A DIFFERENTIAL COOPERATIVE TRANSMISSION SCHEME WITH LOW RATE FEEDBACK

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ABSTRACT

The use of cooperative schemes in wireless networks has recently attracted much attention in scenarios where application of multiple-antenna systems is impractical. In such scenarios, the requirement of having full channel state information (CSI) at the receiver side can be relaxed by using differential distributed (DD) transmission schemes. However, in the DD schemes proposed so far, the decoding complexity as well as the delay requirements increase with the number of relays. In this paper, we propose a low-rate feedback-based DD approach (with one-bit feedback per relay) that enjoys full diversity, linear maximum likelihood (ML) decoding complexity, and unrestrictive delay requirements. In addition, the proposed feedback scheme does not require any CSI knowledge at the receiver, and its implementation is simple. Computer simulations demonstrate substantial performance improvements of the proposed techniques as compared to several popular cooperative transmission schemes.

Index Terms— Cooperative communications, differential distributed transmission, low-rate feedback, wireless relay networks

1. INTRODUCTION

The use of multiple-antenna systems can provide significant performance gains in fading channel scenarios [1]. However, restrictions in size and hardware costs can make the use of such systems impractical in wireless networks. Fortunately, using relays between the transmitter and receiver can provide the so-called *cooperative diversity* and, hence, can be a good alternative to using multiple antennas at the transmitter and/or receiver. Several methods for cooperation between network nodes have been proposed; see [2]-[7] and references therein. Among these methods, techniques using the amplify-and-forward relaying strategy are of practical interest because they do not require signal decoding at the relays.

The use of space-time coding (originally developed for multiple-antenna systems [8]) has been recently proposed in a distributed fashion for relay networks with amplify-and-forward protocols [2], [9]. In this cooperative strategy, the source terminal first transmits the information symbols to the relays. Then, the relays encode their received signals in a linear fashion and transmit them to the receiver. This strategy results in a distributed space-time code (DSTC). When DSTCs are used, the receiver is typically required to have complete CSI to decode the signals. When no CSI is available at the receiver, differential distributed (DD) space-time coding schemes can be employed [10], [11]. In [11], several space-time codes including the Alamouti code, the real square orthogonal space-time block codes (OSTBCs), the Sp(2) code, and the circulant codes have been used to develop DD techniques. The resulting DD Alamouti and real square OSTBCs enjoy linear ML decoding complexity but they are applicable only to quite a particular class of scenarios with a certain number of relays. Moreover, only real-valued constellations can be used in the real square OSTBC scheme. The DD Sp(2) code can be used only in the particular case of four relays, and its decoding complexity is higher than that of the DD OSTBC scheme. The DD circulant code and the differential DSTC of [10] are applicable to any number of relay nodes, but their decoding complexity is high, and the former scheme also suffers from a transmission rate loss. In [12], four-group decodable differential DSTCs have been proposed that are applicable to scenarios with any number of relays. Although these codes offer a reduced decoding cost as compared to the full ML decoder, their complexity still may be quite high, especially in the case of more than four relay nodes. To address the problem of decoding complexity and, at the same time, to improve the code rate and performance in the differential transmission case (where no CSI is available at the receiver), we propose to use a low-rate (one-bit) feedback from the receiver to the relays. The proposed one-bit feedback scheme requires only the received power estimate and, therefore, its implementation is easy. The ML decoding complexity of the proposed scheme is linear for any number of relays and, at the same time, our scheme enjoys flexible delay requirements. Conceptually, the proposed scheme is related to the idea of [13], where the case of coherent relay networks has been addressed; see also [14]-[17] where the idea of partial feedback has been applied to traditional multiple-antenna systems.

