

Effects of Channel estimation on the multi-user Virtual MIMO-OFDMA Relay-based networks

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Abstract

In this paper, a practical multi-user cooperative transmission scheme denoted as *Virtual Maximum Ratio Transmission* (VMRT) for Multiple-Input Multiple-Output - Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) Relay-based networks is proposed and evaluated in the presence of a realistic channel estimation algorithm. It is shown that this scheme is robust against channel estimation errors and offers diversity and array gain keeping the complexity low, although the multi-user and multi-antenna channel estimation algorithm is simple and efficient. Diversity gains larger than 4 can be easily obtained with reduced number of relays. Thus, this scheme can be used to extend coverage or increase system throughput by using simple cooperative OFDMA-based relays.

Index Terms

MIMO-OFDMA, Virtual Maximum Ratio Transmission, Channel estimation, Virtual STBC, beamforming

I. INTRODUCTION

The idea of increasing reliability, coverage and/or capacity in future wireless networks by using cooperative single-antenna relays to reach users' terminals has recently attracted much attention [1]–[15]. Besides, the Multiple-Input Multiple-Output (MIMO) technology has demonstrated that it is a good approach to increase capacity [16], [17]; And, jointly with Orthogonal Frequency Division Multiplexing (OFDM) [18] or Orthogonal Frequency Division Multiple Access (OFDMA) [19], it can also provide reliability. Making work properly all these elements together leverage on an increase in system performance.

Relay schemes can be categorized into three different groups: *Amplify-and-Forward* (AF) [3], [4], [8], [10]–[13], *Compress-and-Forward* (CF) [5], [20] and *Decode-and-Forward* (DF) [1]–[3], [6], [7], [9], [15]. In the AF schemes, relays amplify (and maybe transform [4]) the received signal and broadcast it to the destination. These schemes can be appropriated to extend coverage or solve the problem of attenuation faced by receivers. Besides, some spatial diversity can be provided [1], [6]. In the CF, the relay transmits a quantized and compressed version of the received signal to the destination, and the destination decodes the signal by combining it with its own received signal. These schemes may exploit the redundancy between source and destination, and they assume that the source is able to reach the destination. In the last group, relays in the DF strategy decode the received signal and re-encode (and possibly transform/adapt) the information and send it to destinations. In this paper, we are adopting this last strategy since better performance can be achieved.

In [8], it is shown that the conventional Maximum Ratio Combining (MRC) is the optimum detection scheme for the AF strategy and also that it can achieve full diversity order of $K + 1$, where K is the number of relays, whereas for the DF strategy, the optimum is the Maximum Likelihood (ML) detector [1], [9]. As recognized in [1], performance analysis and implementation of such detector is quite complicated and thus, a suboptimum combiner termed as λ - MRC was derived. Another suboptimum detector is the Cooperative MRC (C - MRC) [10] and Link Adaptive Regeneration (LAR) [11]. In these works, the collaboration is performed at the destination, *viz.*, the receiver treats the relays as a multiple-source transmitter and combines the multiple received signal adequately to obtain the best performance. If we take relays into account also in the design, we can improve the throughput and

This work has been partly funded by projects MULTIADAPTIVE (TEC2008-06327-C03-02) and COMONSENS (CSD2008-00010).

lower the outage probability by selecting the best relays to transmit from [12], [13] (for the AF strategy) and [7] (for the DF). Going further, we can consider the relays as a virtual multiple-input transmitter (if cooperation is used) and thus, leverage on it to improve destination (user) performance. In [14] and [15] the relays are used as a beamformer where full or partial Channel State Information (CSI) is needed on all the elements, and a joint optimization is performed to obtain the best results at the destination. However, in a practical scenario, the knowledge of CSI (even partial) from all the network elements at the source (CSI-T) is not possible.

Besides, the time-frequency structure of OFDMA offers flexibility in terms of multi-user resource management and advantages in terms of dealing with multi-path wireless channel effects. Moreover, next generation wireless mobile networks will use some combination of OFDMA transmission technique [21]. For this reason, in this paper OFDMA has been selected in combination with MIMO to offer a global system design with high data rate capacity and flexibility in terms of multi-user management.

In [22], authors propose and analyze a practical transmission scheme with DF strategy taking the relays as a *Virtual Multiple-Input Transceiver* (VMIT), however, perfect and instantaneous CSI is assumed. In this paper, we design and examine the performance of this scheme in the presence of a realistic and practical channel estimation algorithm. The acquisition of channel state information in a multi-user VMIT must be carried out in an efficient and simple way in order not to have a serious impact on bandwidth efficiency and complexity. Thus, the proposal in [23] is used to fit requirements.

Our contributions in this paper are:

- The comparison of different practical transmission schemes in a MIMO-OFDMA-Relay-based network with a Base Station with N_t transmit antennas, using *Decode-and-Forward* strategy and keeping the complexity low.
- A proposal for the transmission over this network that obtains diversity and array gain at the users' terminals with the increase on system performance and reliability with no CSI-T nor at the Base Station neither at the relays and with low complexity.
- The evaluation of these schemes when there is a degradation in the CSI due to the use of a realistic channel estimation algorithm.

The remaining of this paper is organized as follows. First, in section II, a description of the scenario and the system model is presented. Next, in sections III and IV, the proposed evaluated scheme and the proposed channel estimation are described and summarized, respectively. In section V, the results are presented and discussed. Finally, some conclusions are drawn in section VI.

