Virtual Maximum Ratio Transmission for Downlink OFDMA Relay-based Networks

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Abstract In this paper, a novel and practical transmission scheme for a Multiple Input Multiple Output–Orthogonal Frequency Division Multiple Access (MIMO-OFDMA) relay-based network is proposed and evaluated. We coin the term *Virtual Maximum Ratio Transmission* (VMRT) for the scheme which obtains diversity and array gain at both links in a two-hop transmission, while keeping the complexity low. Besides, the requirements of Channel State Information needed at the different network elements such as the Base Station, Relay Station or User Terminals are also limited, and so the feedback. The obtained global performance by using proposed VMRT outperforms other schemes. Diversity gains larger than 6 can be easily obtained with a reduced number of relays. For this reason, VMRT is a good candidate to achieve high speed transmission or increase coverage and reliability in slow varying channels for relay-based networks.

Keywords MIMO-OFDMA · Beamforming · Virtual STBC ·
Virtual maximum ratio transmission

1 Introduction

The rapid growth in wireless access and its applications have generated a high demand to provide data rate, coverage and reliability. Multiple-Input Multiple-Output (MIMO)

This work has been partly funded by the Spanish government with projects MACAWI (TEC 2005-07477-C02-02), MULTIADAPTIVE (TEC 2008-06327-C03-02), COMONSENS (CDS2008-00010) and CODIV (ICT-2007-215477).

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technology has proven that it is a good approach to increase capacity [1,2]. Jointly with Orthogonal Frequency Division Multiplexing (OFDM) [3] or Orthogonal Frequency Division Multiple-Access (OFDMA) [4] it can also provide reliability. Additionally, the idea of increasing coverage, capacity and reliability in future wireless networks by using cooperative single-antenna relays has recently attracted much attention [5–20].

Relay schemes can be categorized into three different groups: *Amplify-and-Forward* (AF) [7,8,12,15–18], *Compress-and-Forward* (CF) [21,9] and *Decode-and-Forward* (DF) [5–7, 10,11,13,20]. In the AF schemes, relays amplify (and sometimes transform [8]) the received signal and broadcast it to the destination. These schemes can be used to extend coverage or cancel out attenuation faced by receivers. Besides, some spatial diversity can be provided [5,10]. In the CF, also denoted *Estimate-and-Forward*, *Observe-and-Forward* or *Quantize-and-Forward*, each 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 for our design since it is able to provide better performance. Besides, we are assuming that the source or Base Station (BS) is not able to reach the destination (user terminals) directly but only by using the relays, and these relays have some computational capabilities.

In [12] it is shown that the conventional Maximum Ratio Combining (MRC) is the optimum detection scheme for the AF strategy. Besides it can also achieve full diversity order of $K + 1$, where K is the number of relays. For the DF strategy, the optimum scheme is the Maximum Likelihood (ML) detector [5,13]. As recognized in [5], performance analysis and implementation of such detector are quite complicated and thus, a suboptimum combiner termed as λ-MRC was derived. Another suboptimum detector is the Cooperative MRC (C-MRC) [15] and Link Adaptive Regeneration (LAR) [16]. In these works, the collaboration is performed at the destination, i.e., the receiver treats the relays as a multiple-source transmitter and tries to combine the multiple received signals to obtain the best performance. If we take relays also in the design, we can improve the throughput and lower the outage probability by selecting the best relays to transmit from [17,18], for the AF strategy, and [11,20], for the DF.

Going further, we can consider the relays as a virtual multiple-input transceiver, if cooperation is used, and thus, improve and increase the destination (user) performance and throughput. In [19] the relays are used as a beamformer where full or partial Channel State Information (CSI) is needed on all the elements of the network—i.e., CSI at the Transmitter (CSI-T) and CSI at the Receiver (CSI-R)—and a joint optimization is made to obtain the best performance at the destination. However, in a practical scenario, the knowledge at the source of CSI (even partial) from all the network elements is not possible.

In this paper, we propose and analyze a practical transmission scheme in a DF strategy configuring the relays as a *virtual* multiple-input beamformer using OFDMA-based transmissions. By combining the MIMO-OFDMA technology with relays, coding and diversity gains jointly with an increase in coverage, reliability and throughput can be easily obtained with a limited impact on system complexity. Besides, the proposed scheme does not need CSI-T neither at the BS nor at the relays. The main differences with respect to the previous work in the literature are:

- In the *virtual* Maximum Ratio Transmission (VMRT) scheme (see Sect. 3.2), the relays are used as a *virtual* multiple-input transmitter as in [19] or [22] but no CSI is needed

neither at the Base Station nor at the relays since the calculation of the beamforming weights is performed at the user's terminals.
- Relays and user's terminals are DF-based instead of AF as in [17–19], and so, better performance can be achieved.
- The optimization is made in the last hop, i.e., from relays to users instead of in the whole link as in [19], and thus, less complexity and feedback information is needed.
- Our scenario is more general since we consider a source (Base Station) with several transmit antennas, whereas the others only use 1 antenna for the source.
- A multi-user OFDMA-based transmission is used instead of a single-user single-carrier. The OFDMA obtains at the same time robustness against multi-path effects and multi-user diversity [23,24].