2. SYSTEM MODEL

We consider a half-duplex wireless relay network with one single-antenna transmitter, one single-antenna receiver and R single-antenna relay nodes. We assume that the direct link between the transmitter and the receiver can not be established. We denote the channel between the transmitter and the ith relay as f_i, and between the ith relay and the receiver as g_i. The quasi-static flat-fading channel case is considered. The channel block length is denoted as T. The coefficients f_i and g_i are assumed to be independent random variables with the probability density function (pdf) $\mathcal{CN}(0,1)$, where $\mathcal{CN}(\cdot,\cdot)$ denotes the complex Gaussian pdf.

Let T information symbols $\mathbf{s} = [s_1, \ldots, s_T]^T$ be drawn at the transmitter from some M-point constellation $\mathcal{S}$, where $(\cdot)^T$ denotes the transpose. Let the signal $\mathbf{s}$ be normalized as $\mathrm{E}\{\mathbf{s}^H\mathbf{s}\} = 1$, where

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$(\cdot)^H$ and $\mathrm{E}\{\cdot\}$ denote the Hermitian transpose and the statistical expectation, respectively. The transmission is done in two steps. In the first step, from time 1 to T, the transmitter sends $\sqrt{P_0 T}\mathbf{s}$, where P_0 is the average power per channel use at the transmitter. The received signal at the ith relay is given by

$$\mathbf{r}_i = \sqrt{P_0 T} f_i \mathbf{s} + \mathbf{v}_i$$

where $\mathbf{v}_i$ is the noise vector at the ith relay. In the second step, from time $T+1$ to $2T$, the ith relay sends the signal $\mathbf{d}_i$ to the receiver. Assuming perfect synchronization, at the receiver we have

$$\mathbf{x} = \sum_{i=1}^{R} g_i \mathbf{d}_i + \mathbf{n} \tag{1}$$

where $\mathbf{x} = [x_1, \ldots, x_T]^T$ is the received signal and $\mathbf{n} = [n_1, \ldots, n_T]^T$ is the receiver noise. We assume that the entries of the noise vectors $\mathbf{v}_i$ and $\mathbf{n}$ are random variables with the pdf $\mathcal{CN}(0,1)$. The transmit signal $\mathbf{d}_i$ at each relay is assumed to be a linear function of its received signal and its conjugate, that is,

$$\begin{aligned}\mathbf{d}_i &= \sqrt{\frac{P_i}{P_0+1}}\, b_i(\mathbf{A}_i \mathbf{r}_i + \mathbf{B}_i \mathbf{r}_i^*) \\ &= \sqrt{\frac{P_0 P_i T}{P_0+1}}\, b_i(f_i \mathbf{A}_i \mathbf{s} + f_i^* \mathbf{B}_i \mathbf{s}^*) \\ &\quad + \sqrt{\frac{P_i}{P_0+1}}\, b_i(\mathbf{A}_i \mathbf{v}_i + \mathbf{B}_i \mathbf{v}_i^*) \end{aligned} \tag{2}$$

where P_i is the average transmit power at the ith relay, $\mathbf{A}_i$ and $\mathbf{B}_i$ are $T \times T$ complex matrices, $b_i \in \{-1, 1\}$ is a coefficient selected according to the value of the one-bit feedback, and $(\cdot)^*$ denotes the complex conjugate. Below, we consider the case where either $\mathbf{A}_i = \mathbf{O}$ and $\mathbf{B}_i$ is unitary, or $\mathbf{B}_i = \mathbf{O}$ and $\mathbf{A}_i$ is unitary, where $\mathbf{O}$ is the $T \times T$ matrix of zeros. Let us introduce the following notations:

$$\tilde{\mathbf{A}}_i = \mathbf{A}_i,\ \tilde{f}_i = f_i,\ \tilde{\mathbf{v}} = \mathbf{v}_i,\ \tilde{\mathbf{s}}_i = \mathbf{s}, \quad \text{if } \mathbf{B}_i = \mathbf{O}, \tag{3}$$

$$\tilde{\mathbf{A}}_i = \mathbf{B}_i,\ \tilde{f}_i = f_i^*,\ \tilde{\mathbf{v}} = \mathbf{v}_i^*,\ \tilde{\mathbf{s}}_i = \mathbf{s}^*, \quad \text{if } \mathbf{A}_i = \mathbf{O}. \tag{4}$$

