Distributed Differential Space-Time Coding for Wireless Relay Networks

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***Abstract*— Distributed space-time coding is a cooperative transmission scheme proposed for wireless relay networks. With this scheme, antennas of the distributive relays work as transmit antennas of the sender and generate a space-time code at the receiver. When the transmit power is infinitely large, it achieves the maximum diversity. Although the scheme needs no channel information at relays, it requires full channel information at the receiver. In this paper, based on distributed space-time coding, we propose a differential transmission scheme, which requires channel information at neither relays nor the receiver. As distributed space-time coding can be seen as the counterpart of space-time coding in the network setting, this scheme is the counterpart of differential space-time coding. Compared to distributed coherent space-time coding, the differential scheme is 3dB worse. In addition, we show that Alamouti, square real orthogonal, and $Sp(2)$ codes, which are originally proposed for multiple-antenna systems, can be used differentially in networks with corresponding numbers of relays.**

***Index Terms*— Relay network, space-time coding, differential transmission, diversity**

I. INTRODUCTION

It is well-known that due to the fading effect, the transmission over wireless channels suffers from severe attenuation in signal strength. Performance of wireless communication is much worse than that of wired communication. For a point-to-point wireless system, this problem was solved by using multiple antennas at the transmitter and/or the receiver. The performance can be greatly improved using diversity techniques such as space-time coding [1], [2], [28]. Recently, with increasing interest in ad hoc wireless networks, researchers have been looking for methods to exploit spatial diversity provided by antennas of different users to improve the reliability and capacity of transmission [3]–[13]. This improvement is called cooperative diversity since it is achieved by having different users in the network cooperate in some way.

Among the most widely used cooperative strategies are amplify-and-forward [5]–[8], [14], [15] and decode-and-forward [3]–[5], [8], [16]. In [9], the authors proposed the use of space-time codes based on Hurwitz-Radon matrices in wireless relay networks. In [17], a new cooperative strategy, *distributed space-time coding*, was proposed, which uses a two-step 'listen-and-transmit' protocol. In step one, the transmitter sends information to relays and in step two, relays send information to the receiver. The signal sent by every relay in the second step is a linear function of its received signal and its conjugate. It was shown that the distributive relays generate a linear space-time codeword at the receiver. The same as amplify-and-forward, it needs no channel information at relays. But it is more general than amplify-and-forward. Compared to decode-and-forward, it does not require decoding at relays. Therefore, it saves both power and time at relays. Most importantly, it achieves the optimal diversity (in the sense of error rate) when the SNR is high. Distributed space-time coding was generalized to networks with multiple-antenna nodes in [18]. In [19], practical distributed space-time codes were proposed using real orthogonal, complex orthogonal, and quasi-orthogonal designs. Simulations show that they have excellent performance and low decoding complexity. Distributed space-time code designs based on cyclotomic field theory can be found in [20] and designs using commuting sets and doubling construction can be found in [21].

Although distributed space-time coding does not need channel information at relays, it does require full channel information, both the channel from the transmitter to relays and the channel from relays to the receiver, at the receiver. Therefore, training symbols have to be sent from both the transmitter and relays. However, in some situations, because of the cost on time and power and the complexity of channel estimation, training is not desired. Sometimes, training is not even practical due to the rapid change of fading condition. These issues are even more prominent in networks with a large number of relays, in which a long training period is needed. Therefore, it is very useful to develop transmission schemes that require channel knowledge at neither relays nor the receiver.

A decode-and-forward-based differential scheme for relay networks can be found in [16] and an amplify-and-forward-based differential scheme using the single-antenna DPSK technique can be found in [15].

In this paper, based on distributed space-time coding [17], we propose a differential transmission scheme for wireless relay networks that requires no channel information at either relays or the receiver. As distributed space-time coding can be seen as the counterpart of space-time coding in the network setting, this scheme, which we call distributed differential space-time coding, is the counterpart of differential space-time coding [25]–[27]. It is suitable for networks with continuously changing channels. At the receiver, only the channel statistics is needed, which is assumed to be a Rayleigh distribution. Also, the system need to be synchronized at the symbol level, i.e., relays transmit at the same time.

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We show that with this scheme, Alamouti [22] and $Sp(2)$ codes [23] can be used differentially in networks with two and four relays, and square real orthogonal codes [2] can be used differentially in networks with two, four, and eight relays. Due to their special structures, Alamouti and square real orthogonal codes maintain their linear decoding complexity while used differentially in networks. $Sp(2)$ code can be decoded decoded pairwisely or using a sphere decoder. Simulation shows that compared to distributed coherent space-time coding, the differential scheme is 3dB worse.

The paper is organized as follows. In the following section, the wireless relay network model is introduced and coherent distributed space-time coding is reviewed briefly. In Section III, we show a differential scheme for two-relay networks based on Alamouti space-time code. Then in Section IV, we propose distributed differential space-time coding for networks with any relays. Section V provides some distributed differential space-time code designs. These designs are inspired by the well-known Alamouti, square real orthogonal, and $Sp(2)$ space-time codes originally designed for multiple-antenna systems. Simulated performance of some of these differential codes is also given in this section. Section VI contains the conclusion.