Our contributions in this paper are:

- The comparison of different practical transmission schemes in a MIMO-OFDMA-relay-based network with several transmit antennas at the Base Station, using *Decode-and-Forward* strategy and keeping the complexity and the amount of feedback reduced.
- A proposal for the transmission over this network—the VMRT (see Sect. 3.2)—that obtains diversity and array gain at the users' terminals with the increase on system performance and reliability. Besides, it does not need CSI neither at the Base Station nor at the relays, and the complexity is low.
- The evaluation of the effects of quantization of the beamforming weights on the performance.

The rest of this paper is organized as follows. First in Sect. 2, a description of the scenario and the system model is presented. Then in Sect. 3, the different evaluated schemes are described. Those transmission schemes are evaluated by simulation and results for the variation of the different parameters and the quantization of weights, are summarized in Sect. 4. Finally, some conclusions are drawn in Sect. 5.

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, $|\boldsymbol{h}|$ and $||\boldsymbol{h}||$ account for the absolute vale and the square of the 2-norm of $\boldsymbol{h}$, respectively. The square of this norm will be denoted in the paper as gain $(\boldsymbol{h}^H\boldsymbol{h})$. $\boldsymbol{I}_N$ is the identity matrix of size N and $diag\{\boldsymbol{x}\}$ is a diagonal matrix containing $\boldsymbol{x}$ in its diagonal and 0 elsewhere.

2 Description of the Scenario and System Model

The reference scenario is shown in Fig. 1 and is based on a Base Station (BS) with N_t transmit antennas, N_{RS} 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 RSs receive—firs link/hop—, and in phase II, the relays transmit and UTs receive—second link/hop. Some assumptions are made, namely, the CSI, when needed, is perfect and instantaneous; We will see that several schemes do not need CSI. 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

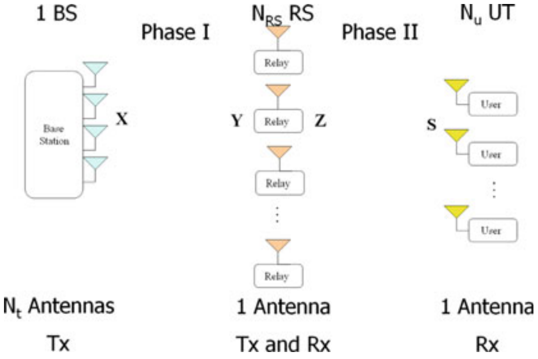

Fig. 1 Scenario used in the paper

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

$$\boldsymbol{X}^k = \boldsymbol{V}\boldsymbol{C}^k \tag{1}$$

where $\boldsymbol{X}^k \in \mathbb{C}^{N_t \times N_s}$ is the transmitted signal from the N_t antennas at k-th sub-carrier during the N_s OFDMA symbols, $\boldsymbol{V} \in \mathbb{C}^{N_t \times N_s}$ is a generic pre-coding vector and $\boldsymbol{C}^k \in \mathbb{C}^{N_s \times N_s}$ are the complex base band data to be 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. It should be noted that $\boldsymbol{V}$ is the same for all the sub-carriers in order to reduce feedback and complexity.

Then, 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

$$\boldsymbol{y}_i^k = \boldsymbol{h}_i^k \boldsymbol{X}^k + \boldsymbol{\psi}^k \tag{2}$$

where $\boldsymbol{y}_i^k \in \mathbb{C}^{1 \times N_s}$ is the received signal by relay i at sub-carrier k, $\boldsymbol{h}_i^k \in \mathbb{C}^{1 \times N_t}$ is the channel frequency response for relay i at sub-carrier k from all the transmit antennas (N_t) and $\boldsymbol{\psi}^k \in \mathbb{C}^{1 \times N_s}$ 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

$$\boldsymbol{Y}^k = \boldsymbol{H}^k \boldsymbol{X}^k + \boldsymbol{\Psi}^k \tag{3}$$

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

For the second hop, i.e., from RS to UT, the frequency-domain joint transmitted signal is[1]

$$\boldsymbol{Z}^k = \boldsymbol{W}\ddot{\boldsymbol{X}}^k \tag{4}$$

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

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

$$\boldsymbol{s}_u^k = \mathfrak{h}_u^k \boldsymbol{Z}^k + \boldsymbol{\phi}_u^k \tag{5}$$

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

$$\boldsymbol{S}^k = \mathcal{H}^k \boldsymbol{Z}^k + \boldsymbol{\Phi}^k \tag{6}$$

being $\boldsymbol{S}^k \in \mathbb{C}^{N_u\times N_s}$ the received signal at all the users on subcarrier k during a block of N_s, the matrix $\mathcal{H}^k \in \mathbb{C}^{N_u\times N_{\mathrm{RS}}}$ 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.

