Relay-Assisted Cooperative Schemes for the UL OFDMA Based Systems

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Abstract — **In this paper we propose and assess the performance of virtual MIMO or relay-assisted cooperative schemes designed for the UL-OFDMA based systems. We consider the use of an antenna array at the base station and a single antenna at the mobile terminals and relay. The proposed cooperative schemes emulate a MIMO channel with 2 transmit antennas. Two types of relays are considered: amplify-and-forward and selective decode-and-forward. The bit error rate is compared with non cooperative systems, considering different scenarios. The proposed relay-assisted schemes are suited for existing and future broadband wireless systems to increase the system capacity and coverage.**

***Index Terms* — OFDMA, virtual MIMO, relay, uplink, cooperative schemes.**

I. INTRODUCTION

Wireless systems are one of the key components for enabling the information society. Thus, it is expected that the demand for wireless services will continue to increase in the near and medium term, calling for more capacity and created the need for cost effective transmission techniques that can exploit scarce spectral resources efficiently. It is anticipated that the broadband mobile component of beyond 3G systems must be able to offer bit rates in excess of 100Mbps in indoor and picocell environments. To achieve such high bit rates, so as to meet the quality of service requirements of future multimedia applications, orthogonal frequency division multiple access (OFDMA) has being adopted in different flavors of broadband wireless systems [1][2].

It is commonly agreed that the provision of the broadband wireless component will probably rely on the use of multiple antennas at transmitter/receiver side. Multiple input and multiple output (MIMO) is a very promising technique to mitigate the channel fading and thus improving the cellular system capacity. By configuring multiple antennas at both the base station (BS) and mobile terminal (MT), the channel capacity may be improved proportionally to the minimum number of the antennas at the transmitter and receiver [3].

However, using an antenna array at the MTs may not be feasible due to size, cost and hardware limitations. Moreover, if the MTs are equipped with multiple antennas, the spatial separation between antennas must be great enough to guarantee the statistical independence of faded signals for optimal performance. These devices are usually small and light and thus this spatial separation requirement is difficult to satisfy. Cooperative communications is a promising solution for wireless systems to overcome the above limitations [4]. It allows single antenna devices to gain some benefits of spatial diversity without the need for physical antenna arrays.

Explicit cooperation of neighboring nodes was considered in [7]. In such transmission scenarios, two or more sources (genuine sources or relays) transmit the same information to a destination, generating a virtual antenna array.

In [8][9], the use of orthogonal space-time block coding in a distributed fashion for implementation of user cooperation has been proposed. Several authors have also addressed the search and design of practical distributed space-time codes for cooperative communications [10]. A cooperative scheme for the UL OFDMA has been proposed in [11]. In this scheme each user transmits his partner's and his own data on different subcarriers.

In this paper we evaluate the performance of virtual MIMO or relay-assisted cooperative schemes designed for the UL OFDMA based systems. In our scheme there is no explicit cooperation between the different users. The proposed cooperative schemes emulate a MIMO channel with 2 transmit and M receive antennas. Two types of relays are considered: amplify-and-forward (AF) and selective decode-and-forward (SDF). Bit error rate (BER) simulation results are compared against the non-cooperative SISO and SIMO systems, considering different scenarios. We show by simulations that the proposed cooperative schemes increase the system capacity and coverage, mainly in dense urban environments where a high path loss (PL) does exist.

The remaining paper is organized as follows: In section II we present a general description of the proposed OFDMA relay-assisted system. In section III, we derive and analyze the link equations for the proposed relay-assisted schemes. In section IV, we assess the performance, in terms of outage capacities and BER, in different scenarios. Finally the main conclusions are pointed out in section V.

II. SYSTEM MODEL

Fig. 1 depicts the proposed uplink OFDMA system, which consists of K MTs, a relay and a BS. In OFDMA, we can pre allocate or dynamically assign the subcarriers to different users. We assume, for simplicity, a static allocation scheme in which the total available subcarriers, N_c, are equally

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distributed among the K users so that each of them occupies N_c / K subcarriers. All the MTs and the relay are equipped with single antenna whereas the BS uses an antenna array.