Using (1)-(4), we have

$$\mathbf{x} = \mathbf{S}(\mathbf{p} \odot \mathbf{h}) + \mathbf{w} \tag{5}$$

where

$$\mathbf{S} \triangleq [\tilde{\mathbf{A}}_1 \tilde{\mathbf{s}}_1 \ \ldots \ \tilde{\mathbf{A}}_R \tilde{\mathbf{s}}_R]$$

is the distributed space-time codeword,

$$\mathbf{h} = [h_1, \ldots, h_R]^T \triangleq [\tilde{f}_1 g_1, \ldots, \tilde{f}_R g_R]^T$$

is the equivalent channel vector,

$$\mathbf{w} = [w_1, \ldots, w_T]^T \triangleq \sum_{i=1}^{R} \sqrt{\frac{P_i}{P_0+1}}\, b_i g_i \tilde{\mathbf{A}}_i \tilde{\mathbf{v}}_i + \mathbf{n} \tag{6}$$

is the equivalent noise vector,

$$\mathbf{p} \triangleq \left[\sqrt{\frac{P_0 P_1 T}{P_0+1}} b_1, \ldots, \sqrt{\frac{P_0 P_R T}{P_0+1}} b_R \right]^T$$

and $\odot$ denotes the Schur-Hadamard matrix product.

3. DIFFERENTIAL TRANSMISSION

In this section, our low-rate feedback-based differential transmission scheme will be introduced. The essence of this scheme is, based on relay transmissions, to select at the receiver proper integer values of b_i ($i = 1, \ldots, R$), and then to feed these values back to the relays using one-bit feedback between the receiver and each relay. It is assumed that $\mathbf{p} \odot \mathbf{h}$ is not known at the receiver.

3.1. Using One-Bit Feedback

Let us first consider the case $T = 1$ in which the matrices $\mathbf{A}_i$ and $\mathbf{B}_i$ are scalars and assume that $\mathbf{A}_i = 1$ and $\mathbf{B}_i = 0$ (the case when $\mathbf{A}_i$ and $\mathbf{B}_i$ are matrices will be considered later). Correspondingly, $\mathbf{x}$, $\mathbf{v}_i$, $\mathbf{n}$, $\mathbf{w}$ and $\mathbf{s} = s_l$ are scalars as well where $\{s_l\}$ is a stream of symbols to be transmitted during the channel coherence time. These symbols are assumed to be selected from some constant-modulo constellation $\mathcal{S}$, i.e., $|s_l| = 1$. The symbols s_l can be differentially encoded as

$$u_l = u_{l-1} s_l, \quad u_0 = 1$$

where u_l is the actual transmitted symbol and u_0 is the first transmitted signal. Using (5), the received signal is given by

$$x_l = \mathbf{1}_R^T (\mathbf{p} \odot \mathbf{h}) u_l + w_l$$

where $\mathbf{1}_R$ is the $R \times 1$ column vector of ones. The ML symbol estimate can be obtained from maximizing [1]

$$\mathrm{Re}\left\{ x_{l-1} x_l^* s_l \right\} \tag{7}$$

over $s_l \in \mathcal{S}$, where $\mathrm{Re}\{\cdot\}$ denotes the real part. From (7), the power of signal component contained in the product $x_{l-1} x_l^*$ is given by

$$\begin{aligned} P_s &= \left(\mathbf{1}_R^T(\mathbf{p} \odot \mathbf{h})\right)\left(\mathbf{1}_R^T(\mathbf{p} \odot \mathbf{h})\right)^* \\ &= \underbrace{\sum_{i=1}^{R} \rho_{i,i} |f_i g_i|^2}_{\gamma} + \underbrace{\sum_{\substack{i,j=1 \\ i \neq j}}^{R} \rho_{i,j} b_i b_j \mathrm{Re}\left\{ f_i g_i f_j^* g_j^* \right\}}_{\beta} \end{aligned} \tag{8}$$