In order to evaluate the performance of the different schemes, we are using the Bit Error Rate (BER) as a measurement over different Signal to Noise Ratios (SNR). Since there are two different links, one from BS to RS and another from RS to UT, we define the SNR for each link. Besides, since the system is MIMO-OFDMA-based, there will exist N_t different channels (in the first link) over N different sub-carriers. For this reason, the average SNR per link is defined as

$$\overline{\mathrm{SNR}} = E_k\left\{E_i\left\{\frac{|\boldsymbol{X}_i^k|^2}{\sigma_i^2}\right\}\right\}, \qquad \begin{array}{l} k = 0\ldots N-1,\\ i = 0\ldots N_t-1 \end{array} \tag{7}$$

As it can be noticed in Eq. 7, the SNR is evaluated averaging over the transmit antennas and the sub-carriers. This way, we obtain a single-value per link to associate with the performance obtained in a given scenario. When transmitting from relays, we will have N_{RS} different channels and in Eq. 7, N_t should be replaced by the number of transmitting relays for the scheme (N_{RS}) and σ by σ'.

It should be noted here that the SNR is used as a way of describing different scenarios for evaluation purposes, but it is not a parameter that needs to be estimated to perform the transmission.

2.1 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 Sect. 3.2), 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 to the RS. It should be pointed out here that, although maximum diversity and orthogonality can only be achieved by transmitting with 2 antennas [25], there exist some STBC for 4 and 8 transmit antennas [26,27] that, although they do not obtain maximum diversity, they are orthogonal and do not decrease the data rate, what is denoted as *"Alamoutitation"* in [27]. In this paper, these codes for 2 (Alamouti), 4 and 8 transmit antennas are used. For this scheme, the pre-coding matrix in Eq. 1 is $\boldsymbol{V} = \boldsymbol{I}_{N_t}$ and the number of OFDMA symbols per block (N_s) is set to N_t. Thus the transmitted signal can be written as

$$\boldsymbol{X}^k\Big|_{STBC} = \boldsymbol{C}_\alpha^k \tag{8}$$

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

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

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

and

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

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

Since all the relays receive the signal and are able to decode it (Multiple Input Single Output-MISO reception and decoding), i.e., $\boldsymbol{y}_i^k$ in Eq. 2, if we group all the received signal by all the relays as in Eq. 3, it yields

$$\boldsymbol{Y}^k\Big|_{STBC} = \boldsymbol{H}^k\ \boldsymbol{X}^k\Big|_{STBC} + \boldsymbol{\Psi}^k. \tag{12}$$

Therefore a *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 $\boldsymbol{y}_i^k$ into $\ddot{\boldsymbol{x}}_i^k$. Again, in the general expression of Eq. 4, the pre-coding matrix is $\boldsymbol{W} = \boldsymbol{I}_{N_{\mathrm{RS}}}$ and thus, arranging into a matrix form all the transmitted signals from the relays, we obtain

$$\boldsymbol{Z}^k\Big|_{2h-STBC} = \ddot{\boldsymbol{X}}_\beta^k \tag{13}$$

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

$$\ddot{\boldsymbol{X}}_2^k = \begin{bmatrix} \ddot{x}_1^k(1) & -\ddot{x}_1^k(2)^* \\ \ddot{x}_2^k(2) & \ddot{x}_2^k(1)^* \end{bmatrix}, \tag{14}$$

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

and

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

being $\ddot{x}_i^k(n)$ the re-encoded transmitted signal by the RS i at n-th OFDMA symbol ($n = 1 \cdots N_s$). 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 $N_{\mathrm{RS}}, N_{R2} > N_t$. 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 CSI-R for coherent demodulation at both links.

2.2 Selection Criteria

When describing the Maximum Ratio Transmission (MRT) [28], the transmitter beamforms the signal to the receiver with the largest channel gain ($\boldsymbol{h}^{\boldsymbol{H}}\boldsymbol{h}$) by using the beamforming weights

$$\boldsymbol{w} = \frac{\boldsymbol{h}_{i^*}}{||\boldsymbol{h}_{i^*}||}, \quad i^* = \arg\max \left\{ \boldsymbol{h}_i^H \boldsymbol{h}_i \right\}. \tag{17}$$

This way, the link is used by the user with the best channel. In the proposed schemes in Sect. 3, either in phase I or phase II, this best channel must be selected in order to beamform the transmission to it. In a single carrier system, it is easy to select the best channel, i.e., the one which has largest gain ($\boldsymbol{h}^{\boldsymbol{H}}\boldsymbol{h}$) or the one which minimizes the BER. However, in multi-antenna multi-carrier systems, this criterion is not as simple as that because we have several channels per user. The trivial extension is to calculate a different weight vector for each sub-carrier. However, this is not practical since the feedback per user is increased N times, and so implementation complexity increases [29]. In order to keep the feedback to one scalar per user, it would be convenient to use a single *quality* parameter that represents a reliable measurement for all the sub-carriers taking into account that the beamforming weights are the same for all of them, minimizing this way the implementation cost [29]. Since our performance measurement is the BER for uncoded signals, we expect that a criteria involving the BER will obtain the best results, although we also evaluate criteria which are capacity-related. Thus, each terminal i transmits the quality q_i and the transmitter selects the best (i^*-th) according to different criteria:

- C1: Mean:
  - $q_i = E_k\left\{\boldsymbol{h}_i^{k^H}\boldsymbol{h}_i^k\right\}, k = 1\cdots N$
  - $i^* = \arg\max q_i$
  - $\theta = E_k\left\{\boldsymbol{h}_{i^*}^k\right\}, k = 1\cdots N$
- C2: Capacity max:
  - $q_i = \max_k\left\{\log_2\left(\left|\boldsymbol{I} + \frac{\boldsymbol{h}_i^{kH}\boldsymbol{h}_i^k}{\sigma^2}\right|\right)\right\}, \quad k = 1\cdots N$
  - $k^* = \arg\max_k\left\{\log_2\left(\left|\boldsymbol{I} + \frac{\boldsymbol{h}_i^{kH}\boldsymbol{h}_i^k}{\sigma^2}\right|\right)\right\}, \quad k = 1\cdots N$
  - $i^* = \arg\max q_i$
  - $\theta = \boldsymbol{h}_{i^*}^{k^*}$
- C3: Capacity mean:
  - $q_i = E_k\left\{\log_2\left(\left|\boldsymbol{I} + \frac{\boldsymbol{h}_i^{kH}\boldsymbol{h}_i^k}{\sigma^2}\right|\right)\right\}, \quad k = 1\cdots N$
  - $i^* = \arg\max q_i$
  - $\theta = E_k\left\{\boldsymbol{h}_{i^*}^k\right\}, \quad k = 1\cdots N$
- C4: min BER max:
  - $q_i = \max_k\left\{BER_i^k\right\}, \quad k = 1\cdots N$
  - $k^* = \arg\max_k\left\{BER_i^k\right\}, \quad k = 1\cdots N$
  - $i^* = \arg\min q_i$
  - $\theta = \boldsymbol{h}_{i^*}^{k^*}$
- C5: min BER mean:
  - $q_i = E_k\left\{BER_i^k\right\}, \quad k = 1\cdots N$
  - $k^* = \arg \mathrm{E}_k\left\{BER_i^k\right\}$
  - $i^* = \arg\min q_i$
  - $\theta = \boldsymbol{h}_{i^*}^{k^*}$

where BER_i^k is the estimated[2] BER at sub-carrier k for i-th terminal. Thus, the weights are computed at the receiver side using

$$\boldsymbol{w} = \frac{\theta}{||\theta||}. \tag{18}$$

Thus, we obtain the best weights valid for all the sub-carriers. Those weights might not be optimal for a specific sub-carrier, but they are the best possible for the whole set.

In Fig. 2, the performance of phase I using Maximum Ratio Transmission (MRT) (to be explained in Sect. 3) is plotted for the different criteria, taking into account that the weights will be the same for all the sub-carriers. The BER is the average BER over all the relays. This Fig. 2 illustrates how important is the adequate criteria selection. Moreover, it highlights that it is possible to obtain gains using the same beamforming weights for all the sub-carriers.

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

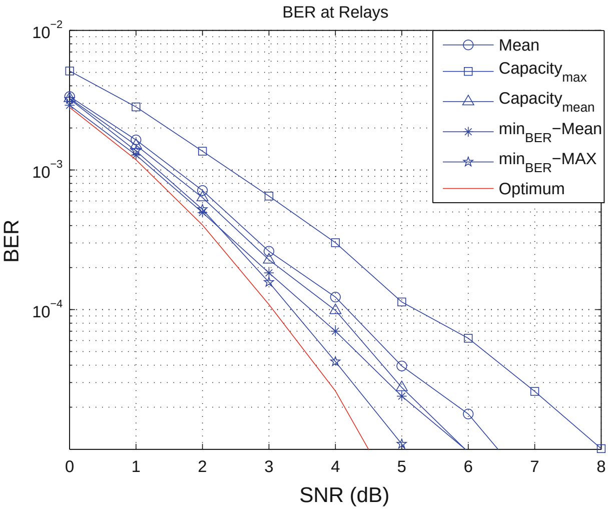

Fig. 2 BER at relays for different criteria. 8 Relays. Uncoded BPSK

Those above criteria have been compared to the optimum (a posteriori).[3] It can be seen that the criterion that is closest to the optimum is the *minimax* BER as it could be expected. The explanation is because the BER follows an *erfc* function and it is dominated by the worst case. Thus, the one that minimizes the maximum BER on a sub-carrier across the antennas leads to the best performance. Another conclusion is that the selection of the criterion can vary significantly the whole performance in the system, especially for high SNR; There are 2 dB between the optimum and the *Capacity max* criterion. In the following, the *minimax* BER criterion has been used for the evaluation of schemes, when applicable. This way, with a feedback of only one scalar per user it is enough to obtain beamforming gain and a performance close to the optimum.

