Single and Multiple Antenna Relay-Assisted Techniques for Uplink and Downlink OFDM Systems

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***Abstract*— In this paper we propose and assess the performance of relay-assisted schemes designed for both the uplink and downlink OFDM based systems, using efficient distributed space-frequency block coding protocols. We consider the use of an antenna array at the base station and a single antenna at the user terminal. At the relay node we consider either single antenna or an antenna array. We assume that some of the user terminals deployed in a certain area could act as relaying-able terminals for the communication of other users. Two types of relay-assisted protocols are considered: equalize-and-forward and decode-and-forward. The optimal maximum ratio combining coefficients are derived for the proposed relay-assisted schemes. The performance of these cooperative schemes is evaluated under realistic scenarios, considering typical pedestrian scenarios based on WiMAX specifications and using channel convolutional turbo code. The proposed schemes are also compared against the non-cooperative OFDM based systems. Numerical results show that the availability of antenna arrays at the relays significantly improves the cooperative systems performance, which outperform the non-cooperative ones in most studied scenarios.**

Keywords - OFDM, relay, multiple antennas, cooperation, downlink and uplink.

I. INTRODUCTION

Wireless systems are one of the key components for enabling the information society. To meet the service requirements of future multimedia applications, Orthogonal Frequency Division Multiplexing (OFDM) is being adopted in various kinds of broadband wireless systems [2][3].

Cooperative communications is one of the fastest growing areas of research, and it is likely to be a key enabling technology for efficient spectrum use in the years to come. The key idea in user-cooperation is that of resource sharing among multiple nodes in a network [4][5]. It is commonly agreed that the provision of the broadband wireless component of the future wireless systems will probably rely on the use of multiple antennas at transmitter/receiver side. Multiple-input, multiple-output (MIMO) wireless communications are effective at mitigating the channel fading and thus improving the cellular system capacity. By configuring multiple antennas at both the base station (BS) and user terminal (UT), the channel capacity may be improved proportionally to the minimum number of the antennas at the transmitter and receiver [6]. However, considering a conventional cellular architecture with co-located antennas there is significant correlation between channels in some environments.

Cooperative diversity is a promising solution for wireless systems to increase capacity, extend coverage and provide fairness, namely for the scenarios where the direct link is in outage and the inter-user channel has good quality [4]. It can be achieved through cooperation of users, which share their antennas and thereby create a virtual antenna array (VAA) system. It is well known that the wireless channel is quite bursty, i.e., when a channel is in a severe fading state, it is likely to stay in the sate for a while. Thus, when a source cannot reach its destination due to severe fading, it will not be of much help trying by leveraging repeating-transmission protocols. However, if a third terminal that receives the data from the source could help via a channel that is independent from source to destination link, the chance for a successful transmission would increase, thus improving the overall system performance [7].

Research on cooperative diversity can be traced back to the pioneering papers of van der Meulen [8] and Cover [9] on the information theoretic properties of the relay channel. Explicit cooperation of neighbouring nodes was considered in [10][11]. Considering various degrees of knowledge of channel state information (CSI), they show that significant gains can be achieved over non-cooperative direct transmission. In [12] the authors have resorted, to solve the half duplex constraint, to a two-stage protocol and have shown in several papers that the use of cooperation provides a spatial diversity gain.

The concept of VAA or virtual MIMO has been introduced in [13], derived from the principles of relaying channel. Recently, the use of space-time block coding (STBC) implemented in a distributed fashion providing user cooperation has been proposed [14][15][16]. However, despite the extensive literature on cooperative relaying diversity, most of the work only considers single antenna relays. Studies and practical schemes with relays equipped with an antenna array are relatively scarce. Furthermore, most of the proposed schemes are not targeting OFDM based systems and/or have been assessed under unrealistic scenarios.

In [17] a theoretical diversity-multiplexing trade-off study is presented for a cooperative system with 1 and 2 antennas in a single relay scheme. In [18], a multiple antenna half-duplex relay–assisted maximum ratio combining (MRC) transmission scheme, that uses the decode-and-forward protocol has been proposed to increase coverage. However, this scheme requires the knowledge of the instantaneous CSI prior to the transmission at the relays. Furthermore, in [19] the Rayleigh performance of a single-relay cooperative scenario with multiple-antenna nodes has been investigated, and pairwise error probability expressions were derived. Recently, a robust MIMO relay for multipoint-to-multipoint communication in wireless networks, and based on amplify and forward (AF) protocol, has been proposed [20].

In this paper we provide a detailed description of the work that we have started and presented at [1], on single/multiple antenna relay-assisted cooperative schemes designed for the uplink (UL) OFDM systems, and at [21], on single antenna relay-assisted cooperative schemes designed for the downlink (DL) OFDM systems. Moreover, we extend the latter scheme from single antenna relay to multiple antenna relay. We consider that some of the user terminals deployed in a certain area could act as relaying-able terminals for the communications of other users. We also assume that these terminals are available idle users connected to the network. The considered relay-assisted (RA) protocols are: equalize-and-forward (EF) and decode-and-forward (DF). Their performance is evaluated under realistic scenarios, considering typical pedestrian scenarios based on WiMAX specifications and channel turbo coding. These schemes are also compared against either SIMO or MISO OFDM non-cooperative uplink or downlink systems, respectively. Simulations reveal that the proposed cooperative schemes outperform the non-cooperative ones in most of the studied scenarios and that the availability of two-antenna arrays at the relay nodes dramatically increases the cooperative systems performance. Cooperating is especially advantageous when the source-to-relay link is better than the source-to-destination link, so that the relay receives data correctly and can have a considerable impact on the final performance.

The remaining paper is organized as follows: in section II we present a general description of the proposed multiple antenna relay-assisted for uplink and downlink systems. In sections III and IV, we derive and analyze the link equations for those relay-assisted schemes for uplink and downlink, respectively. The optimal relay-assisted MRC coefficients are derived. In section V, we assess the performance, in terms of BER, in several communication scenarios. The first part is devoted to discuss the uplink results while second one is for downlink. Finally, the main conclusions are pointed out in section VI.

II. SYSTEM MODEL

Figs. 1 and 2 depict the proposed multiple antenna relay-assisted scheme for both the uplink and downlink OFDM based systems, which consist of a user terminal equipped with a single antenna, a base station equipped with an antenna array and a relay node which can have either one or two antennas.

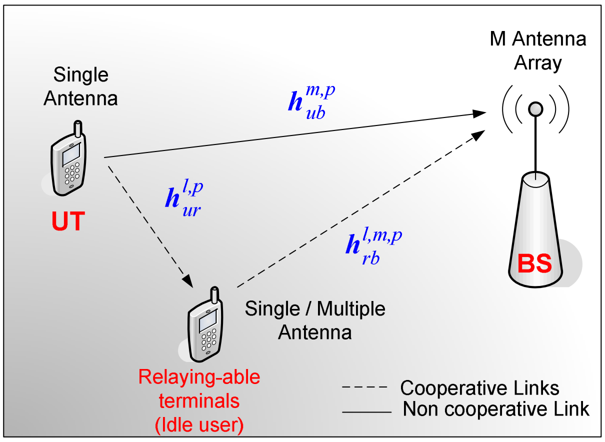

Figure 1. Single/double antenna relay-assisted system model for uplink.

Fig. 1 shows the system model for the uplink. We consider that N_c subcarriers are assigned to the UT. From this scenario, three main links can be identified: the direct UT-to-BS link, represented by $h_{ub}^{m,p}$, $m=1,2$ channels; the UT-to-RN link, formed by channels $h_{ur}^{l,p}$, $l=1,2$; and the RN-to-BS link, represented by channels $h_{rb}^{l,m,p}$, $l=1,2,$ $m=1,2$, where index p denotes the p^{th} subcarrier. If the RN has a single antenna, then L=1 and the UT-to-RN and RN-to-BS links are represented by channels h_{ur}^{p} and $h_{rb}^{m,p}$ $,m=1,2$, respectively.