Notations: Through the paper, the following notation will be used. Bold Capitals and bold faced for matrices and vectors respectively. $E_y\{x\}$ denotes expectation of x over y , $|\mathbf{h}|$ and $\|\mathbf{h}\|$ account for the absolute value and the square of the 2-norm of \mathbf{h} , respectively. The square of this norm will be denoted in the paper as gain ($\mathbf{h}^H \mathbf{h}$). \mathbf{I}_N is the identity matrix of size N and $\text{diag}\{\mathbf{x}\}$ is a diagonal matrix containing \mathbf{x} in its diagonal and 0 elsewhere.

II. DESCRIPTION OF THE SCENARIO AND SYSTEM MODEL

The reference scenario is shown in Figure 1, and is based on a Base Station (BS) with N_t transmit antennas, N_{RS} cooperative Relay Stations (RS), each one with only one antenna for transmission and reception, and N_u User's Terminals (UT), also with one receive antenna each. We assume that the users can not be reached by the BS directly. The used strategy is the *Decode-and-Forward* in a half-duplex transmission, *i.e.*, in phase I, the BS transmits and RS receive - first link/hop -, and, in phase II, the relays transmit and UTs receive - second link/hop. The system is OFDMA-based with N sub-carriers to be allocated to different users, *i.e.*, different UTs use disjoint sets of N_i orthogonal subcarriers. We assume, for simplicity and without loss of generality, that the sub-carriers used in the link BS - RS are the same as in the link RS - UT. The algorithm or policy for the scheduler to assign sub-carriers is out of the scope of the paper. We will consider the transmission of N_s OFDMA symbols as a block, and denote a packet as a group of several blocks. In general N_s can take any value. However, for the Space Time Block Code (STBC)-based schemes that we are proposing, necessarily, the block size must equal the number of transmit antennas, *i.e.*, $N_s = N_t$. This is because we are proposing the use of full-rate STBC.

The frequency-domain transmitted signal from the BS is

$$\mathbf{X}^k = \mathbf{V}\mathbf{C}^k \quad (1)$$

where $\mathbf{X}^k \in \mathbb{C}^{N_t \times N_s}$ is the transmitted signal from the N_t antennas at k -th sub-carrier during the N_s OFDMA symbols, $\mathbf{V} \in \mathbb{C}^{N_t \times N_s}$ is a generic pre-coding vector k and $\mathbf{C}^k \in \mathbb{C}^{N_s \times N_s}$ are the complex base band data to be

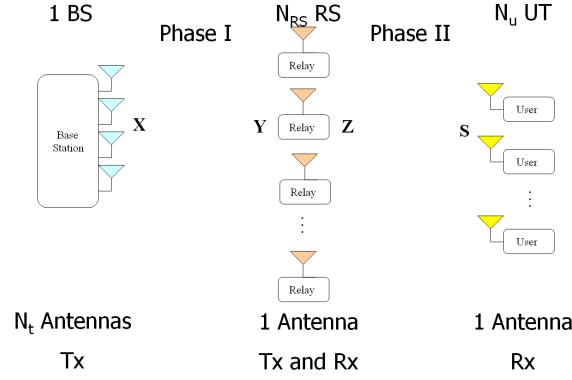


Figure 1. Scenario used in the paper

sent on k -th sub-carrier by all the transmit antennas - assumed here to be M -QAM or M -PSK modulated without loss of generality.

Next, the frequency-domain received signal at i -th relay on k -th sub-carrier after Discrete Fourier Transform (DFT) and discarding the Cyclic Prefix (CP) can be written as

$$\mathbf{y}_i^k = \mathbf{h}_i^k \mathbf{X}^k + \boldsymbol{\psi}^k \quad (2)$$

where $\mathbf{y}_i^k \in \mathbb{C}^{1 \times N_s}$ is the received signal by relay i at sub-carrier k , $\mathbf{h}_i^k \in \mathbb{C}^{1 \times N_t}$ is the channel frequency response for relay i at sub-carrier k from all the transmit antennas (N_t) and $\boldsymbol{\psi}^k$ is the zero-mean Additive White Gaussian Noise (AWGN) vector, each component (k) with variance σ_i^2 . We can arrange the signal received by all the relays in a matrix form as

$$\mathbf{Y}^k = \mathbf{H}^k \mathbf{X}^k + \boldsymbol{\Psi}^k \quad (3)$$

where $\mathbf{Y}^k \in \mathbb{C}^{N_{RS} \times N_s}$ is the received signal by all the relays at k -th sub-carrier during a block of N_s OFDMA symbols, the matrix $\mathbf{H}^k \in \mathbb{C}^{N_{RS} \times N_t} = [\mathbf{h}_1^k \mathbf{h}_2^k \dots \mathbf{h}_{N_{RS}}^k]$ accounts for the channel frequency response on k -th sub-carrier, and $\boldsymbol{\Psi}^k \in \mathbb{C}^{N_{RS} \times N_s}$ contains the zero-mean AWGN. The k -th sub-carrier can be assigned to any user by the scheduler.

