second time slot, one of the relays amplifies its received signal and then forwards it to the destination. During the third time slot, the second relay node amplifies its received signal and then forwards it to the destination, and so does the third relay node during the fourth time slot, and so forth. The received signal at the destination from the i^{th} relay node is given by the following equation.

$$y_{iD}(t+1) = \alpha_i h_{iD}\left(h_{1i}\sqrt{\frac{E_b}{n}}S_1(t) + W_1(t)\right) + W_D(t+1) \tag{2}$$

where $W_D(t+1)$ represents the Gaussian noise observed at the destination node, and α_i represents the amplification factor, which can be written as

$$\alpha_i = \sqrt{\frac{1}{h_{1i}^2 + \frac{N_0}{nE_b}}} \tag{3}$$

where N_0 is the one-sided noise power spectral density of the Gaussian noise observed at the receiver.

At the destination node, all received signals are combined using the MRC technique, and the combined signal is expressed as

$$\begin{aligned} y_{out}(t+n) = {} & \frac{h^*_{1D}\sqrt{E_b/n}}{N_0} y_{1D}(t) \\ & + \textstyle\sum_{i=2}^{n} \frac{\alpha_i^* h_{1i}^* h_{iD}^* \sqrt{Eb/n}}{N_0(\alpha^2|h_{iD}|^2+1)} y_{iD}(t+i) \end{aligned} \tag{4}$$

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

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

where γ_{1D} represents the SNR of the signal coming from the direct path, γ_{1i} represents the SNR of the signal received at relay i, and γ_{iD} represents the SNR of the signal coming from relay i to the destination. Note here that the SNR at the output of the MRC combiner is the sum of all received signals' SNRs. Therefore, the conditional bit error probability of the cooperative scheme can be expressed as

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

where $\gamma_{ij} = \frac{|h_{ij}|^2 E_b}{nN_0}$, $Q(.)$ is the standard Gaussian error function, and N_0 is again the one sided noise power spectral density of the Gaussian noise observed at the receiver.

3.1 BER of Cooperative Scheme

The average BER (bit error rate) of the received signal at the output of the demodulator is given by [14]

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

where $P_b(E/\gamma)$ is the conditional bit error probability represented in Equation (6), 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

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

Since the conditional BER of the cooperative scheme is a function of the total SNR (the sum of all branches' SNRs), Equation (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.

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

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

where $\bar{\gamma}_{1i}$ and $\bar{\gamma}_{iD}$ represent the average received SNRs at relay 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. Equation (10) can be approximated as [1]

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

and the pdf of the one-hop path is

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

By substituting Equations (11) and (12) into Equation (9), the BER becomes

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

where

$$\bar{\gamma}_{1iD} = \frac{\bar{\gamma}_{1i}\bar{\gamma}_{iD}}{\bar{\gamma}_{1i} + \bar{\gamma}_{iD}} \tag{14}$$

3.2 BER of Non-Cooperative Scheme

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 Equation (12), which after being substituted in Equation (7), it gives a BER that is equal to

$$P_b(E) = \frac{1}{2}\sqrt{\frac{n\bar{\gamma}_{1D}}{n\bar{\gamma}_{1D} + 1}} \tag{15}$$

4 Performance Evaluation

In this section, we use Matlab to simulate and evaluate the performance of both the cooperative and the non-cooperative schemes. The performance is evaluated in terms of achievable BER and data throughput. 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. In this simulation study, we assume that all source-to-relay channels experience similar conditions, meaning that $\bar{\gamma}_{1D} = \bar{\gamma}_{12} = ... = \bar{\gamma}_{1n}$, and that all relay-to-destination 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. For a fair comparison, we use the same amount of energy per transmitted bit for both schemes.