Fig. 2 is analogous to Fig. 1, but for the downlink. Since the BS is equipped with 2 transmit antennas (M=2), the non-cooperative link is a 2×1 MISO channel. It is represented by the $h_{bu}^{m,p}$ $,m=1,2$ channels. The cooperative links, BS-to-RN and RN-to-UT, are represented by $h_{br}^{m,l,p}$, $l=1,2,$ $m=1,2$ and $h_{ru}^{l,p}$, $l=1,2$, respectively.

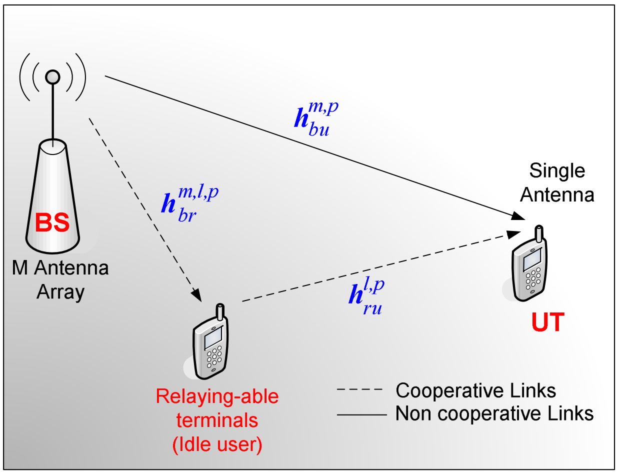

Figure 2. Single/double antenna relay-assisted system model for downlink.

If the RN has a single antenna, the BS-to-RN and RN-to-UT links are represented by channels $h_{br}^{m,p}$ $, m = 1,2$, and h_{ru}^{p} , respectively. Since we assume the relay is half-duplex, the communication cycle for both aforementioned cooperative schemes requires two phases:

- In the first one, the source, UT or BS depending on whether UL or DL systems are considered, broadcasts its own data at full power to its destination (BS or UT), and also to the relay node, which does not transmit data during this stage. For the downlink systems, the data are space-frequency encoded before transmission.
- During the second phase, the relay node can help the source by forwarding the information, also at full power, to the destination node (BS or UT), whereas the source is idle. If the RN is equipped with a 2-antenna array, the data to be transmitted to the BS or UT must also be space-frequency encoded.

The mapping scheme with two transmit antennas used in this work is shown in Table I [23] , where s_p is either the soft or hard decoded data estimated at the relay node on the p^{th} subcarrier for equalize-and-forward or decode-and-forward, respectively. Factor $1/\sqrt{2}$ is included in order to constrain the transmitted energy to one and $(.)^*$ denotes complex conjugation.

TABLE I: SFBC MAPPING SCHEME.

	Antenna 1	**Antenna 2**
Subcarrier *p*	$s_p/\sqrt{2}$	$-s_{p+1}^*/\sqrt{2}$
Subcarrier *p+1*	$s_{p+1}/\sqrt{2}$	$s_p^*/\sqrt{2}$

III. UPLINK RELAY-ASSISTED SCHEMES

We analyze two half-duplex multiple antenna relay-assisted schemes: equalize-and-forward and decode-and-forward. Throughout this paper, we shall refer to these schemes as 1×*L*×*M* RA EF and 1×*L*×*M* RA DF, depending on the number of antennas at the relay node (*L*) and BS (*M*).

Without loss of generality, hereinafter the mathematical formulation refers to a generic subcarrier p .

A. Relay-Assisted Equalize-and-Forward

In this work we consider that the RN node is either equipped with a single antenna or a 2-antenna array. For the first case, the amplify-and-forward protocol studied in [22] is equivalent to the RA EF protocol proposed here. However, if the signal at the relay is collected by two antennas, doing just a simple amplify-and-forward it is not the best strategy. We need to perform some kind of equalization to combine the received signals before re-transmission.

According to the communication cycle adopted in this paper, the received signal during the first communication phase at the BS antenna m , is found to be

$$y_{BS}^{m,p}(t) = d_p h_{ub}^{m,p} + n_{BS}^{m,p}(t), \tag{1}$$

where d_p is the data symbol for the p^{th} subcarrier, with unit power and $h_{ub}^{m,p}$ represents the complex flat Rayleigh fading non-cooperative channel of the p^{th} subcarrier on antenna m . Samples $n_{BS}^{m,p}(t)$ are complex additive white Gaussian noise (AWGN) on antenna *m* with zero mean and variance σ_{d1}^2 .

The received signal at the RN, at instant t and antenna *l*, is

$$y_{RN}^{l,p}(t) = d_p h_{ur}^{l,p} + n_R^{l,p}(t), \tag{2}$$

where $n_R^{l,p}$ are AWGN samples added at the RN with zero mean and variance σ_r^2 . The received signals at the relay antennas at instant t are combined using MRC. The resulting soft decision variable, s_p , is expressed as

$$s_p = \underbrace{\alpha_p d_p \Gamma_{ur}^p}_{\text{Desired Signal}} + \underbrace{\alpha_p \sum_{l=1}^{L} h_{ur}^{l,p*} n_R^{l,p}(t)}_{\text{Relay Noise}}, \tag{3}$$

with $\Gamma_{ur}^p = \sum_{l=1}^{L} \left| h_{ur}^{l,p} \right|^2$ and α_p is a constant whose purpose is to constrain the transmitted power by the RN to one, given by

$$\alpha_p = \frac{1}{\sqrt{{\Gamma_{ur}^{p}}^2 + \sigma_r^2 \Gamma_{ur}^p}}. \tag{4}$$

The following actions that occur at the RA EF relay differ, depending on its number of receiving antennas (*L*).

1) Single Antenna Relay

In the single antenna scenario (*L*=1), the $1 \times 1 \times M$ RA EF can conclude its action by re-transmitting the signal in (3) to the BS. Therefore, the received signals at BS antenna m and instant $t + T_s$, are expressed as

$$y_{BS}^{m,p}(t + T_s) = h_{rb}^{m,p} s_p + n_{BS}^{m,p}(t + T_s), \tag{5}$$

where $h_{rb}^{m,p}$ represents the complex flat Rayleigh fading channel between the RN and antenna m of the BS;

$n_{BS}^{m,p}(t+T_s)$ is AWGN added at $t+T_s$ on antenna m for the p^{th} subcarrier, with zero mean and variance σ_{d2}^2; and, T_s is a symbol transmission duration.

The total noise power of (5), conditioned to a specific channel realization, is related to σ_{d1}^2 by

$$\sigma_{y,p}^2 = \sigma_{d1}^2 \underbrace{(\beta_1 + \alpha_p^2 \Gamma_{ur}^p \left|h_{rb}^{m,p}\right|^2 \beta_2)}_{\beta_{m,p}}. \quad (6)$$

Coefficient β_1 is used to relate the variance of the noise that is added at the BS at instants t and $t+T_s$, $\sigma_{d2}^2 = \beta_1 \sigma_{d1}^2$. In the same manner, β_2 relates the noise that is added at the relay with the one added at BS at instant $t+T_s$, i.e., $\sigma_r^2 = \beta_2 \sigma_{d1}^2$.

At the BS side, MRC is used to combine the received signals from the direct and 2-hop links. Note that MRC is the optimal technique to maximize the overall signal-to-noise ratio (SNR). Since the noise variance of the received signals at the BS at instants t and $t+T_s$ is different, the coefficients that maximize the overall SNR are given by

$$g^{m,p}(\mathrm{t}+kT_s) = \begin{cases} \dfrac{h_{ub}^{m,p*}}{\sigma_{d1}^2}, & k=0 \\ \dfrac{\alpha_p \Gamma_{ur}^p}{\sigma_{d1}^2 \beta_{m,p}} h_{rb}^{m,p*}, & k=1 \end{cases}. \quad (7)$$

The resulting soft decision variable, at the output of the MRC detector, may be expressed as

$$\begin{aligned} \hat{d}_p = {} & \underbrace{\frac{d_p}{\sigma_{d1}^2}\left(\Gamma_{ub}^p + \alpha_p^2 {\Gamma_{ur}^p}^2 \sum_{m=1}^{M} \frac{\Gamma_{rb}^{m,p}}{\beta_{m,p}}\right)}_{Desired\ Signal} \\ & + \underbrace{\frac{1}{\sigma_{d1}^2} \alpha_p^2 \sum_{m=1}^{M} \frac{{\Gamma_{rb}^{m,p}}^2}{\beta_{m,p}} h_{ur}^{p*} n_R^p(t)}_{Relay\ Noise} \\ & + \underbrace{\frac{1}{\sigma_{d1}^2} \sum_{m=1}^{M} \left(h_{ub}^{m,p*} n_{BS}^{m,p}(t) + \frac{\alpha_p \Gamma_{ur}^p}{\beta_{m,p}} n_{BS}^{m,p}(t+T_s) \right)}_{BS\ Noise} \end{aligned}, \quad (8)$$

where $\Gamma_{ub}^p = \sum_{m=1}^{M} \left|h_{ub}^{m,p}\right|^2$.