For the second hop, *viz.*, from RS to UT, the frequency-domain joint transmitted signal is¹

$$\mathbf{Z}^k = \mathbf{W} \tilde{\mathbf{X}}^k \quad (4)$$

where $\mathbf{Z}^k \in \mathbb{C}^{N_{RS} \times N_s}$ is the transmitted signal by relays at k -th sub-carrier during the block of N_s OFDMA symbols, $\mathbf{W} \in \mathbb{C}^{N_{RS} \times N_{RS}}$ is a new generic pre-coding vector for the second hop and $\tilde{\mathbf{X}}^k$ is the estimated \mathbf{X}^k from received \mathbf{Y}^k , and re-encoded transmitted signal. This yields the following frequency-domain received signal at the user's terminal u

$$\mathbf{s}_u^k = \mathbf{h}_u^k \mathbf{Z}^k + \boldsymbol{\phi}_u^k \quad (5)$$

where $\mathbf{s}_u^k \in \mathbb{C}^{1 \times N_s}$ is the received signal for user u at k th sub-carrier during N_s OFDM symbols, $\mathbf{h}_u^k \in \mathbb{C}^{1 \times N_{RS}}$ is the channel frequency response for user u from the N_{RS} relays at k th sub-carrier and $\boldsymbol{\phi}_u^k \in \mathbb{C}^{1 \times N_{RS}}$ is a second AWGN noise vector for sub-carrier k with each component of variance $\sigma_u'^2$. Again, grouping all the received signals by users into a matrix yields

$$\mathbf{S}^k = \mathbf{H}^k \mathbf{Z}^k + \boldsymbol{\Phi}^k \quad (6)$$

being $\mathbf{S}^k \in \mathbb{C}^{N_u \times N_s}$ the received signal at all the users on subcarrier k during a block of N_s , the matrix $\mathbf{H}^k \in \mathbb{C}^{N_u \times N_{RS}}$ the channel frequency response from relays to users at k -th sub-carrier and $\boldsymbol{\Phi}^k \in \mathbb{C}^{N_u \times N_s}$ a second AWGN matrix. Note that since the system uses OFDMA, at reception, each UT selects the sub-carriers with data allocated to it among all the received sub-carriers.

¹It should be noted that each relay transmits one of the rows of the joint matrix \mathbf{Z}^k . Thus, the pre-coding matrix \mathbf{W}^k must be diagonal, otherwise, relays should share transmission information, and therefore the complexity would increase, which is not the case.

In order to evaluate the schemes for different Signal to Noise Ratios (SNR), the average SNR is defined as

$$\overline{SNR} = \frac{E_k\{E_i\{|\mathbf{X}_i^k|^2\}\}}{\sigma_i^2}, \quad \begin{matrix} k = 0 \dots N-1, \\ i = 0 \dots N_t-1 \end{matrix} \quad (7)$$

The SNR is evaluated averaging over the transmit antennas and the sub-carriers. Since there are two different links, one from BS to RS and other from RS to UT, we define a SNR for each link. When transmitting from relays, in eq. (7), N_t should be replaced by the number of transmitting relays for the scheme (N_{RS}), \mathbf{X}_i^k by \mathbf{Z}_i^k , and σ by σ' .

A. A no CSI-T scheme: 2-hop Space-Time Block Code (2h-STBC)

Although our proposal does not need CSI-T at the relays since the UTs compute the beamforming weights (see section III), the selected terminal must send its weights to the relays sometimes. In order to compare the proposed scheme with the case where no CSI-T is needed, a 2-hop Space-Time Block Code is used, denoted as *2h-STBC* throughout the paper; This encoding scheme uses on both links the following STBC codes. In phase I, the BS transmits using Alamouti [24] when using 2 antennas, or [25], [26] when using 4 or 8 antennas, what is denoted as “*Alamoutitation*” in [26]. For this scheme, the pre-coding matrix in eq. (1) is $\mathbf{V} = \mathbf{I}_{N_t}$ and the number of OFDMA symbols per block (N_s) is set to N_t . Thus the transmitted signal can be written as

$$\mathbf{X}^k \Big|_{STBC} = \mathbf{C}_\alpha^k \quad (8)$$

with $\alpha = 2, 4, 8$ when $N_s = 2, 4$ or 8 respectively, and being

$$\mathbf{C}_2^k = \begin{bmatrix} c^k(1) & -c^k(2)^* \\ c^k(2) & c^k(1)^* \end{bmatrix}, \quad (9)$$

$$\mathbf{C}_4^k = \begin{bmatrix} c^k(1) & c^k(2)^* & c^k(3)^* & c^k(4) \\ c^k(2) & -c^k(1)^* & c^k(4)^* & -c^k(3) \\ c^k(3) & c^k(4)^* & -c^k(1)^* & -c^k(2) \\ c^k(4) & -c^k(3)^* & -c^k(2)^* & c^k(1) \end{bmatrix}, \quad (10)$$

and

$$\mathbf{C}_8^k = \begin{bmatrix} c^k(1) & c^k(2)^* & c^k(3)^* & c^k(4) & c^k(5)^* & c^k(6) & c^k(7) & c^k(8)^* \\ c^k(2) & -c^k(1)^* & c^k(4)^* & -c^k(3) & c^k(6)^* & -c^k(5) & c^k(8) & -c^k(7)^* \\ c^k(3) & c^k(4)^* & -c^k(1)^* & -c^k(2) & c^k(7)^* & c^k(8) & -c^k(5) & -c^k(6)^* \\ c^k(4) & -c^k(3)^* & -c^k(2)^* & c^k(1) & c^k(8)^* & -c^k(7) & -c^k(6) & -c^k(5)^* \\ c^k(5) & c^k(6)^* & c^k(7)^* & c^k(8) & -c^k(1)^* & -c^k(2) & -c^k(3) & -c^k(4)^* \\ c^k(6) & c^k(5)^* & c^k(8)^* & -c^k(7) & -c^k(2)^* & c^k(1) & -c^k(4) & c^k(3) \\ c^k(7) & c^k(8)^* & -c^k(5)^* & -c^k(6) & -c^k(3)^* & -c^k(4) & c^k(1) & -c^k(2)^* \\ c^k(8) & -c^k(7)^* & -c^k(6)^* & c^k(5) & -c^k(4)^* & c^k(3) & c^k(2) & -c^k(1)^* \end{bmatrix}, \quad (11)$$

the matrices containing the data to be sent. $c^k(n)$ are the data on sub-carrier k at OFDMA symbol n ($n = 1 \dots N_s$).