II. Distributed Coherent Space-Time Coding

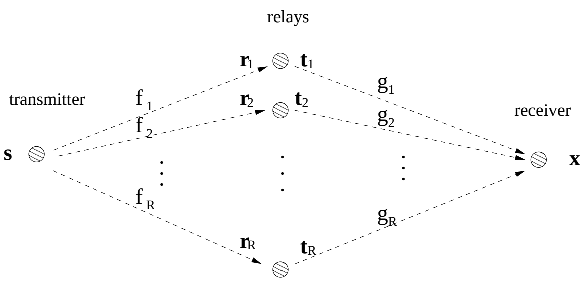

Fig. 1. Wireless relay network.

Consider a wireless network with $R+2$ nodes. As shown in Fig. 1, there is one transmit node and one receive node. All other R nodes work as relays. Every node has a single antenna,[1] which can be used for both transmission and reception. Denote the channel from the transmitter to the ith relay as f_i, and the channel from the ith relay to the receiver as g_i. Assume that the channels are Rayleigh flat fading, i.e., f_i and g_i are i.i.d. zero-mean and unit-variance complex Gaussian random variables. We use a block-fading model by assuming a coherence interval T, i.e., f_i and g_i keep constant for a block of T transmissions and jump to other independent values for another T transmissions.

When there is no channel information at relays but full channel information, both f_i and g_i, at the receiver, distributed space-time coding was proposed in [17], which uses the idea of linear dispersion space-time codes [24] proposed for multiple-antenna systems. Information bits are encoded into groups of T symbols $\mathbf{s} = [s_1, \cdots, s_T]^t$ where A^t indicates the transpose of A. We normalize $\mathbf{s}$ as

$$\mathrm{E}\,\mathbf{s}^*\mathbf{s} = 1, \tag{1}$$

where A^* indicates the Hermitian of A.

A two-step protocol is used, as depicted in Fig. 1. Each step contains T symbol transmissions. During the first step, the transmitter sends $\sqrt{P_1 T}\mathbf{s}$. Thus, the average power per transmission used at the transmitter is P_1. The received signal and noise at the ith relay are denoted by $\mathbf{r}_i$ and $\mathbf{v}_i$. During the second step, the ith relay sends $\mathbf{t}_i$. Denote the received signal and noise at the receiver by $\mathbf{x}$ and $\mathbf{w}$ respectively. The noises are assumed to be i.i.d. zero-mean and unit-variance complex Gaussian random variables. The transmit signal at the ith relay is designed to be a linear function of its received signal and its conjugate:

$$\mathbf{t}_i = \sqrt{\frac{P_2}{P_1+1}}(A_i \mathbf{r}_i + B_i \bar{\mathbf{r}}_i), \tag{2}$$

where

$$\begin{bmatrix} \Re(A_i+B_i) & -\Im(A_i-B_i) \\ \Im(A_i+B_i) & \Re(A_i-B_i) \end{bmatrix} \tag{3}$$

is a $2T \times 2T$ orthogonal matrix. With the normalization $\sqrt{\frac{P_2}{P_1+1}}$ in (2) and the orthogonality of (3), P_2 can be proved to be the average transmit power per transmission used at every relay. Denote the $m \times n$ matrix with all zeros as 0_{mn}. We omit the subscript when there is no confusion. For the case that either $A_i = 0, B_i$ is unitary or $B_i = 0, A_i$ is unitary, the received signal can be calculated to be

$$\mathbf{x} = \sqrt{\frac{P_1 P_2 T}{P_1+1}} S H + W, \tag{4}$$

where

$$S = \left[\begin{array}{ccc} \hat{A}_1 \hat{\mathbf{s}} & \cdots & \hat{A}_R \hat{\mathbf{s}} \end{array}\right], \tag{5}$$

$$H = \left[\begin{array}{ccc} \hat{f}_1 g_1 & \cdots & \hat{f}_R g_R \end{array}\right]^t, \tag{6}$$

$$W = \sqrt{\frac{P_2}{P_1+1}} \sum_{i=1}^{R} g_i \hat{A}_i \hat{\mathbf{v}}_i + \mathbf{w}, \tag{7}$$

and

$$\begin{cases} \hat{A}_i = A_i, \hat{f}_i = f_i, \hat{\mathbf{v}}_i = \mathbf{v}_i, \hat{\mathbf{s}}_i = \mathbf{s} & \text{if } B_i = 0 \\ \hat{A}_i = B_i, \hat{f}_i = \overline{f_i}, \hat{\mathbf{v}}_i = \bar{\mathbf{v}}_i, \hat{\mathbf{s}}_i = \bar{\mathbf{s}} & \text{if } A_i = 0 \end{cases}.$$

$\bar{\mathbf{s}}$ indicates the conjugate of $\mathbf{s}$.