2) *Two Antenna Relay*

In this case before transmission, the RN encodes the soft data estimates represented by (3) with the SFBC encoding algorithm according to the scheme presented in Table I. The received signals at BS antenna m, at instant $t+T_s$, on subcarriers p and $p+1$, are given by

$$\begin{cases} y_{BS}^{m,p}(t+T_s) = \dfrac{1}{\sqrt{2}}\left(h_{rb}^{1,m,p} s_p - h_{rb}^{2,m,p} s_{p+1}^*\right) + n_{BS}^{m,p}(t+T_s) \\ y_{BS}^{m,p+1}(t+T_s) = \dfrac{1}{\sqrt{2}}\left(h_{rb}^{2,m,p+1} s_p^* + h_{rb}^{1,m,p+1} s_{p+1}\right) + n_{BS}^{m,p+1}(t+T_s) \end{cases} \quad (9)$$

where $h_{rb}^{l,m,p}$ represents the complex flat Rayleigh fading channel for the p^{th} subcarrier, between relay antenna l and BS antenna m. The OFDM systems are usually designed so that the subcarrier separation is significantly lower than the coherence bandwidth of the channel. Therefore, the fading in two adjacent subcarriers can be considered flat, i.e., we can consider $h_{rb}^{l,m,p}$ equal to $h_{rb}^{l,m,p+1}$. With this assumption, and defining $\Gamma_{rb}^{m,p}$ as $\sum_{l=1}^{L}\left|h_{rb}^{l,m,p}\right|^2$, the total noise power of (9), conditioned to a specific channel realization, is related to the variance of the noise added at the BS at t, σ_{d1}^2, by

$$\sigma_{y,p}^2 = \sigma_{d1}^2 \underbrace{(\beta_1 + \alpha_p^2 \Gamma_{ur}^p \Gamma_{rb}^{m,p} \beta_2 / 2)}_{\beta_{m,p}}. \quad (10)$$

At the BS side, MRC is also used to optimally combine the received signals from the direct and 2-hop links. The direct link processing is the same as presented for L=1 case.

For the 2-hop link, the signals for antenna m and an arbitrary pair of adjacent subcarriers p and $p+1$, are subject to space-frequency block decoding. The resulting signal is

$$\begin{cases} \hat{s}_{m,p}(t+T_s) = g^{1,m,p*}(t+T_s) y_{BS}^{p}(t+T_s) \\ \qquad\qquad + g_p^{2,m,p}(t+T_s) y_{BS}^{p+1*}(t+T_s) \\ \hat{s}_{m,p+1}(t+T_s) = -g^{2,m,p}(t+T_s) y_{BS}^{p*}(t+T_s) \\ \qquad\qquad + g^{1,m,p*}(t+T_s) y_{BS}^{p+1}(t+T_s) \end{cases}, \quad (11)$$

with equalization coefficients used at both instants given by

$$g^{l,m,p}(t+kT_s) = \begin{cases} \dfrac{h_{ub}^{m,p*}}{\sigma_{d1}^2}, & k=0 \\ \dfrac{\alpha_p \Gamma_{ur}^p}{\sqrt{2}\,\sigma_{d1}^2 \beta_{m,p}} h_{rb}^{l,m,p}, & k=1 \end{cases}. \quad (12)$$

The resulting soft decision variable, at the output of the MRC detector, may be expressed as

$$\hat{d}_p = \underbrace{\frac{d_p}{\sigma_{d1}^2}\left(\Gamma_{ub}^{p} + \frac{1}{2}\alpha_p^2 \Gamma_{ur}^{p\;2} \sum_{m=1}^{M} \frac{\Gamma_{rb}^{m,p}}{\beta_{m,p}}\right)}_{Desired\ Signal} + \underbrace{\frac{1}{2\sigma_{d1}^2}\alpha_p^2 \sum_{m=1}^{M} \frac{\Gamma_{rb}^{m,p\;2}}{\beta_{m,p}} \sum_{l=1}^{L=2} h_{ur}^{l,p*} n_R^{l,p}(t)}_{Relay\ Noise} + \underbrace{\frac{1}{\sigma_{d1}^2}\sum_{m=1}^{M}\left(h_{ub}^{m,p*} n_{BS}^{m,p}(t) + \frac{\alpha_p \Gamma_{ur}^{p}}{\sqrt{2}\beta_{m,p}} \tilde{n}_{BS}^{m,p}(t+T_s)\right)}_{BS\ Noise}, \quad (13)$$

where $\tilde{n}_{BS}^{m,p}(t+T_s)$ is the residual noise which results from SFBC decoding.

B. Relay-Assisted Decode and Forward

In contrast to RA EF, in the RA DF scheme, the relay hard decodes the incoming signals before forwarding them.

The communication cycle for RA DF is as follows. Firstly, the UT transmits at full power for T_s of the time. The expressions for the signals at the receiving antennas of the BS and RN for the first phase are the same as presented in (1) and (2), respectively.

During the second phase, the RN demodulates, decodes and forwards the received signals. Thus, the received signals at the RN at instant t are combined using MRC, and the soft decision in the RN, s_p , is also given by (3). Now, if s_p is successfully detected, then the data to be retransmitted by the RN, here represented by $\bar{s}_p$, is the correct data d_p that the UT transmitted. If the number of transmit antennas of the RN is one, then the RN concludes its action by forwarding $\bar{s}_p$ to the BS. When the RN is equipped with two antennas, the data must be encoded with the presented SFBC scheme before the transmission.

1) Single Antenna Relay

In the single antenna scenario, the received signals at BS antenna m and instant $t+T_s$ are expressed as

$$y_{BS}^{m,p}(t+T_s) = h_{rb}^{m,p}\bar{s}_p + n_{BS}^{m,p}(t+T_s), \quad (14)$$

where $h_{rb}^{m,p}$ and $n_{BS}^{m,p}(t+T_s)$ hold the same meaning as in (5). The total noise power of $y_{BS}^{m,p}(t+T_s)$ is $\sigma_{d1}^2\beta_1$.