Since all the relays receive the signal and are able to decode it, *i.e.*, \mathbf{y}_i^k in eq. (2), grouping all the received signal by all the relays, eq. (3) yields

$$\mathbf{Y}^k \Big|_{STBC} = \mathbf{H}^k \mathbf{X}^k \Big|_{STBC} + \mathbf{\Psi}^k. \quad (12)$$

Therefore a cooperative *Virtual STBC* transmission can be carried out from RS in phase II, assuming that the RS are numbered and perfectly synchronized. Now, each relay - or a group of N_{R2} relays - acts as an antenna re-encoding the received signal \mathbf{y}_i^k into $\tilde{\mathbf{x}}_i^k$. Again, in the general expression of eq. (4), the pre-coding matrix is $\mathbf{W} = \mathbf{I}_{N_{RS}}$ and thus, arranging into a matrix form all the transmitted signals from the relays, we obtain

$$\mathbf{Z}^k \Big|_{2h-STBC} = \tilde{\mathbf{X}}_\beta^k \quad (13)$$

with $\beta = 2, 4, 8$ for $N_{R2} = 2, 4$ or 8 respectively, and

$$\tilde{\mathbf{X}}_2^k = \begin{bmatrix} \tilde{x}_1^k(1) & -\tilde{x}_1^k(2)^* \\ \tilde{x}_2^k(2) & \tilde{x}_2^k(1)^* \end{bmatrix}, \quad (14)$$

$$\tilde{\mathbf{X}}_4^k = \begin{bmatrix} \tilde{x}_1^k(1) & \tilde{x}_1^k(2)^* & \tilde{x}_1^k(3)^* & \tilde{x}_1^k(4) \\ \tilde{x}_2^k(2) & -\tilde{x}_2^k(1)^* & \tilde{x}_2^k(4)^* & -\tilde{x}_2^k(3) \\ \tilde{x}_3^k(3) & \tilde{x}_3^k(4)^* & -\tilde{x}_3^k(1)^* & -\tilde{x}_3^k(2) \\ \tilde{x}_4^k(4) & -\tilde{x}_4^k(3)^* & -\tilde{x}_4^k(2)^* & \tilde{x}_4^k(1) \end{bmatrix}, \quad (15)$$

and

$$\tilde{\mathbf{X}}_8^k = \begin{bmatrix} \tilde{x}_1^k(1) & \tilde{x}_1^k(2)^* & \tilde{x}_1^k(3)^* & \tilde{x}_1^k(4) & \tilde{x}_1^k(5)^* & \tilde{x}_1^k(6) & \tilde{x}_1^k(7) & \tilde{x}_1^k(8)^* \\ \tilde{x}_2^k(2) & -\tilde{x}_2^k(1)^* & \tilde{x}_2^k(4)^* & -\tilde{x}_2^k(3) & \tilde{x}_2^k(6)^* & -\tilde{x}_2^k(5) & \tilde{x}_2^k(8) & -\tilde{x}_2^k(7)^* \\ \tilde{x}_3^k(3) & \tilde{x}_3^k(4)^* & -\tilde{x}_3^k(1)^* & -\tilde{x}_3^k(2) & \tilde{x}_3^k(7)^* & \tilde{x}_3^k(8) & -\tilde{x}_3^k(5) & -\tilde{x}_3^k(6)^* \\ \tilde{x}_4^k(4) & -\tilde{x}_4^k(3)^* & -\tilde{x}_4^k(2)^* & \tilde{x}_4^k(1) & \tilde{x}_4^k(8)^* & -\tilde{x}_4^k(7) & -\tilde{x}_4^k(6) & -\tilde{x}_4^k(5)^* \\ \tilde{x}_5^k(5) & -\tilde{x}_5^k(6)^* & \tilde{x}_5^k(7)^* & \tilde{x}_5^k(8) & -\tilde{x}_5^k(1)^* & -\tilde{x}_5^k(2) & -\tilde{x}_5^k(3) & -\tilde{x}_5^k(4)^* \\ \tilde{x}_6^k(6) & \tilde{x}_6^k(5)^* & \tilde{x}_6^k(8)^* & -\tilde{x}_6^k(7) & -\tilde{x}_6^k(2)^* & \tilde{x}_6^k(1) & -\tilde{x}_6^k(4) & \tilde{x}_6^k(3)^* \\ \tilde{x}_7^k(7) & \tilde{x}_7^k(8)^* & -\tilde{x}_7^k(5)^* & -\tilde{x}_7^k(6) & -\tilde{x}_7^k(3)^* & -\tilde{x}_7^k(4) & \tilde{x}_7^k(1) & -\tilde{x}_7^k(2)^* \\ \tilde{x}_8^k(8) & -\tilde{x}_8^k(7)^* & -\tilde{x}_8^k(6)^* & \tilde{x}_8^k(5) & -\tilde{x}_8^k(4)^* & \tilde{x}_8^k(3) & \tilde{x}_8^k(2) & -\tilde{x}_8^k(1)^* \end{bmatrix}, \quad (16)$$

being $\tilde{x}_i^k(n)$ the re-encoded transmitted signal by the RS i at n -th OFDMA symbol ($n = 1 \dots N_s$). Some remarks should be pointed out here. The first one is that different number of transmit elements can be used on each link, *i.e.*, N_t can be different from N_{RS} and N_{R2} ; In fact, usually $N_{RS}, N_{R2} > N_t$. And the second one is that the transmitted information by relays may not be orthogonal anymore because each relay decodes the received data and some errors can appear. Thus, some degradation in the performance can be expected at the user's end. If some misalignments may exist between RS, not perfectly synchronized, some extra degradation will appear, but this consideration is out of the scope of this paper. This scheme is the simplest method to obtain diversity from both links, so we will use it as a reference. Besides it can be remarked that no CSI-T is needed but only Channel State Information at the Receiver (CSI-R) for coherent demodulation, at both links.