Equation (4) has the same formation as the system equation of a multiple-antenna system with R transmit antennas, one receive antenna, and coherence interval T. Therefore, without decoding, the relays generate a space-time codeword S distributively at the receiver. H is the equivalent channel and W is the equivalent noise. It has been proved that W is a circularly symmetric Gaussian random vector. Its mean and covariance can be calculated to be 0_{T1} and $\left(1 + \frac{P_2}{P_1+1}\sum_{i=1}^R |g_i|^2\right) I_T$, where I_m is the $m \times m$ identity matrix.

If H is known at the receiver, the ML decoding is proved to be

$$\arg\min_{\mathbf{s}} \left\| X - \sqrt{\frac{P_1 P_2 T}{P_1+1}} S H \right\|,$$

[1] Distributed space-time coding has been generalized to networks with multiple-antenna nodes in [18]. Using the same techniques, we can easily generalize out differential scheme proposed in this paper to networks with multiple-antenna nodes as well.

where $\|\cdot\|$ indicates the Frobenius norm. If the total power per symbol transmission used in the whole network is fixed as P, the optimal power allocation that maximizes the expected receive SNR is

$$P_1 = \frac{P}{2} \text{ and } P_2 = \frac{P}{2R}. \tag{8}$$

It is also proved in [17] that when the transmit power P is very high ($\log P \gg 1$), the pairwise error probability of mistaking one signal vector $\mathbf{s}_k$ by another one $\mathbf{s}_l$, averaged over channel realizations, can be upper bounded by

$$\left(\frac{8R}{T}\right)^R \det{}^{-1}(S_k - S_l)^*(S_k - S_l)\left(\frac{\log P}{P}\right)^R, \tag{9}$$

where

$$S_k = \left[\begin{array}{ccc} \hat{A}_1\hat{\mathbf{s}}_k & \cdots & \hat{A}_R\hat{\mathbf{s}}_k \end{array}\right]$$

and

$$S_l = \left[\begin{array}{ccc} \hat{A}_1\hat{\mathbf{s}}_l & \cdots & \hat{A}_R\hat{\mathbf{s}}_l \end{array}\right].$$

S_k and S_l are the distributed space-time codewords corresponding to the information symbols $\mathbf{s}_k$ and $\mathbf{s}_l$. Thus, the diversity of distributed space-time coding in networks with R relays is $\min\{T,R\}\left(1 - \frac{\log\log P}{\log P}\right)$. When $P \to \infty$, distributed space-time coding achieves the maximal diversity $\min\{T,R\}$.

A. Using Alamouti Design in Two-Relay Networks

As an example, we explain the use of Alamouti's orthogonal design in networks with two relays in this subsection. We need the coherence interval to be two. The matrices used at the relays are designed as

$$A_1 = \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array}\right], B_1 = 0, A_2 = 0, B_2 = \left[\begin{array}{cc} 0 & -1 \\ 1 & 0 \end{array}\right]. \tag{10}$$

During the first step, which is composed of two channel uses, the transmitter randomly chooses a information vector $\mathbf{s} = \left[\begin{array}{cc} s_1 & s_2 \end{array}\right]^t$ and transmits it. The two relays receive

$$\mathbf{r}_1 = \left[\begin{array}{c} r_{1,1} \\ r_{1,2} \end{array}\right] \text{ and } \mathbf{r}_2 = \left[\begin{array}{c} r_{2,1} \\ r_{2,2} \end{array}\right],$$

respectively. During the second step, which also has two channel uses, the first relay sends

$$\mathbf{t}_1 = A_1\mathbf{r}_1 + B_1\overline{\mathbf{r}_1} = \left[\begin{array}{c} r_{1,1} \\ r_{1,2} \end{array}\right]$$

and the second relay sends

$$\mathbf{t}_2 = A_2\mathbf{r}_2 + B_2\overline{\mathbf{r}_2} = \left[\begin{array}{c} -\overline{r_{2,2}} \\ \overline{r_{2,1}} \end{array}\right].$$

After simple calculation, the receiver gets

$$\begin{aligned} \left[\begin{array}{c} x_1 \\ x_2 \end{array}\right] &= \sqrt{\frac{P_1P_2T}{P_1+1}}\left[\begin{array}{cc} s_1 & -\overline{s_2} \\ s_2 & \overline{s_1} \end{array}\right]\left[\begin{array}{c} f_1g_1 \\ \overline{f_2}g_2 \end{array}\right] \\ &+ \sqrt{\frac{P_2}{P_1+1}}\left(g_1\left[\begin{array}{c} v_{1,1} \\ v_{1,2} \end{array}\right] + g_2\left[\begin{array}{c} -\overline{v_{2,2}} \\ \overline{v_{2,1}} \end{array}\right]\right) + \left[\begin{array}{c} w_1 \\ w_2 \end{array}\right], \end{aligned} \tag{11}$$

where

$$\mathbf{v}_1 = \left[\begin{array}{c} v_{1,1} \\ v_{1,2} \end{array}\right] \text{ and } \mathbf{v}_2 = \left[\begin{array}{c} v_{2,1} \\ v_{2,2} \end{array}\right]$$

are the noises at the two relays respectively and

$$\mathbf{w} = \left[\begin{array}{c} w_1 \\ w_2 \end{array}\right]$$

is the noise at the receiver.