For RA DF, the soft decision variable at the UT is given by

$$\hat{d}_p = \underbrace{\frac{1}{\sigma_{d1}^2}\left(d_p\,\Gamma_{ub}^{p} + \bar{s}_p \frac{1}{\beta_1}\sum_{m=1}^{M}\Gamma_{rb}^{m,p}\right)}_{\text{Desired Signal}} + \underbrace{\frac{1}{\sigma_{d1}^2}\sum_{m=1}^{M}\left(h_{ub}^{m,p*} n_{BS}^{m,p}(t) + \frac{1}{\beta_1} n_{BS}^{m,p}(t+T_s)\right)}_{\text{BS Noise}}. \quad (15)$$

2) Two Antenna Relay

Since the two-antenna array at the RN requires additional SFBC for transmission in the RN-to-BS link, the 2-hop link contributions at BS antenna m , at instant $t+T_s$, can be obtained from (9) replacing s_p by $\bar{s}_p$. The 2-hop decoded signals are also given by (11). As in RA EF, the BS combines the direct and 2-hop link signals using MRC whose coefficients are given by

$$g^{l,m,p}(t+kT_s) = \begin{cases} \dfrac{h_{ub}^{m,p*}}{\sigma_{d1}^2} & ,k=0 \\ \dfrac{h_{rb}^{l,m,p}}{\sigma_{d1}^2\beta_1} & ,k=1 \end{cases}. \quad (16)$$

The final soft decision variable for subcarrier p is

$$\hat{d}_p = \underbrace{\frac{1}{\sigma_{d1}^2}\left(d_p\,\Gamma_{ub}^{p} + \bar{s}_p \frac{1}{2\beta_1}\sum_{m=1}^{M}\Gamma_{rb}^{m,p}\right)}_{\text{Desired Signal}} + \underbrace{\frac{1}{\sigma_{d1}^2}\sum_{m=1}^{M}\left(h_{ub}^{m,p*} n_{BS}^{m,p}(t) + \frac{1}{\sqrt{2}\beta_1} \tilde{n}_{BS}^{m,p}(t+T_s)\right)}_{\text{BS Noise}}. \quad (17)$$

As it can be seen from (15) and (17), in the outage case when the relay fails to decode the data correctly, it cannot help the UT for the current cooperation round. In such case, the BS will get interference from the cooperative path and cooperation will not be beneficial. For the particular case where $\bar{s}_p = d_p$, i.e., the data sent by UT is successful decoded at the RN, (17) reduces to (18). In practical systems this can be achieved when the link UT-to-RN has high quality.

$$\hat{d}_p = \underbrace{\frac{1}{\sigma_{d1}^2}\left(\Gamma_{ub}^{p} + \frac{1}{2\beta_1}\sum_{m=1}^{M}\Gamma_{rb}^{m,p}\right)d_p}_{\text{Desired Signal}} + \underbrace{\frac{1}{\sigma_{d1}^2}\sum_{m=1}^{M}\left(h_{ub}^{m,p*} n_{BS}^{m,p}(t) + \frac{1}{\sqrt{2}\beta_1} \tilde{n}_{BS}^{m,p}(t+T_s)\right)}_{\text{BS Noise}}. \quad (18)$$

Note that for this particular scenario, this RA scheme can achieve a diversity order of 6 (4 by RN-to-BS link and 2 by the direct one), and an antenna gain of approximately 6 dB.

IV. DOWNLINK RELAY-ASSISTED SCHEMES

Similarly to the previous section, we analyze the two relay-assisted schemes for downlink system, presented in Fig. 2, using also EF and DF relay protocols. These schemes are referred as $M \times L \times 1$ RA EF and $M \times L \times 1$ RA DF, depending on the number of antennas at the relay node and BS, L and M respectively. As for the uplink schemes, we consider the cases with 1 and 2 antennas at the relay. The formulation for single antenna RN was first derived in [21]. The main contribution of this section is to extend the formulation for 2 antennas at the RN.

A. *Relay-Assisted Equalize-and-Forward*

In the single-antenna relay-assisted scheme, the amplify-and-forward protocol is equivalent to the RA EF protocol proposed in [21]. For the relay case with 2 antennas, we need to equalize and estimate the received data at the relay and only after that retransmit the coded data. However, no hard decision is made at the RN.

During the first phase the BS transmits at full power for T_s of the time. Thus, the received signal at the UT, at instant t, is given by

$$\begin{cases} y_{UT}^{p}(t)=\dfrac{1}{\sqrt{2}}\left(h_{bu}^{1,p}\, d_p - h_{bu}^{2,p}\, d_{p+1}^{*}\right)+n_{UT}^{p}(t) \\ y_{UT}^{p+1}(t)=\dfrac{1}{\sqrt{2}}\left(h_{bu}^{2,p+1}\, d_p^{*} + h_{bu}^{1,p+1}\, d_{p+1}\right)+n_{UT}^{p+1}(t) \end{cases}, \quad (19)$$

where d_p is the data symbol for the p^{th} subcarrier, with unit power; $h_{bu}^{m,p}$, with $m=1,2$, represents the complex Rayleigh flat fading channel between m^{th} BS antenna and UT; and, samples $n_{UT}^{p}(t)$ are zero mean complex additive AWGN samples on the UT with variance σ_{d1}^2.

The received signals at the l^{th} relay antenna (which can be l=1 or l=1,2, depending whether the RN is equipped with 1 or 2 antennas), at instant t, are given by

$$\begin{cases} y_{Rl}^{p}(t)=\dfrac{1}{\sqrt{2}}\left(h_{br}^{1,l,p}\, d_p - h_{br}^{2,l,p}\, d_{p+1}^{*}\right)+n_{Rl}^{p}(t) \\ y_{Rl}^{p+1}(t)=\dfrac{1}{\sqrt{2}}\left(h_{br}^{2,l,p}\, d_p^{*} + h_{br}^{1,l,p}\, d_{p+1}\right)+n_{Rl}^{p+1}(t) \end{cases}, \quad (20)$$

where $h_{br}^{m,l,p}$, with $m=1,2$ and $l=1,2$ represents the complex Rayleigh flat fading channel between m^{th} BS antenna and l^{th} RN antenna, and, $n_{Rl}^{p}(t)$ represents zero mean complex additive AWGN samples on the l^{th} relay antenna, with variance σ_r^2.

During the second phase, the RN comprises several tasks over the received signals, which include: equalization plus space-frequency decoding, power normalization and forwarding. Since the mathematical formulation for RA EF depends on the availability of a 2-antenna array at the relay node, we treat these cases separately, deriving the final decision variables for both schemes, with L=1 and L=2.

1) *Single Antenna Relay*

When the relay is equipped with a single antenna, i.e., L=1, the soft decision variable in this terminal is expressed as

$$\begin{cases} s_p = g_r^{1,p*} y_R^{p}(t) + g_r^{2,p} y_R^{p+1*}(t) \\ s_{p+1} = -g_r^{2,p} y_R^{p*}(t) + g_r^{1,p*} y_R^{p+1}(t) \end{cases}, \quad (21)$$

where the equalization coefficients are defined as

$$g_r^{m,p} = \frac{h_{br}^{m,p}}{\sqrt{2}\Gamma_{br}^{p}}, \quad (22)$$

with m=1,2 and $\Gamma_{br}^{p} = \frac{1}{2}\sum_{m=1}^{2}\left|h_{br}^{m,p}\right|^2$ represents the BS-to-RN equivalent channel gain. The expression for s_p can be simplified to the expression that follows

$$s_p = d_p + \tilde{n}_{R1}^{p}, \quad (23)$$

where $\tilde{n}_{R1}^{p}$ is the noise that results from SFBC decoding with variance $\sigma_{\tilde{r}1}^2 = \dfrac{\sigma_r^2}{\Gamma_{br}^{p}}$.

The following task that the RN does is to normalize the overall transmit power of $\hat{s}_p$ to one. The pertinent normalization constant is

$$\alpha_p = \frac{1}{\sqrt{1+\dfrac{\sigma_r^2}{\Gamma_{br}^{p}}}}. \quad (24)$$

At the UT, for the cooperative link the received signal, on subcarrier p, is given by

$$y_{UT}^{p}(t+T_s) = h_{ru}^{p}\alpha_p s_p + n_{UT}^{p}(t+T_s), \quad (25)$$

where h_{ru}^{p} represents the complex flat Rayleigh fading channel between RN and UT; $n_{UT}^{p}(t+T_s)$ is AWGN noise added in the UT, during the second phase, with zero mean and variance σ_{d2}^2.