3 Transmission Schemes

In this section, two transmission schemes are proposed and evaluated:

- Maximum Ratio Transmission-Single Link
- Virtual Maximum Ratio Transmission

3.1 Maximum Ratio Transmission-Single Link (MRT-SL)

In [11], an optimized transmission scheme based on relays is proposed. The BS uses a single-antenna and selects the best relay to transmit to. Next, from this relay, the signal is forwarded to the destination. Adapting [11] 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

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[3] Once all the relays have received the signal, it is decoded and BER is calculated. The one which obtains the best performance is selected. This is not possible in practical scenarios, but it is used as a baseline for comparison purposes.

beamforms the transmission to it according to the maximum ratio transmission criterion [28]. Thus, transmitted signal can be written as

$$\boldsymbol{X}^k\Big|_{\mathrm{MRT-SL}} = \boldsymbol{V}|_{\mathrm{MRT-SL}}\ \boldsymbol{C}^k\Big|_{\mathrm{MRT-SL}} \tag{19}$$

with $\boldsymbol{C}^k\big|_{\mathrm{MRT-SL}} \in \mathbb{C}^{N_t \times N_s} = diag\{\boldsymbol{c}^k\}$, $\boldsymbol{c}^k$ (a column vector with the N_s data to be sent in this block on sub-carrier k), and $\boldsymbol{V}|_{\mathrm{MRT-SL}} \in \mathbb{C}^{N_t \times N_s}$ is the matrix formed by the repetition of N_s times vector $\boldsymbol{v} \in \mathbb{C}^{N_t \times 1}$, which are the beamforming weights according to the *minimax* BER criterion (see Sect. 2.2), calculated as Eq. 18 with criterion C4.

$$\boldsymbol{v} = \frac{\boldsymbol{h}_{i^*}^{k^*}}{||\boldsymbol{h}_{i^*}^{k^*}||}, \quad \begin{array}{ll} i^* = \arg\min_i \left\{\max_k \left\{BER_i^k\right\}\right\} & k = 1 \cdots N \\ k^* = \arg\max_k \left\{BER_i^k\right\} & i = 1 \cdots N_{\mathrm{RS}} \end{array}. \tag{20}$$

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

This scheme follows [11] 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. As it will be seen in Sect. 4, this scheme offers poor performance. It has the advantage with respect to [19] that CSI-T is needed at the BS only for the link BS-RS, instead of the whole link CSI-T.

3.2 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, the following scheme is proposed. We coin the term *Virtual Maximum Ratio Transmission* since the relays are used as a 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 will appropriately format 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 in [30]: 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 Sect. 2.2, this metric is the one which obtains the closest performance to the optimum. UTs send this *quality* to RS, this value is a scalar. All RS receive these values from each UT and the one with the minimum maximum BER—best *quality* according to minimax BER criterion—is scheduled to transmit, i.e., if qualities are sorted out in descending order so that $q_1 < q_2 < \cdots < q_{N_u}$, 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, and each RS uses the adequate weight to perform the cooperative virtual maximum ratio transmission, i.e., Eq. 20, is used but channel frequency response corresponds to transmit from RS to UT. Thus, transmitted signal $\boldsymbol{Z}^k$ in (4) will use (12) with $\boldsymbol{W} = diag\{\boldsymbol{w}\}$, calculated similar as in (20)

$$\boldsymbol{w} = \frac{\mathfrak{h}_{j^*}^{k^*}}{||\mathfrak{h}_{j^*}^{k^*}||}, \quad \begin{array}{ll} j^* = \arg\min_i \left\{\max_k \left\{BER_j^k\right\}\right\} & k = 1 \cdots N \\ k^* = \arg\max_k \left\{BER_j^k\right\} & i = 1 \cdots N_{\mathrm{RS}} \end{array}. \tag{21}$$

Table 1 VMRT. Description of the procedure to beamform signal from relay to users

RS	UT
	1 Each UT estimates the channel from all the relays ($\mathfrak{h}_i^k$). 2 Each UT calculates the quality of its channel. 3 Each UT feeds back to RS a scalar representing its quality.
4 Coordinator selects the best UT according to a criterion. 5 Coordinator informs selected terminal.	
	6 Selected terminal feeds back the beamforming weights ($\boldsymbol{w}$) to obtain the quality.
7 Since all the relays receive the beamforming weights $\boldsymbol{w}$ sent by the selected user, each RS uses the adequate weight, based on its number, to perform the cooperative virtual MIMO transmission.	

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, including the second one, what is specially interesting since usually, the number of RS is higher than the number of transmit antennas. A summary of the procedure is depicted in Table 1.

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 (sent 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 changed 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. In this approach, some computational load is moved to the user's terminals—calculate the pre-coding weights, —but it is limited. 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 Sect. 4, this scheme obtains the best performance over the whole range of SNR.

3.2.1 Complexity and Feedback Requirements

Our proposed approach, the VMRT, is characterized by its low complexity and low feedback requirements. The complexity at the BS is reduced since it only needs to encode data across antennas using the specific full rate STBC mentioned in previous section. The relays need to be numbered in order to know which *antenna* they represent in the virtual MIMO transmission scheme. This issue is easily accomplished at the time of starting up each relay. One of the relays acts as coordinator, what means that it selects the user with minimum *quality* factor (that corresponds to the highest quality according to our definitions). As explained before, all the relays will receive the *quality* from all the UTs. Regarding the User Terminals, they need to estimate the channel from each relay and compute the *quality* according to criterion C4 in Sect. 2.2. The channel estimation is also needed for coherent demodulation, so there is no extra computation in this step. Next, only the selected user calculates the weights according to criterion C4 and Eq. 18.