Thus, an Alamouti space-time codeword

$$S = \left[\begin{array}{cc} s_1 & -\overline{s_2} \\ s_2 & \overline{s_1} \end{array}\right]$$

is formed at the receiver. It can be proved that the equivalent noise

$$\sqrt{\frac{P_2}{P_1+1}}\left(g_1\left[\begin{array}{c} v_{1,1} \\ v_{1,2} \end{array}\right] + g_2\left[\begin{array}{c} -\bar{v}_{2,2} \\ \bar{v}_{2,1} \end{array}\right]\right) + \left[\begin{array}{c} w_1 \\ w_2 \end{array}\right]$$

is a circularly symmetric complex Gaussian random vector whose mean and covariance matrix are 0_{T1} and $\left[1 + \frac{P_2}{P_1+1}\left(|g_1|^2 + |g_2|^2\right)\right] I_2$. The ML decoding at the receiver is thus

$$\arg\min_{s_1,s_2}\left\|\left[\begin{array}{c} x_1 \\ x_2 \end{array}\right] - \sqrt{\frac{P_1P_2T}{P_1+1}}\left[\begin{array}{cc} s_1 & -\overline{s_2} \\ s_2 & \overline{s_1} \end{array}\right]\left[\begin{array}{c} f_1g_1 \\ \overline{f_2}g_2 \end{array}\right]\right\|_F^2.$$

Due to the special structure of the distributed space-time codeword S, this decoding is equivalent to

$$\begin{aligned} &\arg\min_{s_1}\left|s_1 - \sqrt{\frac{P_1+1}{P_1P_2T}}\frac{\overline{f_1g_2}x_1 + \overline{f_2}g_2\overline{x_2}}{|f_1g_1|^2 + |f_2g_2|^2}\right|^2 \\ &+ \arg\min_{s_2}\left|s_2 + \sqrt{\frac{P_1+1}{P_1P_2T}}\frac{\overline{f_2}g_2\overline{x_1} + \overline{f_1g_1}x_2}{|f_1g_1|^2 + |f_2g_2|^2}\right|^2 \end{aligned}$$

The decoding complexity at the receiver is linear since the two information symbols are decoupled.

III. A Differential Scheme for Two-Relay Networks Using Alamouti Design

It can be seen that the distributed space-time coding scheme in Section II needs channel information f_i and g_i at the receiver. Therefore, training has to be done before data transmission. However, in some situations, training is not desired in networks because it takes extra time and power. For some systems, training is not even practical because of the mobility of the users or surrounding objects. Compared to multiple-antenna systems, these issues are even more prominent in sensor networks, whose size is generally large and total transmit power is often limited. Therefore, a differential transmission scheme with channel information at neither relays nor the receiver is very useful.

In this section, we propose a differential transmission scheme for wireless networks with two relays and no channel information at either the relays or the receiver. The scheme is based on distributed coherent Alamouti space-time coding described in Section II-A. In the protocol described in Section II-A, we call the transmission of two symbols a block. Therefore, a block actually contains four channel uses: two channel uses for each step. The same as differential unitary space-time coding for multiple-antenna systems [25]–[27], our differential scheme uses two blocks that overlap by one block. One block acts as a reference for the next.

For generality, we consider the $(\tau-1)$th block and the τth block. During the $(\tau-1)$th block,

$$\mathbf{s}^{(\tau-1)} = \begin{bmatrix} s_1^{(\tau-1)} \\ s_2^{(\tau-1)} \end{bmatrix}$$

is sent by the transmitter. From (4) or (11), the received signal can be written as

$$\begin{aligned}&\mathbf{x}^{(\tau-1)} \\ &= \sqrt{\frac{P_1P_2T}{P_1+1}}\left[\, A_1\mathbf{s}^{(\tau-1)} \;\; B_2\overline{\mathbf{s}^{(\tau-1)}}\,\right] H^{(\tau-1)} + W^{(\tau-1)}.\end{aligned}$$

The equivalent channel, $H^{(\tau-1)}$, and noise matrix, $W^{(\tau-1)}$, can be obtained from (6) and (7).

We encode the message to be transmitted to the receiver into unitary matrices with Alamouti structure, that is, the data set is

$$\mathcal{U} = \left\{ \frac{1}{\sqrt{|u_1|^2+|u_2|^2}} \begin{bmatrix} u_1 & -\overline{u_2} \\ u_2 & \overline{u_1} \end{bmatrix} | u_1 \in \mathcal{F}_1, u_2 \in \mathcal{F}_2 \right\}, \tag{12}$$

where $\mathcal{F}_1$ and $\mathcal{F}_2$ are some finite sets, for example, the PSK or QAM modulations.