The total noise variance of (25), conditioned to a specific channel realization is referred to as $\sigma_{y,u}^2$ and is found to be

$$\sigma_{y,u}^2 = \alpha_p^2 \left| h_{ru}^{1,p} \right|^2 \sigma_r^2 / \Gamma_{br}^p + \sigma_{d2}^2 . \qquad (26)$$

Now we define factor β_1 as the relation between the noise variance added at the UT at instants t and $t+T_s$. In the same way, β_2 is defined as the relation between σ_{d1}^2 and the variance of the noise added at the RN. In (27) we express $\sigma_{y,u}^2$ as a function of σ_{d1}^2.

$$\sigma_{y,u}^2 = \beta_{y,u}\sigma_{d1}^2 = \left(\frac{\alpha_p^2 \left| h_{ru}^p \right|^2 \beta_2}{\Gamma_{br}^p} + \beta_1 \right) \sigma_{d1}^2 . \qquad (27)$$

At the UT, MRC is used to combine the received signal from the direct path and the 2-hop cooperative links. Thus, the estimated signal for an arbitrary pair of adjacent subcarriers, at instants t and $t+T_s$, after the space-frequency combining scheme being applied, is expressed as

$$\begin{cases} \hat{d}_p = g^{1,p*}\left(t+T_s\right) y_{UT}^p\left(t+T_s\right) + \\ \qquad g^{1,p*}\left(t\right) y_{UT}^p\left(t\right) + g^{2,p}\left(t\right) y_{UT}^{p+1*}\left(t\right) \\ \hat{d}_{p+1} = g^{1,p*}\left(t+T_s\right) y_{UT}^p\left(t+T_s\right) - \\ \qquad g^{2,p}\left(t\right) y_{UT}^{p*}\left(t\right) + g^{1,p*}\left(t\right) y_{UT}^{p+1}\left(t\right) \end{cases} \qquad (28)$$

where the equalization coefficients $g^{m,p}\left(\mathrm{n}+kT_s\right)$ are defined as

$$g^{m,p}(t+kT_s) = \begin{cases} \dfrac{\dfrac{h_{bu}^{m,p}}{\sqrt{2}\sigma_{d1}^2}}{\dfrac{1}{2\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{y,u}^2}\alpha_p^2 \left| h_{ru}^p \right|^2} & ,k=0 \\ \dfrac{\alpha_p \dfrac{h_{ru}^p}{\sigma_{y,u}^2}}{\dfrac{1}{2\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{y,u}^2}\alpha_p^2 \left| h_{ru}^p \right|^2} & ,k=1 \end{cases} . \qquad (29)$$

Here we used normalized coefficients to allow higher order modulations. The resulting soft decision variable, for subcarrier p, may be expressed as

$$\hat{d}_p = d_p + \underbrace{\psi \frac{\left| h_{ru}^p \right|^2 \alpha_p^2}{\beta_{y,u}} \tilde{n}_R^p(t)}_{\text{Relay Noise}} + \underbrace{\psi \frac{h_{ru}^{p*}\alpha_p}{\beta_{y,u}} n_U^p(t+T_s) + \psi \tilde{n}_U^p(t)}_{\text{UT Noise}} , \qquad (30)$$

with $\psi = \dfrac{1}{\Gamma_{bu}^p + \dfrac{1}{\beta_{y,u}} \left| h_{ru}^{1,p} \right|^2 \alpha_p^2}$ and $\Gamma_{bu}^p = \dfrac{1}{2} \sum\limits_{m=1}^{2} \left| h_{bu}^{m,p} \right|^2$.

2) *Two Antenna Relay*

When the RN is equipped with a 2-antenna array (i.e., L=2), the soft decision variable at the l^{th} relay antenna (l=1,2), is expressed as follows

$$\begin{cases} s_p = \sum\limits_{l=1}^{2}\left(g_r^{1,l,p*} y_{Rl}^p\left(t\right) + g_r^{2,l,p} y_{Rl}^{p+1*}\left(t\right) \right) \\ s_{p+1} = \sum\limits_{l=1}^{2}\left(-g_r^{2,l,p} y_{Rl}^{p*}\left(t\right) + g_r^{1,l,p*} y_{Rl}^{p+1}\left(t\right) \right) \end{cases} , \qquad (31)$$

where the equalization coefficients, $g_r^{m,l,p}$, for m=1,2, are defined as

$$g_r^{m,l,p} = \frac{\left(\dfrac{h_{br}^{m,l,p}}{\sqrt{2}} \right)}{\dfrac{1}{2} \sum\limits_{l=1}^{2} \sum\limits_{m=1}^{2} \left| h_{br}^{m,l,p} \right|^2} . \qquad (32)$$

After this processing, the RN retransmits $\hat{s}_p$ according to the SFBC mapping scheme and sends it to the UT. Thus, the received signals in the UT, at instant $t+T_s$, on subcarriers p and p+1, are given by

$$\begin{cases} y_{UT}^p\left(t+T_s\right) = \dfrac{1}{\sqrt{2}}\left(h_{ru}^{1,p} s_p - h_{ru}^{2,p} s_{p+1}^* \right) + n_{UT}^p\left(t+T_s\right) \\ y_{UT}^{p+1}\left(t+T_s\right) = \dfrac{1}{\sqrt{2}}\left(h_{ru}^{2,p} s_p^* + h_{ru}^{1,p} s_{p+1} \right) + n_{UT}^{p+1}\left(t+T_s\right) \end{cases} . \qquad (33)$$

The total noise variance of the received signal in UT, during the second phase, is also referred as $\sigma_{y,u}^2$ and now is given by

$$\sigma_{y,u}^2 = \beta_{y,u}\sigma_{d1}^2 = \left(\frac{\alpha_{EF,p}^2 \Gamma_{ru}^p \beta_2}{\sum_{n=1}^{2} \Gamma_{br}^{l,p}} + \beta_1 \right) \sigma_{d1}^2 , \tag{34}$$

with $\Gamma_{br}^{l,p} = \frac{1}{2}\sum_{m=1}^{2} \left| h_{br}^{m,l,p} \right|^2$.

At the UT side, MRC is used to combine the received signals from both phases, obtaining

$$\begin{cases} \hat{d}_p = \sum_{k=0}^{1} \left(\begin{array}{r} g^{1,p*}\left(t+kT_s\right) y_{UT}^{p}\left(t+kT_s\right) \\ + g_p^{2,p}\left(t+kT_s\right) y_U^{p+1*}\left(t+kT_s\right) \end{array} \right) \\ \hat{d}_{p+1} = \sum_{k=0}^{1} \left(\begin{array}{r} -g^{2,p}\left(t+kT_s\right) y_{UT}^{p*}\left(t+kT_s\right) \\ + g^{1,p*}(t+kT_s) y_U^{p+1}\left(t+kT_s\right) \end{array} \right) \end{cases} , \tag{35}$$

where now the equalization coefficients are given by

$$g^{q,p}\left(\mathrm{t}+kT_s\right) = \begin{cases} \dfrac{\dfrac{h_{bu}^{q,p}}{\sqrt{2}\sigma_{d1}^2}}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{y,u}^2}\Gamma_{ru}^p} & ,k=0 \\ \dfrac{\dfrac{h_{ru}^{q,p}}{\sqrt{2}\sigma_{y,u}^2}}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{y,u}^2}\Gamma_{ru}^p} & ,k=1 \end{cases} , \tag{36}$$

with $\Gamma_{ru}^p = \frac{1}{2}\sum_{l=1}^{2} \left| h_{ru}^{l,p} \right|^2$ and q represents the antenna script for BS (for k=0) and for RN (k=1).

The final expression for signal estimation would be

$$\begin{array}{l} \hat{d}_p = d_p + \underbrace{\psi \sum_{l=1}^{2} \left(\frac{\alpha_p^2}{\beta_{y,u}} \Gamma_{ru}^p \tilde{n}_{Rl}^p(t) \right)}_{\text{Relay Noise}} \\ \qquad\qquad + \underbrace{\psi \frac{\alpha_p}{\beta_{y,u}} \tilde{n}_U^p(t+T_S) + \tilde{n}_U^p(t)}_{\text{UT Noise}} \end{array} , \tag{37}$$

with $\psi = \dfrac{1}{\Gamma_{bu}^p + \dfrac{\alpha_p^2}{\beta_{y,u}} \Gamma_{ru}^p}$.

B. Relay-Assisted Decode-and-Forward

In this scheme, during the second phase, the relay first demodulates and hard decodes the incoming signals before forwarding it. Mathematical expressions for the estimated symbols for schemes with *L*=1 and *L*=2, are made separately.