One of the most important advantages of the VMRT is its low feedback requirements. First, the feedback is only needed between UTs and RS, so we do not have the two hop delay, and the feedback is reduced. And second, this feedback is only one scalar—the *quality* q_i—per user. Moreover, this feedback is not continuous but needs only be sent when large channel changes occur, as explained in the implementation comments in previous section. Only the selected user feeds back its weights once, and they are received by all the RS. This yields to a feedback of $N_u \times NB_q + N_{\text{RS}} \times NB_w$ bits—when needed—, where NB_q is the number of bits needeed for encoding the *quality* and NB_w is the number of bits to encode the weights. Compared to the *2h-STBC* which does not require any feedback, the amount of information fed-back is very reduced and the obtained gains are large. Compared to other already existing methods as in [11] adapted to the MIMO scheme and OFDMA, which requires to feed-back the channel coefficient from all the relays and all the users to the BS: $N_{\text{RS}} \times NB_c \times N_t + N_u \times NB_c \times N_{\text{RS}}$ bits continuously, where NB_c is the number of bits to encode the channel coefficients Assuming that $NB_w = NB_c$, for moderate to large number of relays, the reduction of VMRT is approximately of $1/(N_t + N_u)$ compared to the MIMO-OFDMA version of [11].

4 Simulation Results

Several simulations have been carried out using Monte Carlo methodology to obtain results and compare the performance of the schemes. All simulations use $N = 64$ sub-carriers and a Cyclic Prefix of 16 samples over a SUI-3 channel model [31]. Different parameters have been evaluated such as the number of transmit antennas at the BS (N_t), the number of relays (N_{RS}) and the number of relays in the VMRT scheme (N_{VMRT}) for different modulation schemes: BPSK and 64-QAM. The number of users was fixed to 2.

First, a *reduced scenario* with small number of transmit antennas ($N_t = 2$) and relays ($N_{\text{RS}} = 4$) has been simulated to evaluate the performance of different schemes in relatively equal conditions. It can be seen in Figs. 3 and 4, for BPSK and 64-QAM respectively, that the VMRT scheme offers the best performance over the whole range of SNR. The diversity order[4] of this scheme is about 2, the same as schemes *2h-STBC* 2×1 ($N_{\text{RS2}} = 2$) and *2h-STBC* 4×1 ($N_{\text{RS2}} = 4$) because both use the same number of transmitting elements. However, VMRT exhibits an array gain due to the beamforming about 3 dB, and thus, its global performance is better than that of the other schemes. Besides, it can be observed that schemes using single link transmission on the second hop have diversity 1 and present similar performance. In Figs. 5 and 6, the results for a *dense scenario* with larger number of relays ($N_{\text{RS}} = 16$) and transmit antennas ($N_t = 4$) for BPSK modulation are shown. It can be seen that, since *2h-STBC* scheme uses the same transmission's elements as in Figs. 3 and 4, the diversity gain is the same (around 1.5) although the number of transmit antennas at the BS (N_t) is twice. However, the VMRT scheme obtains a diversity close to 3 when the number of relays used for VMRT is $N_{\text{VMRT}} = 8$ and close to 3.5 when is $N_{\text{VMRT}} = 16$. Since

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[4] The diversity order d is defined as $d = -\lim_{P\to\infty} \frac{\ln \bar{p}_e}{\ln P}$, where $\bar{p}_e$ is the average error probability and P is the total transmit power.