During block τ, to transmit the message $U^{(\tau)} \in \mathcal{U}$, the signal vector sent by the transmitter is encoded differentially as

$$\mathbf{s}^{(\tau)} = \sqrt{P_1T}U^{(\tau)}\mathbf{s}^{(\tau-1)}. \tag{13}$$

Since $U^{(\tau)}$ is unitary, $\mathbf{s}^{(\tau)}$ satisfies the normalization (1). The received signal at the τth block can be written as

$$\begin{aligned}&\mathbf{x}^{(\tau)} \\ &= \sqrt{\frac{P_1P_2T}{P_1+1}}\left[\, A_1\mathbf{s}^{(\tau)} \;\; B_2\overline{\mathbf{s}^{(\tau)}}\,\right] H^{(\tau)} + W^{(\tau)} \\ &= \sqrt{\frac{P_1P_2T}{P_1+1}}\left[\, A_1U^{(\tau)}\mathbf{s}^{(\tau-1)} \;\; B_2\overline{U^{(\tau)}\mathbf{s}^{(\tau-1)}}\,\right] H^{(\tau)} + W^{(\tau)}.\end{aligned}$$

Proposition 1: For any $U \in \mathcal{U}$, that is defined in (12), and A_1, B_2, that are defined in (10), we have

$$A_1U = UA_1 \quad \text{and} \quad B_2\overline{U} = UB_2.$$

Proof: Since A_1 is the identity matrix, $A_1U = UA_1$ for any 2×2 matrix. The second part of the proposition, $B_2\overline{U} = UB_2$ can be proved by direct matrix multiplication. ∎

Therefore, we have

$$\begin{aligned}&\mathbf{x}^{(\tau)} \\ &= \sqrt{\frac{P_1P_2T}{P_1+1}}U^{(\tau)}\left[\, A_1\mathbf{s}^{(\tau-1)} \;\; B_2\overline{\mathbf{s}^{(\tau-1)}}\,\right] H^{(\tau)} + W^{(\tau)} \\ &= \sqrt{\frac{P_1P_2T}{P_1+1}}U^{(\tau)}S^{(\tau-1)}H^{(\tau)} + W^{(\tau)}.\end{aligned}$$

If the channels f_i and g_i keep invariant for two blocks of transmissions, i.e. $H^{(\tau)} = H^{(\tau-1)}$, we have

$$\begin{aligned}\mathbf{x}^{(\tau)} &= U^{(\tau)}\left(\mathbf{x}^{(\tau-1)} - W^{(\tau-1)}\right) + W^{\tau} \\ &= U^{(\tau)}\mathbf{x}^{(\tau-1)} + W^{\tau'},\end{aligned} \tag{14}$$

where

$$W^{\tau'} = W^{\tau} - U^{(\tau)}W^{(\tau-1)}.$$

Since W^{τ} and $W^{\tau-1}$ are independent Gaussian vectors with mean zero and covariance $\left[1+\frac{P_2}{P_1+1}\left(|g_1|^2+|g_2|^2\right)\right]I_2$ and $U^{(\tau)}$ is unitary, $W^{\tau'}$ is also a Gaussian vector with mean zero but covariance $2\left[1+\frac{P_2}{P_1+1}\left(|g_1|^2+|g_2|^2\right)\right]I_2$. Therefore, we can decode the message $U^{(\tau)}$ using the following ML decoding:

$$\arg\max_{u_1,u_2} \left\|\mathbf{x}^{(\tau)} - U^{(\tau)}\mathbf{x}^{(\tau-1)}\right\|_F^2,$$

which is equivalent to

$$\begin{aligned}&\arg\min_{u_1}\left|u_1 - \frac{\overline{x_1^{(\tau-1)}}x_1^{(\tau)} + x_2^{(\tau-1)}\overline{x_2^{(\tau)}}}{\left|x_1^{(\tau-1)}\right|^2 + \left|x_2^{(\tau-1)}\right|^2}\right|^2 \\ &+ \arg\min_{u_2}\left|u_2 + \frac{\overline{x_2^{(\tau-1)}}x_1^{(\tau)} + \overline{x_1^{(\tau-1)}}x_2^{(\tau)}}{\left|x_1^{(\tau-1)}\right|^2 + \left|x_2^{(\tau-1)}\right|^2}\right|^2.\end{aligned}$$

This decoding does not need any channel information. The same as the decoding of distributed coherent space-time coding, because of the special structure of $U^{(\tau)}$, the information symbols u_1 and u_2 are decoupled at the receiver. Thus the decoding complexity is linear in the transmission rate and system dimension.

IV. Distributed Differential Space-Time Coding

In this section, we generalize the differential scheme for networks with two relays in the previous section to a general network with R relays. Again, as in distributed coherent space-time coding, we assume that $T = R$ and call the transmission of T symbols a block, which contains $2T$ channel uses: T channel uses for each step. Our differential scheme uses two blocks that overlap by one block. One block acts as a reference for the next.