1) Single Antenna Relay

When the RN is equipped with a single antenna, the soft decision variable at the relay is expressed in (21). The hard decision of s_p , also represented by $\overline{s}_p$, is forwarded to the UT. The received signal at UT is

$$y_{UT}^p\left(t+T_s\right) = h_{ru}^p\, \overline{s}_p + n_{UT}^p\left(t+T_s\right). \tag{38}$$

Signals received in both phases are then combined using MRC, resulting in (28), but now with the equalization coefficients defined as

$$g^{q,p}(t+kT_s) = \begin{cases} \dfrac{\dfrac{h_{bu}^{q,p}}{\sqrt{2}\sigma_{d1}^2}}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{d2}^2}\left|h_{ru}^{1,p}\right|^2}, & k=0 \\ \dfrac{\dfrac{h_{ru}^{p*}}{\sigma_{d2}^2}}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p + \dfrac{1}{\sigma_{d2}^2}\left|h_{ru}^{1,p}\right|^2}, & k=1 \end{cases} . \tag{39}$$

The final expression for the estimated signal is given by

$$\begin{array}{l} \hat{d}_p = \underbrace{\psi \left(\Gamma_{bu}^p s_p + \frac{1}{\beta_1} \left| h_{ru}^p \right|^2 \overline{s}_p \right)}_{\text{Desired Signal}} \\ \qquad\qquad \underbrace{+ \psi \tilde{n}_U^p(t) + \frac{\psi}{\beta_1} h_{ru}^{p*} n_U^p(t+T_s)}_{\text{UT Noise}} \end{array} , \tag{40}$$

with $\psi = \dfrac{1}{\Gamma_{bu}^p + \left|h_{ru}^p\right|^2 \big/ \beta_1}$.

The optimal situation occurs when the data is successfully detected at the RN, i.e., $\overline{s}_p = s_p$. On other hand, when the relay fails in decoding the data correctly, the UT will get interference from the cooperative path and cooperation will not be beneficial.

2) *Two Antenna Relay*

Considering the RA scheme with a 2-antennas relay, the decoding expressions for the relay received signals, in the first phase, is expressed as (31) with the equalization coefficients defined as (32). After that, the RN hard decodes and then re-encodes the data and forwards it to the UT. If the decoded data at the RNs is correct, the data to be retransmitted by the RN antenna *l*, i.e., $\overline{s}_p$, is the data d_p that the BS broadcasted.

Signals received in both phases are then combined using MRC as in (35), with the coefficients defined as

$$g^{q,p}(t+kT_s)=\begin{cases}\dfrac{\dfrac{h_{bu}^{q,p}}{\sqrt{2}\sigma_{d1}^2}}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p+\dfrac{1}{\sigma_{d2}^2}\Gamma_{ru}^p}, & k=0\\[2ex] \dfrac{\left(\dfrac{h_{ru}^{q,p}}{\sqrt{2}\sigma_{d2}^2}\right)}{\dfrac{1}{\sigma_{d1}^2}\Gamma_{bu}^p+\dfrac{1}{\sigma_{d2}^2}\Gamma_{ru}^p}, & k=1\end{cases}. \tag{42}$$

The final expression for the estimated signal for subcarrier *p* may be expanded as

$$\hat{d}_p=\underbrace{\psi\left(\Gamma_{bu}^p d_p+\frac{1}{\beta_2}\Gamma_{ru}^p\overline{s}_p\right)}_{\text{Desired Signal}}+\underbrace{\psi\tilde{n}_U^p(t)+\frac{\psi}{\beta_2}\tilde{n}_U^p(t+T_s)}_{\text{UT Noise}}, \tag{43}$$

with $\psi=\dfrac{1}{\Gamma_{bu}^p+\Gamma_{ru}^p\big/\beta_2}$.

As in the previous scheme, RA DF with *L*=1, the optimal situation occurs when the data is successfully detected at the RN, i.e., $\overline{s}_p=d_p$ and for this specific situation (43) reduces to

$$\hat{d}_p=\underbrace{d_p}_{\text{Desired Signal}}+\underbrace{\psi\tilde{n}_U^p(t)+\frac{\psi}{\beta_2}\tilde{n}_U^p(t+T_s)}_{\text{UT Noise}}. \tag{44}$$

V. NUMERICAL RESULTS

In order to evaluate the performance of the presented relay-assisted schemes we considered a typical pedestrian scenario, based on WiMAX specifications. The main simulation settings are summarized in Table II.

With the aim of having the same spectral efficiency between both cooperative and non-cooperative schemes, we used 2 different modulation and coding modes: for the relay-assisted schemes we used QPSK and a CTC, with a block size of (7200, 3600); for the non-cooperative schemes we used BPSK and a CTC with block a size of (3600, 1800). For both cases, the code rate was set to 1/2 and a Max Log MAP algorithm with 8 iterations was used.

TABLE II: MAIN SIMULATIONS PARAMETERS.

<table>
<tr><td>WiMAX General Signal Definitions [24]</td><td colspan="3">• FFT size: 1024;
• number of available carriers: 400;
• sampling frequency: 11.20 MHz;
• useful symbol duration: 91.43µs;
• cyclic prefix length: 11.43µs;
• overall OFDM symbol duration: 102.86µs;
• sub-carrier separation: 10.94 kHz;
• number of OFDM symbols per block: 9;</td></tr>
<tr><td>Nodes's Antenna Array Size</td><td colspan="3">• UT: 1 Tx/Rx antenna
• RN: 1 ou 2 Tx/Rx antennas (<i>L</i>=1 or 2)
• BS: 2 Tx/Rx antennas (<i>M</i>= 2)</td></tr>
<tr><td>Channel Model</td><td colspan="3">• ITU pedestrian model B for 3km/h [25]
• modified tap delays according to the sampling frequency defined for WiMAX.</td></tr>
<tr><td>UT and RN velocities</td><td colspan="3">3 km/h</td></tr>
<tr><td>Channel Code</td><td colspan="3">Convolutional Turbo Code (CTC)</td></tr>
<tr><td>Channel Decoder</td><td colspan="3">Max Log MAP algorithm with 8 iterations</td></tr>
<tr><td rowspan="3">Modulation and coding schemes for (CTC)</td><td>Constellation</td><td>Code rate</td><td>CTC code size (N, K)</td></tr>
<tr><td>BPSK</td><td>1/2</td><td>(3600,1800)</td></tr>
<tr><td>QPSK</td><td>1/2</td><td>(7200, 3600)</td></tr>
</table>

Concerning the MIMO model and for the uplink system, we extended the ITU time model to space-time, assuming that the distance between antenna elements is far apart enough to assume *LM* independent channels, i.e, we assume independent fading processes. We consider that the UT has just one antenna, the BS has 2 receiving antennas (*M* =2) and the relay can have either 1 or 2 antennas (*L*=1 or 2). We further assume perfect channel state information at both RN and UT and the overall transmitted power is normalized to 1. For the downlink system, we use spatial transmitter correlation matrix with an average angle of departure (AoD) of 50°, the standard deviation of AoD set to 8°, and a spatial receiver matrix (at RN and UT when equipped with an antenna array) with an average angle of arrival (AoA) of 67.5°, standard deviation of AoA set to 68°, and antenna spacing at both transmitter and receiver set to 0.5 wavelength.

The results of the relay-assisted and non-cooperative schemes are presented in terms of the average BER as function of E_b/N_0, where E_b is the received energy per bit and $N_0/2$ the bilateral power spectral density of the noise added at the BS in the direct link. Since the aim is to compare the performance using single or multiple antenna relay in scenarios with different link qualities, we present results considering different values of E_b/N_0 for each links: direct link Source-to-Destination (E_b/N_0); Source-to-RN (E_b/N_R), and RN-to-Destination (E_b/N_2), as shown in Table IV. We define and focus our simulation efforts on three scenarios, which will be referred to as scenarios I (all links with similar quality), II (RN has a good connection to the source) and III (RN have a good connection to the source and destination). These scenarios definitions hold for UL and DL communications as presented in Table III. Relay assignment algorithms were not considered in this work, i.e., algorithms to select the best terminals to cooperate. However, some relay assignment algorithms can be found in [26].