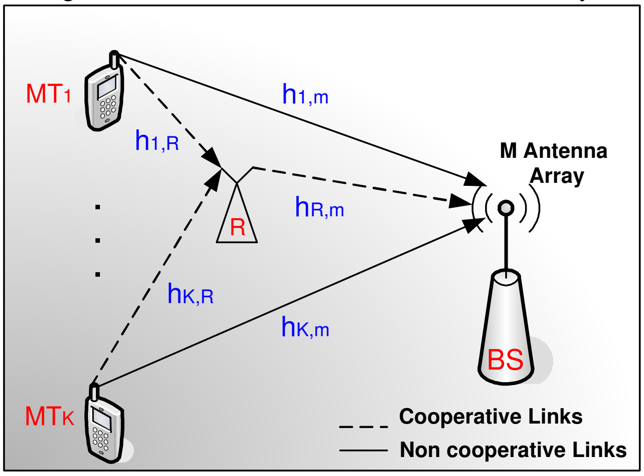

Fig. 1. Virtual MIMO Scheme for OFDMA based systems.

In the first phase all users broadcast their own information, $d_1 \ldots d_k$, to the relay and BS. The relay is idle during this time. In the second phase the MTs do not transmit data, and the relay transmits the received information to the BS.

III. RELAY-ASSISTED COOPERATIVE SYSTEMS

We analyze both non-cooperative systems and two half-duplex virtual MIMO schemes: amplify-and-forward and selective decode-and-forward based relays.

A. Non-Cooperative MISO system

The classical system is included to act as a reference for comparison of the advantages and disadvantages offered by the relay-assisted schemes. Without loss of generality, we focus our analysis on a generic user *k*. We also assume that the number of subcarriers is equal to the number of active users, i.e., $N_c = K$.

Thus, the received signal at the BS, at instant *n+Ts* and antenna *m* is given by

$$y_{BS,k,m}(n+T_s) = d_k h_{k,m} + n_m(n+T_s) \tag{1}$$

where d_k is the data symbol of the k^{th} user, with unit power, $h_{k,m}$ represents the complex flat Rayleigh fading non-cooperative channel of the k^{th} user and of the m^{th} antenna, and $n_m(n+T_s)$ are the zero mean complex additive white Gaussian noise (AWGN) samples on antenna *m* at instant $n+T_s$. In these classical systems, the signals received on each antenna are combined using maximum ratio combining (MRC). Thus, the soft decision variable of the k^{th} user is

$$\hat{d}_k = \underbrace{d_k \sum_{m=1}^{M} \left|h_{k,m}\right|^2}_{Desired\ Signal} + \underbrace{\sum_{m=1}^{M} h^*_{k,m} n_m (n+T_s)}_{\text{BS } noise} \tag{2}$$

B. Amplify and Forward

In this scheme, during the first phase the MTs transmit at full power for $T_s / 2$ of the time. During the second phase the relay can also transmit at full power for $T_s / 2$ to make up the full time slot. Thus, the received signal at the BS, at instant $n+T_s/2$ and antenna *m* is expressed by

$$y_{BS,k,m}(n+T_s/2) = d_k h_{k,m} + n_m(n+T_s/2) \tag{3}$$

The received signal at the BS at instant *n+Ts* is given by

$$\begin{aligned} y_{BS,k,m}(n+T_s) = \alpha_k \left(d_k h_{k,R} + n_R(n+T_s/2)\right) h_{R,m} \\ + n_m(n+T_s) \end{aligned} \tag{4}$$

where $n_R(n+T_s/2)$ are the AWGN samples on relay, $h_{R,m}$ and $h_{k,R}$ represent the complex flat Rayleigh fading cooperative channels from the relay to the BS and from user *k* to the relay, respectively. The constant α_k is used to constrain the transmit relay power to one and thus is given by

$$\alpha_k = \frac{1}{\sqrt{\left|h_{k,R}\right|^2 + N_R}} \tag{5}$$

where N_R is the noise power at the relay.