For generality, we consider the $(\tau-1)$th block and the τth block. From (4), when either $A_i = 0, B_i$ is unitary or $B_i = 0, A_i$ is unitary, the system equation at the $(\tau-1)$th block is

$$\mathbf{x}^{(\tau-1)} = \sqrt{\frac{P_1P_2T}{P_1+1}}S^{(\tau-1)}H^{(\tau-1)} + W^{(\tau-1)},$$

where

$$S^{(\tau-1)} = \left[\, \hat{A}_1\hat{\mathbf{s}}_1^{(\tau-1)} \quad \cdots \quad \hat{A}_R\hat{\mathbf{s}}_R^{(\tau-1)}\,\right].$$

is the distributed space-time codeword of the $(\tau-1)$th block.

The message is encoded as $T\times T$ unitary matrices. The set of possible messages or codewords is denoted as $\mathcal{U}$. During block τ, to transmit message $U^{(\tau)} \in \mathcal{U}$, the signal sent by the transmitter is encoded differentially as

$$\mathbf{s}^{(\tau)} = \sqrt{P_1T}U^{(\tau)}\mathbf{s}^{(\tau-1)}. \tag{15}$$

For the first block, we can transmit any vector with unit-norm. Here, the same as differential space-time coding, having $U^{(\tau)}$ unitary preserves the transmit power.

The system equation of the τth block is

$$\mathbf{x}^{(\tau)} = \sqrt{\frac{P_1P_2T}{P_1+1}}S^{(\tau)}H^{(\tau)} + W^{(\tau)},$$

where

$$S^{(\tau)} = \left[\begin{array}{ccc} \hat{A}_1 \hat{U}^{(\tau)} \hat{\mathbf{s}}_1^{(\tau-1)} & \cdots & \hat{A}_R \hat{U}^{(\tau)} \hat{\mathbf{s}}_R^{(\tau-1)} \end{array} \right]$$

is the distributed space-time codeword of the τth block and

$$\hat{U}^{(\tau)} = \begin{cases} U^{(\tau)} & \text{if } B_i = 0 \\ \overline{U^{(\tau)}} & \text{if } A_i = 0 \end{cases}.$$

If $U^{(\tau)} \hat{A}_i = \hat{A}_i \hat{U}^{(\tau)}$, or equivalently,

$$\begin{cases} U^{(\tau)} A_i = A_i U^{(\tau)} \\ U^{(\tau)} B_i = B_i \overline{U^{(\tau)}} \end{cases}, \tag{16}$$

we have

$$S^{(\tau)} = U^{(\tau)} S^{(\tau-1)}. \tag{17}$$

Assume that f_i and g_i keep constant for two blocks, i.e., $H^{(\tau)} = H^{(\tau-1)}$. The same as in the two-relay case discussed in Section III, from (15), (16), and (17),

$$\mathbf{x}^{(\tau)} = U^{(\tau)} \mathbf{x}^{(\tau-1)} + W^{(\tau)'}, \tag{18}$$

where

$$W^{(\tau)'} = W^{(\tau)} - U^{(\tau)} W^{(\tau-1)}.$$

With fixed g_i during every two consecutive blocks, $W^{(\tau-1)}$ and $W^{(\tau)}$ are independent complex Gaussian random vectors with mean 0 and covariance $\left(1 + \frac{P_2}{P_1+1} \sum_{i=1}^R |g_i|^2\right) I_T$. Thus, $V^{(\tau)}$ is a Gaussian random vector with mean 0 and covariance $2\left(1 + \frac{P_2}{P_1+1} \sum_{i=1}^R |g_i|^2\right) I_T$. The ML decoding of distributed differential space-time coding is

$$\arg\max_U \left\| \mathbf{x}^{(\tau)} - U \mathbf{x}^{(\tau-1)} \right\|.$$

No channel information is required.

Note that although the noise covariance depends on the channel coefficients g_i, since the covariance matrix is a multiple of I_T, entries of $W^{(\tau)'}$ are i.i.d. Gaussian random variables. Therefore, the ML decoding does not depend on the variance of the noises.

The equivalent system equation of the differential scheme in (18) has exactly the same formation as the one of the coherent scheme in (4). But in (18), the covariance of the noises is twice that of the noises in (4). If f_i and g_i are independent Rayleigh distributed, following the analysis in [17], when the total transmit power is very large ($\log P \gg 1$), the pairwise error probability of mistaking one data matrix U_k by another one U_l of the differential scheme can be upper bounded by

$$\left(\frac{16R}{T}\right)^R \det{}^{-1} (U_k - U_l)^* (U_k - U_l) \left(\frac{\log P}{P}\right)^R. \tag{19}$$

Thus, the same diversity, $R\left(1 - \frac{\log\log P}{\log P}\right)$, can be achieved if the data set $\mathcal{U}$ is fully diverse. Comparing (19) to (9), we can see that, the same as differential and coherent space-time coding schemes for multiple-antenna systems [25]–[27], distributed differential space-time coding is 3dB worse than distributed coherent space-time coding.