We compare the proposed relay-assisted schemes against the non-cooperative or co-located uplink and downlink systems. In the former, the non-cooperative system is represented by the SISO and $1\times M$ MRC point-to-point communication systems, i.e., cellular systems with a single antenna at the UT and a BS with M antennas, where the signals of each antenna are MRC combined.

In the latter, the non-cooperative systems used as reference are the 2×1 and 2×2 MRC SFBC Alamouti point-to-point communication systems. Moreover, we compare the single antenna relay-assisted schemes against the multiple antenna ones. For the sake of simplicity, the numerical results used for assessing the performance of the RA schemes in the UL and DL communication will be presented in two separate sections.

TABLE III: UPLINK AND DOWNLINK SIMULATION SCENARIOS.

Scenario for UL/DL	E_b/N Relations with E_b/N_0	Observations
I	$E_b/N_0=E_b/N_R = E_b/N_2$	All links exhibit similar quality
II	$E_b/N_R = E_b/N_0+10\text{dB}$	RN has a good connection to the Source Node
III	$E_b/N_R = E_b/N_2 = E_b/N_0 +10\text{dB}$	RN has a good connection to the Source and Destination Nodes

TABLE IV: EB/N NOTATION FOR EACH LINK.

DL	UL	E_b/N
BS-to-UT	UT-to-BS	E_b/N_0
BS-to-RN	UT-to-RN	E_b/N_R
RN-to-UT	RN-to-BS	E_b/N_2

1) *Uplink Relay-Assisted Schemes*

In order to assess RA schemes in UL communication, we consider the different scenarios presented in Table III. The first one assumes that all links have the same quality (scenario I), i.e., $E_b/N_0= E_b/N_R= E_b/N_2$. In the second one, the quality of the UT-to-RN link is made 10 dB higher than the direct link, i.e., $E_b/N_R= E_b/N_0+10\text{dB}$. This second scenario is more realistic, since the RN is assumed to be near the UT. In practical cellular systems the cooperative mode is only activated if an active UT can see an idle one with a high link quality. In the third scenario, the quality of the UT-to-RN and RN-to-BS links is made 10 dB higher than the direct link, i.e., $E_b/N_R= E_b/N_2=E_b/N_0+10$ dB.

Fig. 3 shows results for the case at which all links have similar quality. It suggests that the systems whose relay is equipped with an antenna array outperform the ones that use single antenna relays. In fact, the existence of an antenna array at the RN dramatically improves the UT-to-RN link, because it turns this channel into 1×2 SIMO, which provide both 2-order diversity and antenna gain of approximately 3dB. Also, Fig. 3 shows that 1×1×2 RA DF is not working properly, since the information that is erroneously hard decoded at the relay will be seen as interference at the BS and will not improve the system behavior. In this scenario, EF schemes are preferable, as the relay only takes a soft decision over the incoming data and the hard-decision is left for the BS (after combining both signals received from direct and cooperative links).For a BER target of 10^{-4}, the 1×2×2 RA EF scheme yields about 3.6 dB of increase in E_b/N_0, over the non cooperative 1×2 MRC system.

Fig. 4 shows the performance of cooperative schemes for scenarios where the UT-to-RN link is significantly better than the other links. We consider the case where $E_R/N_0=E_b/N_0+10\text{dB}$ and $E_b/N_0=E_{b2}/N_0$. Since the UT-to-RN link is improved with respect to the previous scenario, all RA systems reveal relative performance improvements.

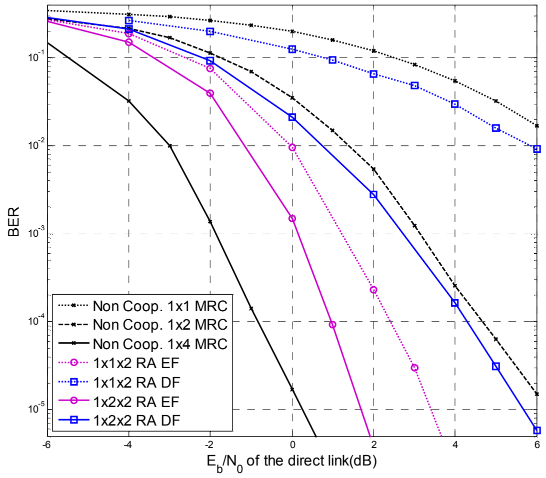

Figure 3. Performance comparison of RA schemes for the uplink: when $Eb/N_0= E_b/N_R= E_b/N_2$ (Scenario I).

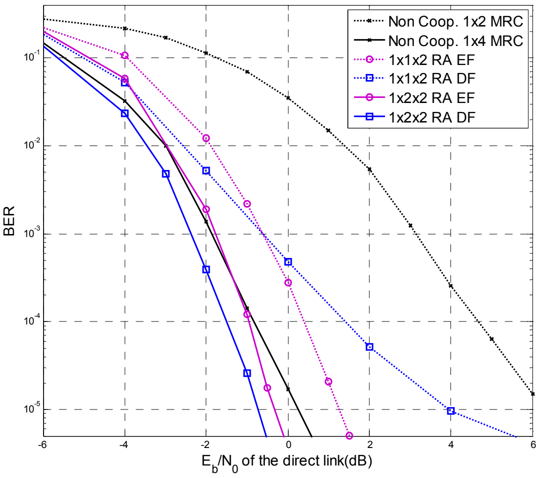

Figure 4. Performance comparison of RA schemes for the uplink: when E_b/N_R= E_b/N_0+10dB (Scenario II).

In the 1×1×2 RA schemes, we observe that, for increasingly higher E_b/N_0 values (above 0 dB), 1×1×2 RA EF outperforms 1×1×2 RA DF. The explanation for the 1×1×2 RA DF malfunction is the fact that the UT-to-RN SISO channel is still not good enough to allow for proper hard decoding at the RN. In the cases where the relay has a 2-antenna array, the UT-to-RN link is not the performance bottleneck anymore. The RA schemes are once again improved by the use of 2 antennas at the relay and are now better than non cooperative 1×2 MRC systems.

The performance of the 1×2×2 EF non cooperative is similar to the one obtained with the 1×4 MRC systems. Moreover, the 1×2×2 DF is even slightly better than 1×4 MRC in the studied range. This non cooperative system can achieve a diversity order of 4 and an antenna gain of 6dB, while the 1×2×2 DF can achieve a diversity order of 6 and an antenna gain of 6 dB for the case where the data is successfully decoded at RN. For a BER target of 10^{-4}, 1×2×2 RA DF yields a gain of 6 dB and 0.7 dB with respect to non cooperative 1×2 MRC and 1×4 MRC, respectively.

Fig. 5 summarizes results for the scenario when E_b/N_2 and E_b/N_R are equal to E_b/N_0+10 dB (scenario III). It evidences the fact that the proposed 1×2×2 RA schemes are clearly better than the 1×1×2 RA ones, clearly showing the benefit of using a 2-antenna array at the RN. It also confirms that RA DF outperforms RA EF for low E_b/N_0 values and the opposite situation occurs as E_b/N_0 increases. For a BER target of 10^{-4}, 1×2×2 RA schemes offer a gain of about 4 dB with respect to non cooperative 1×4 MRC.

2) *Downlink Relay-Assisted Schemes*

To assess the RA schemes in DL communication, we also consider the different scenarios presented in Table III.

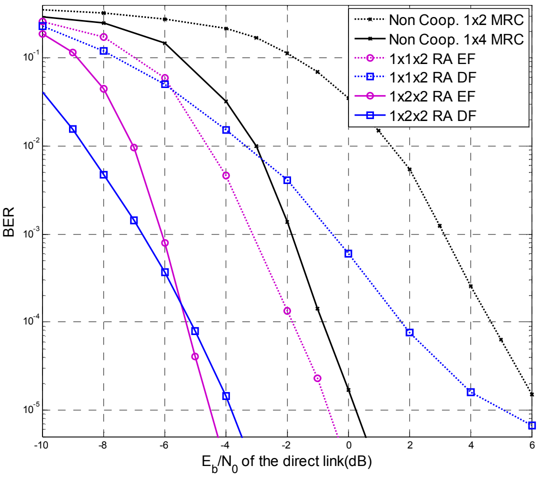

Figure 5. Performance comparison of single and multiple antenna RA schemes for the uplink: when E_b/N_R= E_b/N_0+10dB and E_b/N_2= E_b/N_0+10dB (scenario III).