where

$$\rho_{i,j} \triangleq \sqrt{P_i P_j} P_0 T / (P_0 + 1).$$

Generally, the second term in (8) can take negative values, making the received signal power low. This reduction in the signal power yields some loss in diversity. However, we will show that the values of b_i and b_j in (8) can always be chosen so that $\beta \geq 0$. Moreover, it can be proved that if $\beta \geq 0$, then the diversity order of $R\left(1 - \frac{\log \log P}{\log P}\right)$ can be achieved where

$$P = \sum_{i=0}^{R} P_i$$

is the network total power. To obtain positive values of β, the following simple sequential feedback bit assignment scheme is proposed. Beginning with $b_1 = 1$, the values $b_2 = \pm 1$ have to be examined to select b_2 at the receiver that results in the largest P_s. This yields

$$b_2 = \mathrm{sign}\left(\mathrm{Re}\left\{ f_1 g_1 f_2^* g_2^* \right\}\right)$$

where $\mathrm{sign}(a)$ is equal to 1 if $a \geq 0$, and is equal to -1 otherwise. Subsequently, the values $b_3 = \pm 1$ have to be examined to select b_3 at the receiver that results in the largest P_s, that is,

$$b_3 = \mathrm{sign}\left(\rho_{1,3} \mathrm{Re}\left\{ f_1 g_1 f_3^* g_3^* \right\} + b_2 \rho_{2,3} \mathrm{Re}\left\{ f_2 g_2 f_3^* g_3^* \right\}\right).$$

The same greedy algorithm can be continued to compute b_i for all indices $i > 2$, so that the contribution to P_s in each step is maximum. This is equivalent to selecting b_i as

$$b_i = \text{sign}\left(\sum_{j=1}^{i-1} b_j \rho_{j,i} \text{Re}\left\{f_j g_j f_i^* g_i^*\right\}\right).$$

In general, as the above process does not necessarily maximize β as a function of $b_i \in \{-1, 1\}$, it may only result in suboptimal values for b_i. However, its main advantage is in its simplicity: it does not require any knowledge of the channel coefficients at the receiver and needs only one bit of feedback to deliver the selected b_i from the receiver to the ith relay node. The overall transmission strategy for selecting b_i can be summarized as follows:

1. Set $b_i = 1, i = 1, \ldots, R$. Transmit u_0 from the source to obtain $x_1 = \mathbf{1}_R^T(\mathbf{p} \odot \mathbf{h})u_0 + w_1$ at the receiver.
2. For $j = 2, \ldots, R$:
   - At the jth relay, set $b_j = -1$ and, using (2), obtain the signal d_j to be transmitted from this particular relay. This corresponds to updating the output of the jth relay.
   - Transmit signals from all relays to obtain $x_j = \mathbf{1}_R^T(\mathbf{p} \odot \mathbf{h})u_0 + w_j$ at the receiver.
   - If $|x_j|^2 > |x_{j-1}|^2$, then feed "1" from the receiver back to the relay; otherwise feed "0" back to the relay. In the latter case, set $x_j = x_{j-1}$.
   - If the received feedback at the jth relay is 1, then select $b_j = -1$. Otherwise, select $b_j = 1$.

3.2. Extended Distributed Alamouti Code

The feedback rate of the proposed scheme can be further reduced by using one feedback bit per each pair of relays, and adopting the extended distributed Alamouti code as presented in [13]. In the sequel, the derivations for the case of even number of relays $R = 2K$ will be presented, where K is a positive integer, and $T = 2$. Note that our results can be straightforwardly extended to the case of odd number of relays as well.