III. VIRTUAL MAXIMUM RATIO TRANSMISSION (VMRT)

In order to obtain diversity in both links without complexity and reduced CSI in all the elements in the network, in [22], the following scheme is proposed, denoted as *Virtual Maximum Ratio Transmission* because the relays are used as a cooperative virtual beamformer. In this scheme, the BS uses STBC (2, 4 or 8 scheme) to reach relays (first hop) as in the *2h-STBC* scheme. Therefore, the signal model is the same until the first hop as in *2h-STBC*. In the second hop, instead of using again a STBC, here, the relays are configured as a virtual beamformer, and they conform the signal to the user with the best channel quality. All the relays or a group of N_{VMRT} relays can be used. In order to reduce the complexity at the relays and the CSI requirements, we use an approach similar to the one of [27]: user's terminals estimate the channel matrix and compute the MRT weights. Next, each UT computes the link *quality* (q_i) only over its sub-carriers, according to the *minimax* BER criterion. As it was shown in [22], this metric is the one which obtains the closest performance to the optimum. Next, UTs send this *quality* to RS, it should be noted that this value is only a scalar per user. All RS receive this value from each UT and the one with the minimum maximum BER - best *quality* according to minimax BER criterion -, is scheduled to transmit. If qualities are sorted out in descending order so that $q_1 < q_2 < \dots < q_{N_u}$, the UT with q_1 is selected. One RS can act as *coordinator* and informs the selected UT. After that, the selected user sends to relays the pre-coding weights vector to obtain the already calculated fed-back quality (q_1), and each RS uses the adequate weight to perform the cooperative virtual maximum ratio transmission. Thus, transmitted signal \mathbf{Z}^k in (4) will use (12) with $\mathbf{W} = \text{diag}\{\mathbf{w}\}$, calculated by using the *minimax* BER criterion as [22]

$$\mathbf{w} = \frac{\mathbf{h}_{j^*}^{k*}}{\|\mathbf{h}_{j^*}^{k*}\|}, \quad \begin{aligned} j^* &= \arg \min \left\{ \max_k \left\{ BER_j^k \right\} \right\} \quad k = 1 \dots N. \\ k^* &= \arg \max_k \left\{ BER_j^k \right\} \end{aligned} \quad (17)$$

where BER_i^k is the estimated²BER at sub-carrier k for i -th terminal.

²For example, for QPSK modulation, BER at sub-carrier k for i -th terminal (BER_i^k) can be estimated as $\text{erfc} \left(\sqrt{\frac{\sigma_i^2}{2}} \mathbf{h}_i^k \mathbf{h}_i^{kH} \right) - \frac{1}{4} \left(\text{erfc} \left(\frac{\sigma_i^2}{2} \mathbf{h}_i^k \mathbf{h}_i^{kH} \right) \right)^2$, whereas for 64-QAM, BER can be estimated as $\frac{1}{4} \text{erfc} \left(\sqrt{\frac{3\sigma_i^2}{5}} \mathbf{h}_i^k \mathbf{h}_i^{kH} \right)$. Where $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$.

It should be noted that, although it is a multi-carrier system, only one weight per transmit antenna is needed³, since using the *minmax BER criterion*, the best weight per transmit antenna for all the sub-carriers is obtained. This way, the required feedback is reduced and independent from the number of sub-carriers.

Statistically, on average, all the terminals will exhibit similar performance since all of them will experiment the best *quality* channel sometimes on the average. By using this scheme, diversity is exploited in both links, especially on the second one, since usually, the number of RS is higher than the number of transmit antennas. See [22] for more details.

A couple of practical comments are in order. Although transmission from relays is beamformed to the user which presents the best link *quality*, all of them are able to decode the data because they *listen* to the transmitted pre-coding weights (by the selected UT) and so, they can decode the amount of data addressed to them in other sub-carriers, with a BER penalty though. Besides, in order to reduce even more the feedback, the beamforming weights are not modified until the *quality* of the current selected UT q_1 raises above q_2 or until another UT obtains a quality below q_1 . This way, for a slow varying channel, which is generally the case in high speed data transfer scenarios, the feedback is reduced.

It should be pointed out that this scheme exploits more diversity from RS to UT than from BS to RS as mentioned above, what is good for dense relays networks, where there exist a large number of relays, whereas having large number of antennas, even at the BS, is not possible in general. In this scheme, N_{RS} can be arbitrarily large and does not have the constraint of being 2, 4 or 8 as in the 2h-STBC scheme. Besides, this scheme does not need CSI-T neither at BS side nor at relays, only CSI-R for coherent demodulation, since the weights' calculation is performed at the UT. As it will be shown on section V, this scheme obtains the best performance.