Considering that $\bar{h}_{k,R,m} = \alpha_k h_{k,R} h_{R,m}$, we can write

$$\begin{aligned} y_{BS,k,m}(n+T_s) = d_k \bar{h}_{k,R,m} + \alpha_k h_{R,m} n_R(n+T_s/2) \\ + n_m(n+T_s) \end{aligned} \tag{6}$$

At the BS, the received signals at instants $n+T_s/2$ and $n+T_s$ on each antenna are combined by using the MRC and then the combined signals at each instant are added. Thus, the soft decision variable of the k^{th} user may be expressed as

$$\begin{aligned} \hat{d}_k = & \underbrace{d_k \sum_{m=1}^{M} \left(\left|h_{k,m}\right|^2 + \frac{\left|\bar{h}_{k,R,m}\right|^2}{\beta_1 + \alpha_k^2 \left|h_{R,m}\right|^2 \beta_2} \right)}_{Desired\ Signal} \\ & + \underbrace{\sum_{m=1}^{M} \frac{h_{R,m}\, \bar{h}^*_{k,R,m}}{\beta_1 + \alpha_k^2 \left|h_{R,m}\right|^2 \beta_2} n_R\left(n + \frac{T_s}{2}\right)}_{Relay\ noise} \\ & + \underbrace{\sum_{m=1}^{M} \left(h^*_{k,m} n_m \left(n + \frac{T_s}{2}\right) + \frac{\bar{h}^*_{k,R,m}}{\beta_1 + \alpha_k^2 \left|h_{R,m}\right|^2 \beta_2} n_m(n+T_s) \right)}_{BS\ noise} \end{aligned} \tag{7}$$

where $(.)^*$ denotes complex conjugation. We can observe that this scheme emulates a MIMO channel with 2 transmit and *M* receive antennas. The variance of the additive noise at the BS for the signals that cross the MTs-BS channel is denoted by σ^2. The noise variance of the signals that cross the relay-BS and MTs-relay channels are related to σ^2 by $\sigma_1{}^2 = \sigma^2\beta_1$ and $\sigma_2{}^2 = \sigma^2\beta_2$, respectively.

C. Selective Decode and Forward

It has been shown that fixed DF transmission does not offer diversity gains for large SNR, because requiring the relay to fully decode the information transmitted by MTs limits the performance of this scheme to that of non-cooperative systems [9]. A selective DF scheme can be used to overcome the fixed DF shortcomings.

In this scheme, during the first phase the MTs transmit at full power for $T_s / 2$ of the time. The received signal at the BS, at *n+Ts/2* and antenna *m* is also given by (3). During the second phase, the relay first demodulates and decodes the received signals. Upon success, it re-encodes the data and forwards to the BS. Thus, the received signal on antenna *m* at instant *n+Ts* can be written by

$$y_{BS,k,m}\left(n+T_s\right) = d_k h_{R,m} + n_m(n+T_s) \tag{8}$$

At the BS, the received signals are combined using the MRC criterion. The k^{th} user's resulting soft decision variable is found to be

$$\hat{d}_k = \underbrace{d_k \sum_{m=1}^{M}\left(\left|h_{k,m}\right|^2 + \left|h_{R,m}\right|^2/\beta_1\right)}_{Desired\ Signal} + \underbrace{\sum_{m=1}^{M}\left(h_{k,m}^* n_m(n+T_s/2) + \frac{h_{R,m}^*}{\beta_1} n_m(n+T_s)\right)}_{BS\ Noise} \tag{9}$$

As can be seen from (9), in the case of successful decoding at the relay, this scheme yields a diversity gain of *2.M* under perfect conditions with respect to a non-diversity scheme and a gain of 2 with respect to a non-cooperative SIMO system, i.e., a cellular system with a single antenna at the MTs and a BS equipped with *M* antennas, where the signals of each antenna are combined using the MRC.