V. Some Distributed Differential Space-Time Codes

The distributed differential space-time code design problem is thus the design of both the matrices A_i and B_i and the set of data matrices $\mathcal{U}$ such that (16) is satisfied. In this section, we show the differential use of Alamouti [22], square real orthogonal [2], and $Sp(2)$ [23] codes in relay networks. Their simulated performance is also exhibited.

A. Alamouti Code

For networks with two relays, we can use Alamouti code [22], which has full diversity and linear decoding complexity. The details have been presented in Section III. We give a brief summary here.

If we design the matrices used at the two relays as (10) and design the set of codewords as in (12), Condition (16) is satisfied according to Proposition 1. Thus, the distributed differential space-time coding scheme can be used.

An interesting fact is that the distributed space-time codewords formed at the receiver have the same Alamouti structure as the data matrices.

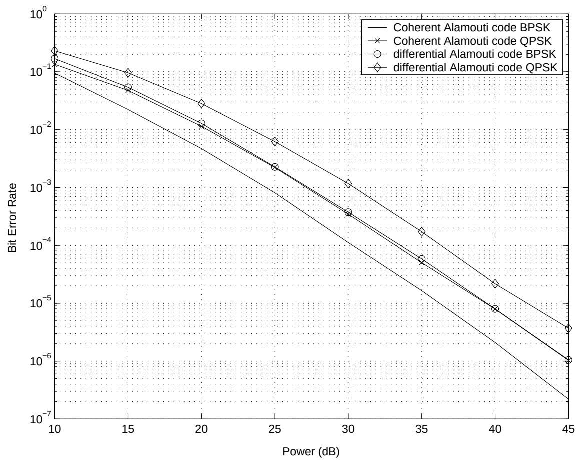

Fig. 2. Performance of two-relay networks.

In Fig. 2, we show the performance of a wireless relay network with two relays using distributed differential Alamouti space-time codes. Information symbols are chosen from BPSK and QPSK. Therefore, the transmission rates are 0.5 and 1 bit per channel use, respectively. We can see that diversity two is achieved at high transmit powers. Compared with the corresponding coherent scheme, the differential scheme is about 3dB worse.

B. Square Real Orthogonal Codes

Square real orthogonal codes were proposed in [2]. They also have full diversity and linear decoding complexity. They only exist for dimensions two, four, and eight. In this subsection, we show how they enable differential transmission in networks with two, four, and eight relays.

Since the constellations are real, we have $B_i = 0$. The A_i matrices are designed as follows. For networks with two relays, let

$$A_1 = I_2 \quad \text{and} \quad A_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}. \tag{20}$$

For networks with four relays, let

$$A_1 = I_4, A_2 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}, A_4 = \begin{bmatrix} 0 & 0 & 0 & -1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}. \tag{21}$$

For networks with eight relays, let

$$A_1 = I_8,$$

$$A_2 = \begin{bmatrix} 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \end{bmatrix},$$

$$A_4 = \begin{bmatrix} 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \end{bmatrix},$$

$$A_5 = \begin{bmatrix} 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_6 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_7 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$A_8 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{22}$$

Proposition 2:

1) A 2×2 matrix commutes with the set $\{A_1, A_2\}$ defined in (20) if and only if it has the following 2×2 square orthogonal structure:

$$\begin{bmatrix} u_1 & -u_2 \\ u_2 & u_1 \end{bmatrix}. \tag{23}$$

2) A 4×4 matrix commutes with the set $\{A_1, A_2, A_3, A_4\}$ defined in (21) if and only if it has the following 4×4 square orthogonal structure:

$$\begin{bmatrix} u_1 & -u_2 & -u_3 & -u_4 \\ u_2 & u_1 & u_4 & -u_3 \\ u_3 & -u_4 & u_1 & u_2 \\ u_4 & u_3 & -u_2 & u_1 \end{bmatrix}. \tag{24}$$

3) An 8×8 matrix commutes with the set $\{A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8\}$ defined in (22) if and only if it has the following 8×8 square orthogonal structure:

$$\begin{bmatrix} u_1 & -u_2 & -u_3 & -u_4 & -u_5 & -u_6 & -u_7 & -u_8 \\ u_2 & u_1 & -u_4 & u_3 & -u_6 & u_5 & u_8 & -u_7 \\ u_3 & u_4 & u_1 & -u_2 & -u_7 & -u_8 & u_5 & u_6 \\ u_4 & -u_3 & u_2 & u_1 & -u_8 & u_7 & -u_6 & u_5 \\ u_5 & u_6 & u_7 & u_8 & u_1 & -u_2 & -u_3 & -u_4 \\ u_6 & -u_5 & u_8 & -u_7 & u_2 & u_1 & u_4 & -u_3 \\ u_7 & -u_8 & -u_5 & u_6 & u_3 & -u_4 & u_1 & u_2 \\ u_8 & u_7 & -u_6 & -u_5 & u_4 & u_3 & -u_2 & u_1 \end{bmatrix}. \tag{25}$$

Proof: It can be proved by direct matrix multiplication. For the conciseness of the paper, we omit the tedious details. ■

Thus, for networks with two, four, and eight relays, we design data matrices to have the square real orthogonal structure in (23), (24), and (25). Note that Proposition 2 does not need the information symbols u_i to be constrained to real constellations. They can be any complex numbers and the proposition still holds. However, for the distributed differential space-time coding scheme to work, the data matrices must be unitary. This demands that u_i must be selected from a real modulation such as PAM. That is, the data matrices must be real orthogonal matrices. Due to this special structure, the information symbols can be decoupled at the receiver. The decoding complexity of square real orthogonal designs is linear.