At the transmitter, a unitary matrix $\mathbf{S}_l$ is formed with the information symbols s_{2l-1} and s_{2l} scaled by $1/\sqrt{2}$:

$$\mathbf{S}_l = \frac{1}{\sqrt{2}}\begin{bmatrix} s_{2l-1} & -s_{2l}^* \\ s_{2l} & s_{2l-1}^* \end{bmatrix}. \tag{9}$$

The differential encoding

$$\mathbf{u}_l = \mathbf{S}_l \mathbf{u}_{l-1} \tag{10}$$

is used at the transmitter that sends the vector

$$\mathbf{u}_l = [u_{2l-1}\ u_{2l}]^T$$

to relays where l denotes the block number. The first vector $\mathbf{u}_l$ can be chosen as $\mathbf{u}_0 = [1, 0]^T$. The relays use the following matrices to form the transmitted signal:

$$\tilde{\mathbf{A}}_{2k-1} = \mathbf{I}_2,\ \ \mathbf{B}_{2k-1} = \mathbf{O},\ \ \tilde{\mathbf{A}}_{2k} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix},\ \ \mathbf{A}_{2k} = \mathbf{O}.$$

As a result, the following equivalent relation can be obtained

$$\mathbf{x}_l = \mathbf{S}_l \mathbf{U}_{l-1}\left(\sum_{k=1}^{K} \mathbf{p}_k \odot \mathbf{h}_k\right) + \mathbf{w}_l \tag{11}$$

where

$$\begin{aligned} \mathbf{U}_{l-1} &= \begin{bmatrix} u_{2l-3} & -u_{2l-2}^* \\ u_{2l-2} & u_{2l-3}^* \end{bmatrix}, \quad \mathbf{U}_0 = \mathbf{I}_2 \\ \mathbf{p}_k &= \left[\sqrt{\frac{P_0 P_{2k-1} T}{P_0 + 1}} b_k, \sqrt{\frac{P_0 P_{2k} T}{P_0 + 1}} b_k\right]^T \\ \mathbf{h}_k &= [f_{2k-1} g_{2k-1}, f_{2k}^* g_{2k}]^T. \end{aligned}$$

The ML decoding amounts to maximizing [1]

$$\text{Re}\left\{\text{tr}\left(\mathbf{x}_{l-1}\mathbf{x}_l^H \mathbf{S}_l\right)\right\} \tag{12}$$

over $s_{2l-1}, s_{2l} \in \mathcal{S}$, where $\text{tr}(\cdot)$ stands for the trace of a matrix. Note that detection can be done symbol-by-symbol. As in the previous scheme, the diversity order of $R\left(1 - \frac{\log\log P}{\log P}\right)$ can be achieved if the values of b_k are selected so that $\beta_a \geq 0$ where

$$\beta_a = \sum_{\substack{i,j=1 \\ i \neq j}}^{K} b_i b_j \text{Re}\left\{\rho_{2i-1,2j-1} h_{2i-1} h_{2j-1}^* + \rho_{2i,2j} h_{2i} h_{2j}^*\right\}.$$

The selection of b_k, $k = 1, \ldots, K$ can be made in the following way:

1. Set $b_i = 1, i = 1, \ldots, K$. Transmit $\mathbf{u}_0$ from the source to obtain $\mathbf{x}_1 = \mathbf{U}_0\left(\sum_{k=1}^{K} \mathbf{p}_k \odot \mathbf{h}_k\right) + \mathbf{w}_1$ at the receiver.
2. For $j = 2, \ldots, K$:
   - At the $(2j-1)$th and $(2j)$th relays, set $b_j = -1$ and, using (2), obtain the signals $\mathbf{d}_{2j-1}$ and $\mathbf{d}_{2j}$ to be transmitted from this relay pair. This corresponds to updating the output of the jth relay pair.
   - Transmit signals from all relays to obtain $\mathbf{x}_j = \mathbf{U}_0\left(\sum_{k=1}^{K} \mathbf{p}_k \odot \mathbf{h}_k\right) + \mathbf{w}_j$ at the receiver.
   - If $\|\mathbf{x}_j\|^2 \geq \|\mathbf{x}_{j-1}\|^2$, then feed "1" from the receiver back to the relay; otherwise feed "0" back to the relay. In the latter case, set $\mathbf{x}_j = \mathbf{x}_{j-1}$.
   - If the received feedback at the $(2j-1)$th and $(2j)$th relays is 1 then select $b_j = -1$. Otherwise, select $b_j = 1$.