Fig. 6 shows performance results for RA and non-cooperative schemes for scenario I. From this figure we can see that both RA schemes have a performance that is between non cooperative 2×1 and 2×2 MRC SFBC systems. For L=1, RA EF is preferable, whereas for L=2, RA DF is better and also outperforms 2×1 MRC SFBC. The explanation for the DF improvement relates to its high sensitivity to the cooperative link. As its reliability improves (as happens when the BS-to-RN link becomes MIMO 2×2 instead of MISO 2×1), the hard-decoding process that takes place at the relay is more effective and less likely to produce decoding errors, which will be regarded as interference noise at the UT side. RA DF with L=2 yields a performance improvement greater than 6 dB with respect to SISO, for a BER target of 10^{-4}.

In Fig. 7 we show the schemes performance under the definitions of scenario II. The choice of this scenario for downlink derives from the fact that, in most real situations, the cooperative link has higher transmission quality conditions than the direct link. From this figure we can observe that the performance of both RA schemes is improved in comparison with the previous scenario and that all schemes also outperform non cooperative 2×1 MRC SFBC. This is due to the fact that in the case that the links between BS and RNs are highly reliable, most information is successfully detected at the RN.

We also observe that cooperative systems perform almost the same. Note that in the RN-to-UT link, where most of the errors occur, the schemes behave as a SISO for 1 relay scheme and as a MISO for 2-antenna relay scheme, which have similar performances for low SNRs.

It is interesting to observe that the cooperative schemes outperform the co-located MIMO system, already expected for this scenario.

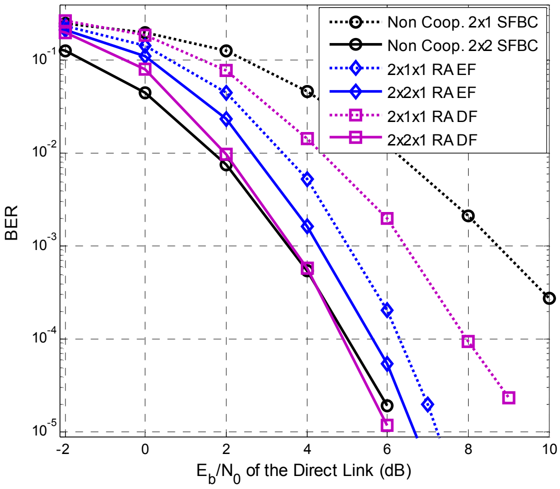

Figure 6. Performance comparison of single and multiple antenna RA schemes for the downlink: when E_b/N_0= E_b/N_R= E_2/N_0 (scenario I).

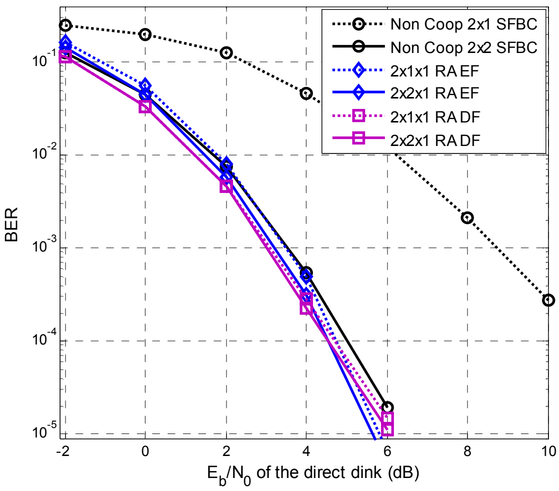

Figure 7. Performance comparison of single and multiple antenna RA schemes for the downlink: when E_b/N_R= E_b/N_0+10dB (scenario II).

Despite almost all information being successfully detected at the relay node, we particularly note that in the reference MIMO case the channels of the two receiver antennas are strongly correlated, while for the relay based systems the channels between RN-to-UT and BS-to-UT links are uncorrelated, increasing the diversity order and thus the overall system performance. Note that for the downlink scenario uncorrelated channels between both receiver and transmitter antennas are not assumed.

Further performance improvements are verified when the whole cooperative link is now 10 dB better than the direct link, as is illustrated in Fig. 8, where the results for scenario III are summed up.

In contrast with Fig. 7, Fig. 8 exhibits a slight performance improvement of RA DF with respect to RA EF. This is due to the fact that DF is decoding properly and effectively eliminating the RN thermal noise, whereas the EF scheme is being limited by the impact of that noise. We also observe that, due to the antennas correlation and the high quality of the cooperative links (BS-to-RN and RN-to-UT are MIMO 2×L and L×1 channels, respectively), the gains of RA systems with L=2 with respect to L=1 are smaller in scenario III than in scenario I.

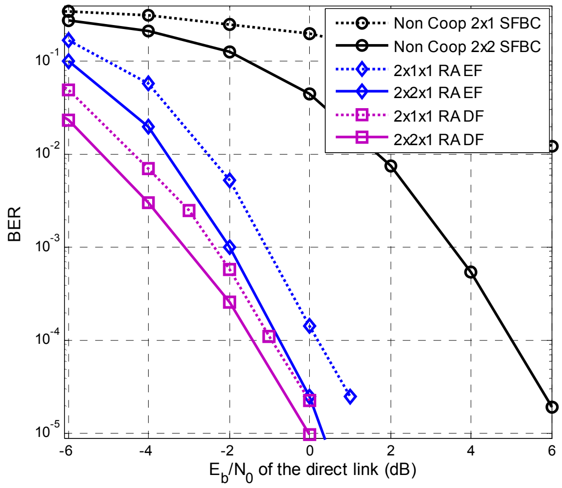

Figure 8. Performance comparison of single and multiple antenna RA schemes for the downlink: when E_b/N_R= E_b/N_0+10dB and E_b/N_2= E_b/N_0+10dB (scenario III).

The aforementioned results suggest that the RA schemes are severely limited by the relative quality of the cooperative links, specially the BS-to-RN link. Thus, the success of the cooperative schemes lies upon the choice of the relay in the network. Ideally, it should be chosen so that the BS-to-RN link is highly reliable.

V. CONCLUSION

We proposed and evaluated single and multiple antenna relay-assisted schemes designed for both the UL and DL OFDM based systems. For each configuration, two types of relay-assisted protocols were analyzed: equalize and forward and decode and forward. These schemes were evaluated under realistic scenarios based on WIMAX specifications and compared against the non-cooperative/co-located SISO, MISO, SIMO and MIMO systems.

Concerning UL systems, results have shown that all the proposed relay-assisted schemes have better performances than the non-cooperative ones in the studied scenarios. Furthermore, it was shown that RA DF schemes outperform RA EF when E_b/N_0 is low and the quality of the UT-to-RN link is of good quality. Otherwise, RA EF based relays are preferable.

For DL systems, results have also shown that all the proposed relay-assisted schemes perform better than the non-cooperative ones. In scenarios where all the links have approximately the same quality the RA EF outperforms the RA DF. However, when the BS-to-RN link has good quality is preferable to implement RA DF instead. In short, the UL and DL results have shown that it is possible to achieve dramatic improvements in systems performance if the proposed cooperative schemes are implemented, especially if the relays are equipped with two-antenna arrays.

It is clear from the presented results that the proposed cooperative schemes can be used to increase the coverage and provide fairness, especially in scenarios where the quality of the direct link is poor, as in urban environments cluttered with buildings. Also, it is crucial to select the best terminal to cooperate, i.e., the one with the higher source-relay link quality in order to achieve better performances. Thus, efficient algorithms to select the best terminal are absolutely fundamental in practical cellular systems.

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