In the outage case where the relay fails to decode the data correctly, it cannot help the MTs for the current cooperation round. Thus the BS only uses the signal received directly from the MTs and the soft decision variable is given by (2).

IV. NUMERICAL RESULTS

The performance of the proposed cooperative schemes is assessed through BER. The main simulation parameters are set according to the signal definitions for WiMAX, and we used CTC coding in all simulations [12]. It was further assumed that the receivers (BS and relay) had perfect knowledge of the channels, which were uncorrelated and had a profile according to the specifications for CLB1 channels [12]. The overall transmitter power of each user is normalized to one in all presented schemes.

We compare the proposed cooperative schemes against the non-cooperative systems, considering different AWGN noise variance values at the input of the relay and BS antennas.

We refer to the cooperative relay-assisted schemes as VMISO AF or SDF when all devices are equipped with a single antenna. For the case when the BS is equipped with an antenna array with two elements, and both the MT and relay have a single antenna, we refer to the same schemes as VMIMO AF or SDF. We assume that the distance between antenna elements is far apart to assume *M* independent channels, i.e, we assume independent fading processes.

Fig. 2 shows the performance results of the non and cooperative schemes in terms of the average bit error rate as function of E_b/N_o, where E_b is the transmitted energy per bit and No/2 the bilateral power spectral density of the noise.

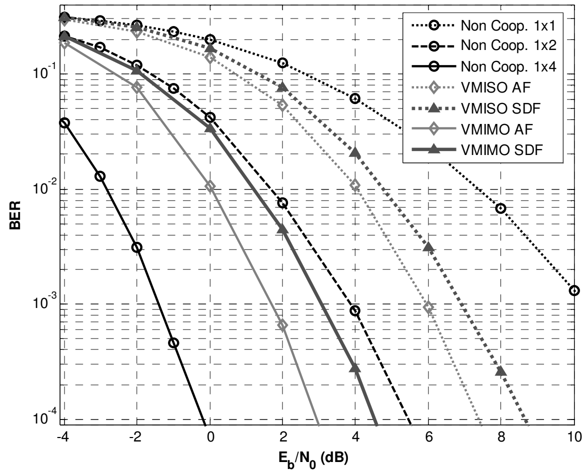

Fig. 2. Performance comparison of non and cooperative schemes: when all channels have the same quality.

These results were obtained considering that all paths have similar quality. From this figure we can see that, for the particular case where all the devices are equipped with a single antenna, the two proposed cooperative schemes, VMISO AF and SDF outperform the non-cooperative 1x1 SISO system. When the BS is equipped with two antennas, both VMIMO schemes outperform the non-cooperative 1x2 SIMO system. However, the performance improvement of cooperative schemes against non-cooperative is lower than in single antenna case. Also, we notice that the AF cooperative scheme outperforms the AF cooperative scheme. Such result is explained by the fact that SDF only re-transmits to the BS the information that was successfully detected at the relay, ie, the performance of the SDF scheme is limited by the MTs - relay channels. Indeed, if these channels are often in outage, the relay will be idle for most of the time and will not to increase the overall system performance. In opposition to the SDF scheme, AF always contributes to the signal estimation at the BS. Figure 2 shows, for a BER target of 1.0e-3, a gain of about 5 dB and 2dB of VMISO and VMIMO AF against non-cooperative 1x1 SISO and 1x2 SIMO, respectively.

In Fig. 3 we show the performance of the same schemes presented in Fig. 2 with the difference that the channels between MTs and relay are 10dB better that the other channels. From this figure we can observe that the performance of the all cooperative schemes is improved in comparison with the previous scenario. The performance of the VMISO and VMIMO schemes is very close the ones obtained by the non-cooperative 1x2 SIMO and 1x4 SIMO, respectively. When the channels between MTs and relay are good the probability of outage decreases and almost all the information are successfully decoded at the relay.