IV. CHANNEL ESTIMATION

The use of coherent demodulation implies the knowledge of the CSI-R at the receivers. To acquire the required CSI, a pilot-aided channel estimation scheme is proposed [23]. The first OFDMA symbol of the transmission packet (preamble)⁴ is used to transmit pilots. In our MIMO system, $N_t \times N_{RS}$ or $N_{RS} \times N_u$ channels need to be estimated and so, in order to improve the system's efficiency, we propose that the preamble was shared among all transmit paths. From BS or RS, superimposed pilots sequences are sent by the different N_t transmit antennas (in the case of relays, different N_{RS} relays). To mitigate the resulting co-channel interference, orthogonal phase-shift sequences are used on each path, where each transmit antenna path uses a distinct pilot sequence p_ℓ^k according to:

$$p_\ell^k = \exp\left(-2\pi j \frac{\ell}{N_t} k\right) \quad (18)$$

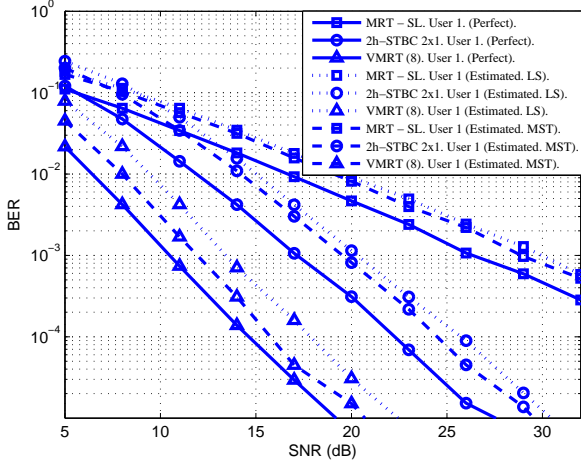
where $\ell \in \{0, \dots, N_T - 1\}$ is the index of the BS transmit antenna and $k \in \{0, \dots, N - 1\}$ is the sub-carrier index. For the Relay - User link, N_t in (18) must be replaced to N_{RS} . Denoting $r_i(t)$ as the time-domain received signal at relay i (after removing the cyclic prefix), and considering that, in the most common channel models, the taps of the time domain channel impulse response are uncorrelated and typically limited to a number of non-vanishing terms much lower than the Fast Fourier Transform (FFT) length, since the amplitude of the sequence in (18) is one, at the receiver, the time-domain channel impulse response estimate from transmit antenna ℓ to relay i , $\hat{h}_{\ell,i}$, is

$$\hat{h}_{\ell,i}(\tau) = r_i(\ell m + \tau) \quad (19)$$

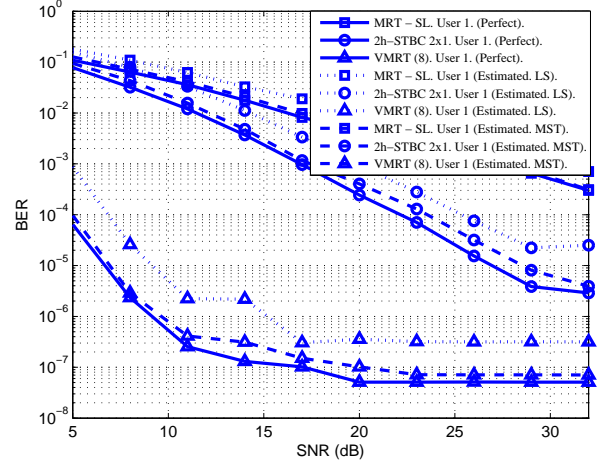
where $m = N/N_t$ represents the number of samples that are collected from each antenna, and $\tau \in \{0, \dots, m\}$. It should be noted that m is also the limit for the maximum channel delay (normalized to the system's sampling interval). This value is especially important on the second hop, limiting the number of relay channels that can be estimated using only one OFDMA symbol. Going over this limit will result in some performance degradation due to the distortion caused by the co-channel interference. To obtain the frequency-domain channel response, a FFT is applied on \hat{h}_ℓ . Since we use OFDMA, the multi-user channel estimation is performed using only the desired frequencies. This channel estimator will be denoted throughout the paper as Least Squares (LS), since it follows the LS criterion.

³Note that \mathbf{w} is not dependent on the sub-carrier index k .

⁴A packet will be composed by several blocks as mentioned before in section II.



(a) Scenario A



(b) Scenario B

Figure 2. Effect of channel estimation. Uncoded QPSK. SUI 3 channel. $N_t = 4$, $N_{RS} = 8$, $N_{VMRT} = 8$, $N_u = 4$.

If the channel impulse response estimate contains more samples than the normalized channel length, some of them will only contain noise and thus, these samples will degrade the channel estimation performance. For this reason, we also implement the Most Significant Tap (MST) channel estimation [28], applied to [23], where we only take the L most significant taps. This low cost improvement of (19) will be denoted as MST throughout the text and it provides significant performance improvements, as it will be seen in section V.

V. SIMULATION RESULTS

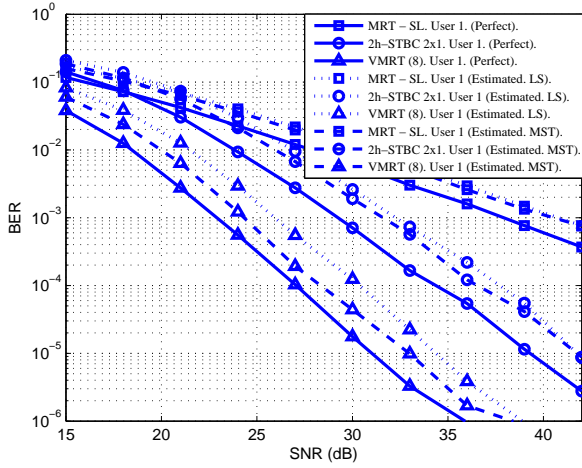
Several simulations have been carried out using Monte Carlo method to obtain results and validate the scheme. All simulations use $N = 128$ sub-carriers and a Cyclic Prefix of 16 samples over a SUI-3 [29] or HiperLAN 2 B channel model [30]. Since we are not focused on sub-carriers scheduling policies, a block of N/N_u contiguous sub-carriers are assigned to each user. Only user 1 results are presented because similar performance is obtained with the different users. In [22] it is shown that we can obtain diversity and array gain on both hops, and this gain increases as the number of RS does. In [22], an exhaustive simulation testbed is carried out on different parameters, and the influence on them is evaluated. However, since this paper is focused on channel estimation errors, we fixed the number of transmit antennas at the BS to 4, the number of relays to 8, and the number of users to 4. Obtained results can be extrapolated to other configurations because they do not depend on these parameters. The two channel estimation algorithms proposed in the paper, namely, the LS and the MST have been evaluated over two different scenarios, namely, Scenario A: the two links have the same SNR, and Scenario B: the SNR of the first link is fixed to 20 dB.