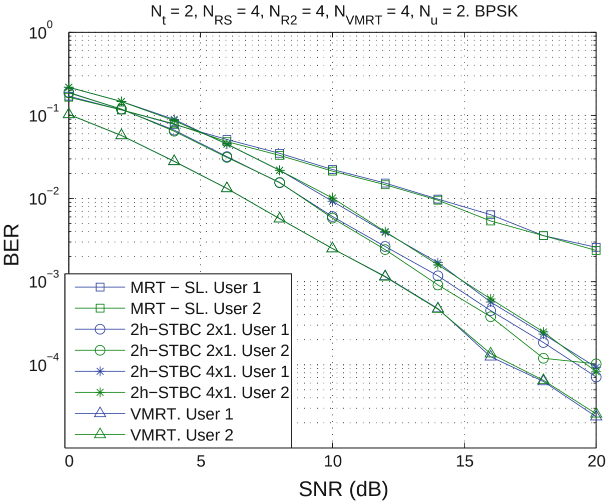

Fig. 3 BER at users for different schemes. Uncoded BPSK. Reduced Scenario

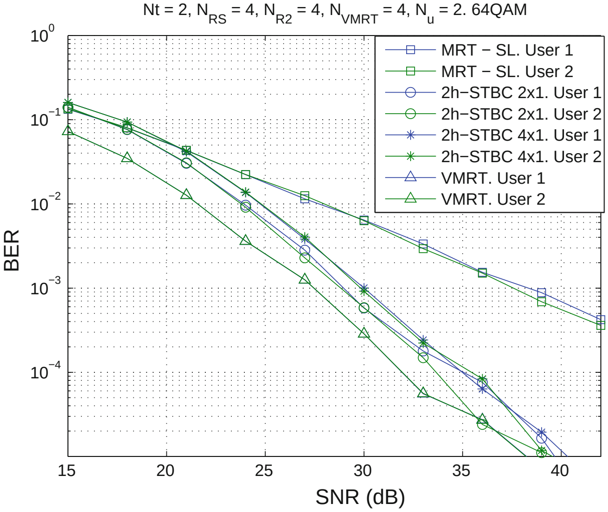

Fig. 4 BER at users for different schemes. Uncoded 64-QAM. Reduced Scenario

part of this *diversity* is due to the second hop, where the number of relays—transmission's elements—can be arbitrarily large, it can be increased with low cost. Thus, this scheme can be used to improve system throughput in an already deployed network or even to extend coverage. Next, in Figs. 7 and 8, the results for the same system's setup, but with the SNR fixed to 20 dB in the first link, are presented. It can be observed that, again, the larger the number of relays in the beamformer the higher coding gains. For the the VMRT, gains around 6 and 7 dB with respect to the Figs. 5 and 6 can be noticed, respectively. Moreover, from these figures it can be concluded that more diversity is exploited on the second link, as stated before.

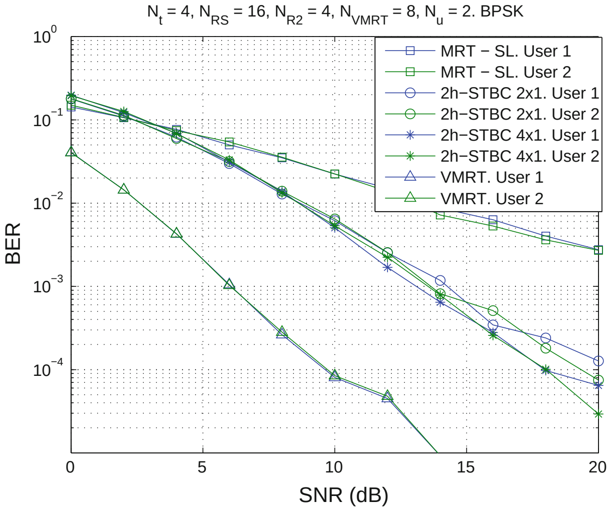

Fig. 5 BER at users for different schemes. Uncoded BPSK. Dense Scenario. $N_{\text{VMRT}} = 8$

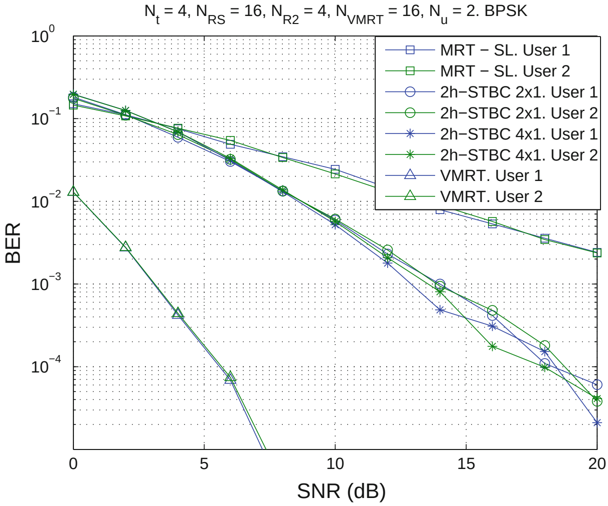

Fig. 6 BER at users for different schemes. Uncoded BPSK. Dense Scenario. $N_{\text{VMRT}} = 16$

4.1 Effect of the Number of Relays (N_{VMRT})

In order to evaluate the effect of the number of relays for the VMRT, in Fig. 9, results increasing the number of relays are shown. It can be observed that *diversity* increases as the number of relays does, i.e., it is 4.4, 4.7, 5 and 6.25 for $N_{\text{VMRT}} = 16, 32, 64, 128$, respectively. Besides, some additional *array gain* can be noticed due to the use of large number of transmission elements on the *virtual beamformer*.