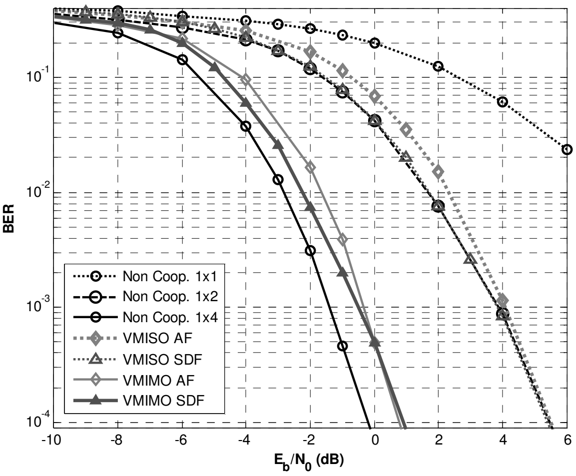

Fig. 3. Performance comparison of non and cooperative schemes: when the MTs-relay channels are 10 dB better that the other channels.

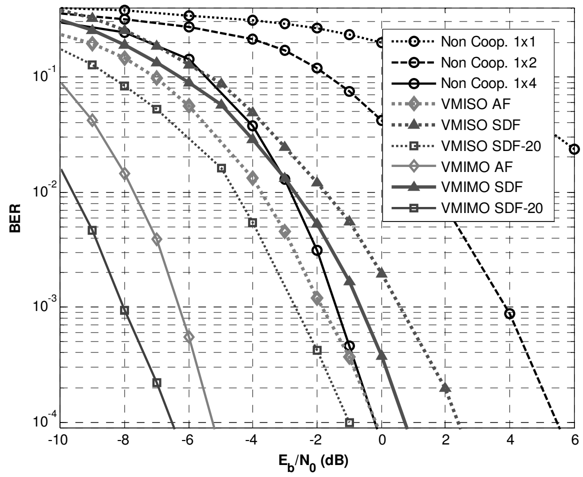

Fig. 4. Performance comparison of non and cooperative schemes: when the MTs-relay and relay-BS channels are 10 dB better than the ones between the MTs-BS ones.

Fig. 4 shows the performance of the same schemes but now considering that the Eb/No at the channels between MTs-relay and relay-BS is 10 dB superior to the MTs-BS ones. This scenario evidences the performance improvement of cooperative based schemes. For the VMISO AF and VMIMO AF and a BER target of 1.0e-3, we obtained a gain of approximately 10 dB and 4 dB against non-cooperative 1x2 SIMO. Moreover, for low values of Eb/No, all VMIMO schemes outperform the non-cooperative 1x4 SIMO system. This means that when the direct link is in outage the use of cooperative based schemes dramatically increases the systems performance. Within Fig. 4, we also include two curves for SDF for the case when the MTs-relay channels are 20dB superior to the MTs-BS ones (VMISO SDF-20 and VMIMO SDF-20). These results evidence the fact that SDF has the potential to outperform AF, but only if the MTk-relay channels allow for correct decoding at the relay.

V. CONCLUSION

We proposed and evaluated virtual MIMO schemes designed for the UL OFDMA based systems. Two types of relays were analyzed: amplify and forward and selective decode and forward. BER results were compared against the non-cooperative systems, considering different scenarios.

The results have shown that the performance of the proposed cooperative schemes dramatically increases as compared with the non-cooperative SISO and SIMO systems. Furthermore, the results have shown that AF based relays outperform the SDF based one if the quality of the MTs-Relay channels is not high in comparison with the remaining ones. It is clear from the presented results that the proposed cooperative schemes, mainly the AF scheme, allow a significant improvement in user capacity and coverage in comparison to non-cooperative systems, above all in dense urban scenarios where a severe path loss does exist.

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