A. Maximum Ratio Transmission - Single Link (MRT - SL)

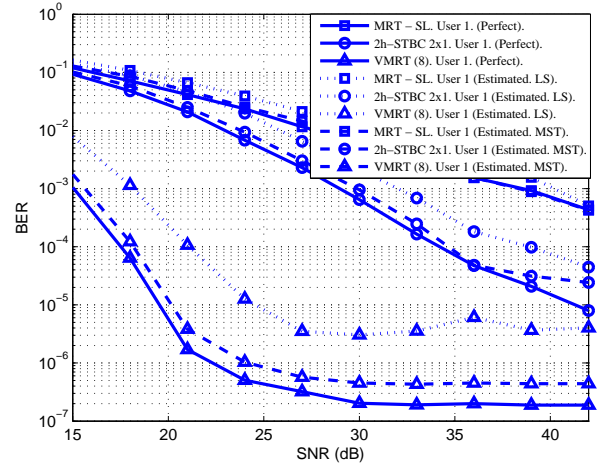
Before presenting the results, in the following, a comparison model is introduced. In [7], an optimized transmission scheme based on relays is proposed. The BS uses a single-antenna and selects the best relay to transmit to. Then, from this relay the signal is forwarded to the destination. Adapting [7] to be used with multiple antennas at the BS, we have the *Maximum Ratio Transmission - Single Link* (MRT - SL). In this scheme, the BS, based on the channel state information in the link BS - RS, selects the best relay to transmit to and beamforms the transmission to it according to the maximum ratio transmission criterion [31]. Thus, transmitted signal can be written as

$$\mathbf{X}^k|_{MRT-SL} = \mathbf{V}|_{MRT-SL} \mathbf{C}^k|_{MRT-SL} \quad (20)$$

with $\mathbf{C}^k|_{MRT-SL} \in \mathbb{C}^{N_t \times N_s} = \text{diag}\{\mathbf{c}^k\}$, \mathbf{c}^k (a column vector with the N_s data to be sent in this block on sub-carrier k), and $\mathbf{V}|_{MRT-SL} \in \mathbb{C}^{N_t \times N_s}$ is the matrix formed by the repetition of N_s times vector $\mathbf{v} \in \mathbb{C}^{N_t \times 1}$,



(a) Scenario A



(b) Scenario B

Figure 3. Effect of channel estimation. Uncoded 64QAM. SUI 3 channel. $N_t = 4$, $N_{RS} = 8$, $N_{VMRT} = 8$, $N_u = 4$.

which are the beamforming weights, again, according to the *minimax* criterion. Thus

$$\mathbf{v} = \frac{\mathbf{h}_{i^*}^{k^*}}{\|\mathbf{h}_{i^*}^{k^*}\|}, \quad i^* = \arg \min \left\{ \max_k \{BER_i^k\} \right\} \quad k = 1 \cdots N. \quad (21)$$

$$k^* = \arg \max_k \{BER_i^k\}$$

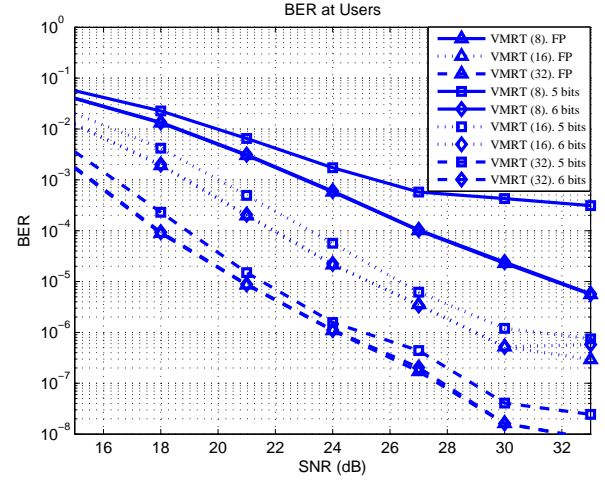
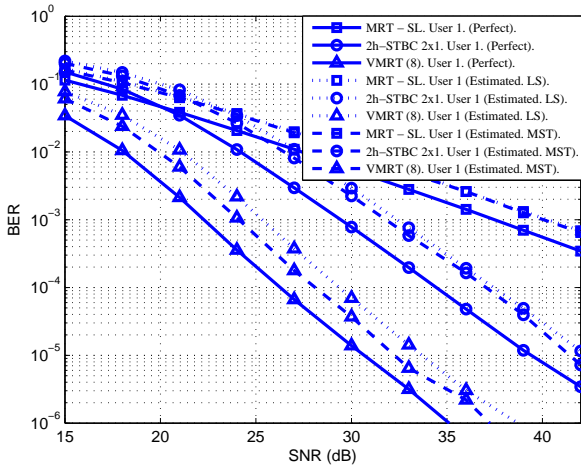
Again, $N_t = N_s$. This way, only the i -th relay is able to decode the data. Then, from this relay, data are sent to the users in a Single Input Single Output (SISO) link, *i.e.*, \mathbf{W} in equation (4) is $w_{j,\ell} = 0, \forall j \neq i, \ell \neq i$ and $w_{i,i} = 1$.