4.1 BER Analysis

Fig. 3 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., the number of relays $(n-1)$ 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 medium-to-high average received SNR values, the greater the number of relays, the lower

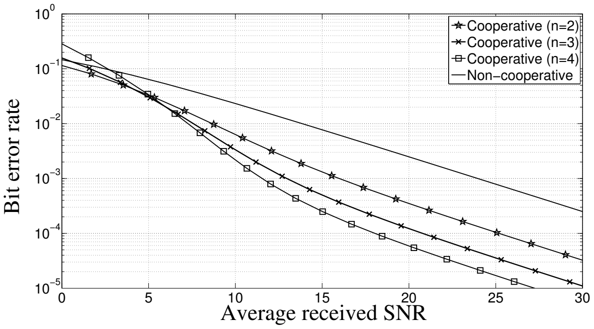

Fig. 3. BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=10dBs for different values of the number of relays.

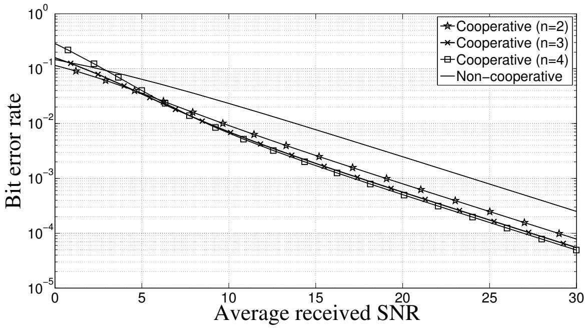

Fig. 4. BER of the non-cooperative and cooperative schemes when relay-to-destination SNR=5dBs for different values of the number of relays.

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 $n = 3$. At low values of received SNR (less than 3.5dB), however, the BER of the cooperative scheme can be worse than the non-cooperative one. Hence, we conclude that cooperation is beneficial only when the received SNR value is medium-to-high. For completeness, we present in Fig. 4 these same results but when the relay-to-destination SNR value is 5dBs. We observe similar performance behaviors also when the relay-to-destination SNR is reduced to 5dBs. The gap in BER between that of the cooperative and that of the non-cooperative is smaller though.

4.2 Throughput Analysis

In this section, we 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.

Figs. 5 and 6 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 5dBs. 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, 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 90% (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 5dBs as shown in Fig. 6), the throughput gain is slightly less substantial.

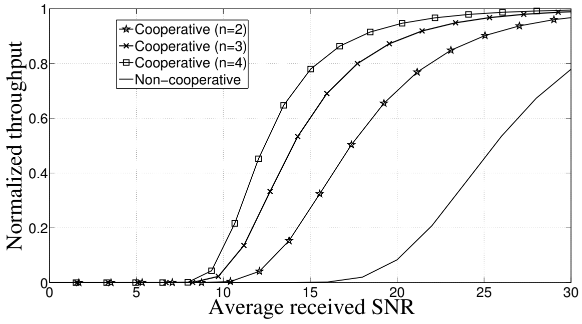

Fig. 5. Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=10dBs

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

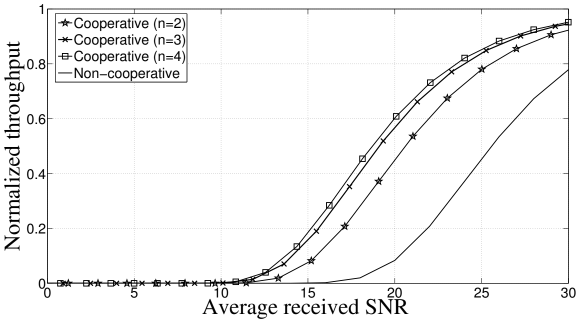

Fig. 6. Throughput of the non-cooperative and the cooperative schemes when relay-to-destination channel SNR=5dBs

5 Conclusion

This paper studies the cooperative transmission technique when applied in the context of femtocells. We show that femtocell cooperation in the downlink communication can substantially improve the data throughput achievable by macrocell users. Using simulations, we show that under reasonable SNR values, the cooperative schemes improve both the bit-error rate and the data throughput significantly when compared with the traditional, non-cooperative scheme.

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