4. SIMULATIONS

We assume a network with $R = 4$ relays and plot the block error rate (BLER) versus the total transmitted power P. The optimal power allocation is used that maximizes the expected receive signal-to-noise ratio (SNR), that is, $P_0 = P/2$ and $P_i = P/2R$ [11]. In Fig. 1, the proposed schemes are compared with the DD Sp(2) code of [11], the coherent distributed quasi-orthogonal space-time block code (QOSTBC) of [18] (this code requires the complete CSI knowledge at the receiver), and the relay selection technique with differential transmission in which the relay with the largest receive power is selected (this approach requires a total of 2 feedback bits). In the DD Sp(2) approach, we use the 3-PSK constellation for the first two symbols and the 5-PSK constellation for the other two symbols to achieve the total rate of 0.9767 bpcu. The other schemes use QPSK symbol constellations to achieve the total rate of 1 bpcu. We refer to the schemes proposed in Sec. 3.1 and Sec. 3.2 as "proposed scheme #1" and "proposed scheme #2", respectively. In the case of scheme #1, for the sake of fair comparison with the DD Sp(2) approach, BLER is computed using four-symbol blocks. For the same

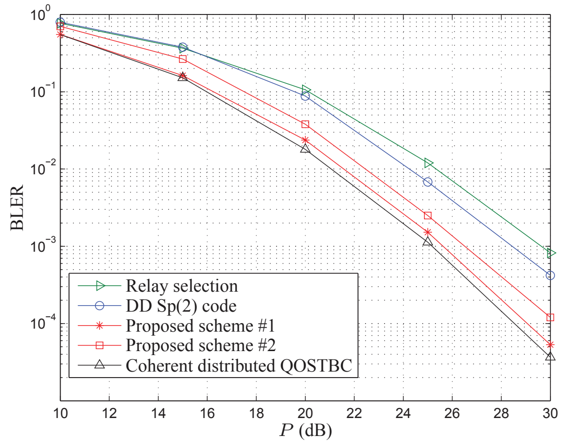

Fig. 1. BLER versus total network power.

reason, a block of two two-symbol subblocks is used in scheme #2 to compute BLER. As follows from Fig. 1, the proposed two schemes outperform the DD Sp(2) code and the relay selection approach, and their performance is very close to the distributed QOSTBC (which requires the full CSI knowledge). These improvements come at the price of three bits and one bit of the total feedback for the proposed schemes #1 and #2, respectively. Also, note that scheme #1 requires $(R+1)+(R-1) = 8$ auxiliary time-slots before starting the transmission of the information bits. In turn, scheme #2 and the DD Sp(2) approach require $(2K + 2) + (K - 1) = 7$ and $2R = 8$ auxiliary time-slots, respectively.

5. CONCLUSIONS

In this paper, a novel low-rate feedback-based distributed differential approach has been proposed for cooperative transmission in relay networks. The proposed feedback schemes do not require any CSI knowledge at the receiver and have simple implementation. In particular, our techniques achieve maximum diversity offered by the relay network, enjoy low-complexity linear ML decoding, and avoid long decoding delays. Moreover, they are applicable to any number of relays. Simulations validate remarkable performance improvements of the proposed techniques as compared to several popular distributed cooperative transmission schemes.

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