This scheme follows [7] but adapted for a scenario with multiple transmit antennas and without MRC performed at the destination. As it will be seen later, this scheme does not exploit diversity on the second hop. Indeed, the best relay from the point of view of BS might not be the best one to reach users. It has the advantage that CSI-T is needed at the BS only for the link BS-RS instead of the whole link CSI-T as in [14]. This scheme will be used for comparison purposes.

B. Effect of the Channel Estimation

Results have been obtained using the channel estimated by the proposed algorithms at each of the steps in the transmission link. For the *2h-STBC*: the channel estimation has been performed at the reception of RS and UT, for coherent demodulation. For the *MRT-SL*: at the RS for two purposes, namely, to calculate the beamforming weights and for coherent demodulation, and at the reception of UT for coherent demodulation. And for the *VMRT*: the channel estimation has been utilized at the reception of RS for coherent demodulation and at the UT also for two purposes, again, to calculate the beamforming weights and for coherent demodulation. It should be noted that for schemes using MRT, the channel estimation errors will cause a twofold effect: first, the beamforming weights will be corrupted by these errors, and second, the coherent demodulation will also be affected.

In Figure 2, the channel estimation effect on different schemes is shown for a QPSK modulation over SUI 3 channel and the two scenarios. It can be observed that the VMRT scheme outperforms the others. It can be seen a diversity gain and an array gain due to the multiple transmit elements (relays) on the second hop as stated in [22]. Besides, in Figure 2(a), it can be observed that all the schemes behave similar when the proposed LS channel estimation is used (around 3 dB of loss in SNR with respect to perfect CSI). However, in the case of MST estimation, the obtained gain depends on the scheme. By using MST estimation with VMRT, we obtain a gain (with respect to the LS estimation) of around 1.5 dB whereas for the 2h-STBC is around 1 dB, and for the MRT-SL the gain is less than 0.5 dB. This means that the VMRT scheme is more robust against channel estimation errors but it is also more sensible to the algorithm used to estimate the channel. Indeed, the proposed design with MST channel estimation obtains only a degradation around 1 dB with respect to a perfect CSI. For the results on the Scenario B in Figure 2(b), it can be observed that there exists an error floor caused by the errors on the first



(a) Effect of channel estimation. HiperLAN 2 B channel. $N_t = 4$, (b) Effect of the quantization on the VMRT. $N_T = 4$, $N_{RS} = 8$ and $N_{VMRT} = 8, 16, 32$. Full Precision (FP) and the number of bits for precision.

Figure 4. Performance results for Uncoded 64QAM.

link that can not be recovered, although, this error floor is lower (around $7 \cdot 10^{-8}$) for the VMRT than the other schemes (around $3 \cdot 10^{-6}$).

Similar results are obtained when 64-QAM modulation is used over a SUI 3 channel, as it can be observed in Figure 3, what is interesting since results do not depend on the modulation; There exists only a shift in the SNR values for QPSK with respect to 64-QAM.

Next, in Figure 4(a), the same results as in Figure 3(a) are presented but over an HiperLAN 2 B channel (more frequency selective channel, used to check the robustness of the scheme and the channel estimator). It can be observed that the estimator is robust.

Finally, these results can be further improved by using Forward Error Correction (FEC) codes.

C. Effect of the feedback quantization

Another important aspect is the number of bits needed for the quantization of weights in the VMRT scheme. In Figure 4(b), the effect of the number of bits in a fixed point feedback is shown. It can be observed that if the number of bits is too low there exist a degradation on the performance (even an error floor may appear), but once the number of bits is enough (and not very high), the system performs almost equal than in the case of using full precision. Besides, it can also be appreciated that the degradation decreases with large number of relays. The reason is because when increasing the number of relays, quantization errors may compensate each other. It should be noted that, although it is a multi-user MIMO system, on the second hop only one user feeds-back its weights (the selected one), so the feedback does not depend on the number of users but only on the number of transmit elements (N_{RS}). This is indeed another advantage of this cooperative scheme.

Moreover, in order to compress even more the feedback requirements, the value of the *quality* of each user can be quantized. It has been shown in [32] that with one or two bits (per user) is enough to reach more than 95 % of possible throughput.

VI. CONCLUSIONS

In this paper, the scheme denoted as *Virtual Maximum Ratio Transmission* is proposed for a cooperative MIMO OFDMA-Relay-based network and evaluated in the presence of realistic propagation channels such as SUI 3 or HiperLAN 2 B channels, and a practical, simple and efficient multi-user MIMO channel estimation algorithm.

It has been shown that, in order to obtain *diversity* at the users' point, the VMRT is the scheme that better fits the constraints: low complexity, minimum CSI requirements, minimum transmission power and maximum performance. Moreover, this scheme offers diversity and array gains. We have also shown that the scheme is robust against channel

estimation errors and quantization/feedback errors of the beamforming weights. Thus, the VMRT is a cooperative transmission scheme that can increase coverage and system throughput without increasing users' hardware and/or complexity.

ACKNOWLEDGEMENTS

The first author would like to thank Jae-Yun Ko for his valuable help at the beginning of the work.

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