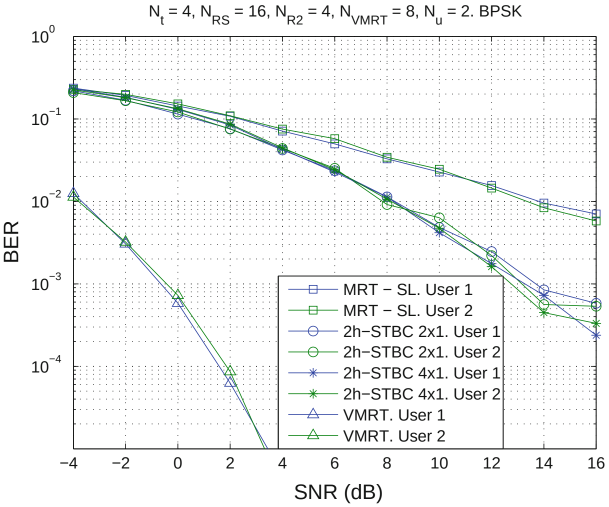

Fig. 7 BER at users for different schemes. Uncoded BPSK. SNR fixed to 20 dB in First Link. Dense Scenario. $N_{\text{VMRT}} = 8$

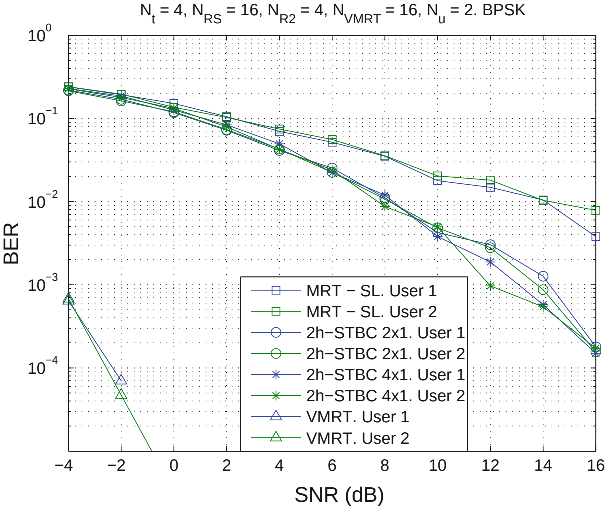

Fig. 8 BER at users for different schemes. Uncoded BPSK. SNR fixed to 20 dB in the First Link. Dense Scenario. $N_{\text{VMRT}} = 16$

4.2 Effect of the Feedback Quantization

Another important aspect is the number of bits needed for the quantization of weights. In Fig. 10, 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 exists a degradation on the performance, even an error floor may appear, but once the number of bits reaches a moderate value, the system performs almost equal as if using full precision. Besides, it can also be appreciated that the

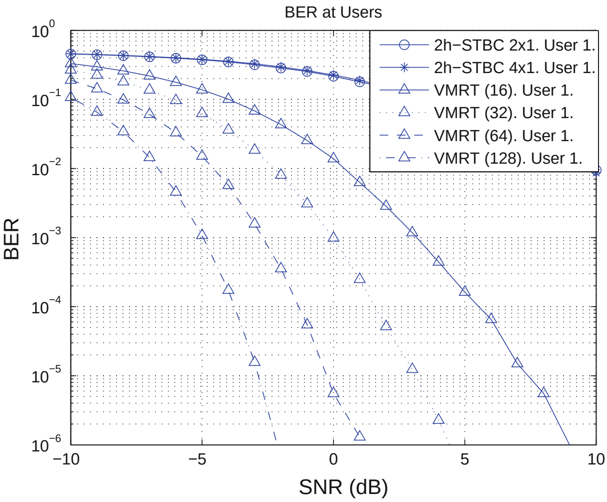

Fig. 9 Effect of the number of relays for VMRT on the global performance. Uncoded BPSK

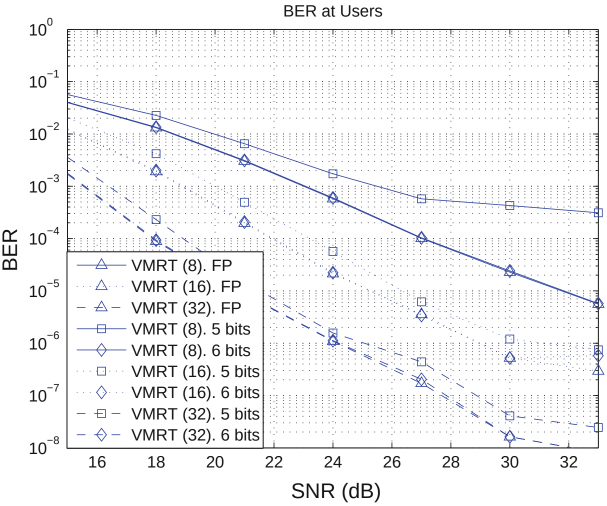

Fig. 10 Effect of the quantization on the VMRT. Uncoded 64QAM. Full Precision (PF) and Fixed number of bits

degradation decreases with large number of relays. The reason is because when increasing the number of relays, quantization errors may compensate each other.

5 Conclusions

In this paper, a transmission scheme for a MIMO OFDMA-relay-based network has been proposed and evaluated. It has been shown that VMRT is able to obtain *diversity* at the users' end with low complexity, minimum CSI requirements and good performance. Moreover, this scheme offers diversity and array gains and those can be tuned by increasing/decreasing the number of involved relays. This is very interesting because keeping the number of receiver antennas to 1, we can obtain diversity by means of relays, whose number can be large. We have also shown that the scheme is robust against quantization/feedback errors of the beamforming weights. Thus, the VMRT is a transmission scheme that can increase coverage and system throughput without increasing users' hardware and complexity.

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

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