It is interesting to see that the distributed space-time codewords generated at the receiver have the same square real orthogonal structure as the data matrices.

C. $Sp(2)$ Code

Although square real orthogonal codes are fully diverse and have linear decoding complexity, since the constellations of the information symbols have to be real, half of the degrees of freedom are lost. In this subsection, we discuss the differential use of $Sp(2)$ code in networks with four relays.

$Sp(2)$ code was proposed in [23]. It is a generalization of Alamouti code to dimension four. Its symbol rate is one. The code has the following structure:

$$\mathcal{U} = \left\{ \frac{1}{\sqrt{2}} \begin{bmatrix} V_1 V_2 & V_1 \overline{V_2} \\ -\overline{V_1} V_2 & \overline{V_1 V_2} \end{bmatrix} \right\}, \qquad (26)$$

where, for $i = 1, 2$,

$$V_i = \frac{1}{\sqrt{|a_i|^2 + |b_i|^2}} \begin{bmatrix} a_i & -\overline{b_i} \\ b_i & \overline{a_i} \end{bmatrix}, \qquad (27)$$

and $a_i \in \mathcal{F}_i, b_i \in \mathcal{G}_i$ are information symbols. $\mathcal{F}_i$ and $\mathcal{G}_i$ are finite sets. Choices of $\mathcal{F}_i$ and $\mathcal{G}_i$ are arbitrary and are not constraint to be real. Sufficient and necessary condition for full diversity of $Sp(2)$ code with PSK signals was provided in [23]. If we define

$$\begin{aligned} u_1 &= \frac{a_1 a_2 - b_1 \overline{b_2}}{\sqrt{2} \prod_{i=1}^{2} \sqrt{|a_i|^2 + |b_i|^2}}, \\ u_2 &= -\frac{\overline{a_1} \overline{b_2} + \overline{b_1} a_2}{\sqrt{2} \prod_{i=1}^{2} \sqrt{|a_i|^2 + |b_i|^2}}, \\ u_3 &= -\frac{\overline{a_1} a_2 - \overline{b_1 b_2}}{\sqrt{2} \prod_{i=1}^{2} \sqrt{|a_i|^2 + |b_i|^2}}, \end{aligned}$$

and

$$u_4 = \frac{a_1 \overline{b_2} + b_1 a_2}{\sqrt{2} \prod_{i=1}^{2} \sqrt{|a_i|^2 + |b_i|^2}},$$

from (27), matrices in (26) can be written as:

$$\begin{bmatrix} u_1 & -\overline{u_2} & -\overline{u_3} & u_4 \\ u_2 & \overline{u_1} & -\overline{u_4} & -u_3 \\ u_3 & -\overline{u_4} & \overline{u_1} & -u_2 \\ u_4 & \overline{u_3} & \overline{u_2} & u_1 \end{bmatrix}. \qquad (28)$$

Therefore, $Sp(2)$ code is actually a special kind of quasi-orthogonal space-time block code [28], [29]. However, the main difference between these two codes is that $Sp(2)$ code is unitary due to the special choices of the information symbols u_i.[2] These special choices are obtained from the analysis on the special unitary Lie group $Sp(2)$ [23]. Unitarity is a crucial property for differential transmission.

[2]Note that u_1, u_2, u_3, u_4 are related.

We design the matrices used at the relay as

$$\begin{aligned} A_1 &= I_4, B_1 = 0_4, \\ A_2 &= 0_4, B_2 = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \\ A_3 &= 0, B_3 = \begin{bmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \\ A_4 &= \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}, B_4 = 0. \end{aligned} \qquad (29)$$

Proposition 3: With the design in (29), a matrix U satisfies (16) if and only if it has the quasi-orthogonal structure in (28).

Proof: Again, this proposition can be proved by direct matrix multiplication. For the conciseness of the paper, we omit the tedious details. ■

Therefore, we design the set of data matrices to be a $Sp(2)$ code defined in (26) and (27). They have both quasi-orthogonal structure and unitarity. As shown in [23], decoding of $Sp(2)$ code can be done by a sphere decoder. Because the code has quasi-orthogonal structure as well, the information symbols can also be decoded pairwisely [29].

It is interesting to see that the distributed space-time codewords formed at the receiver also have the quasi-orthogonal structure of (28).

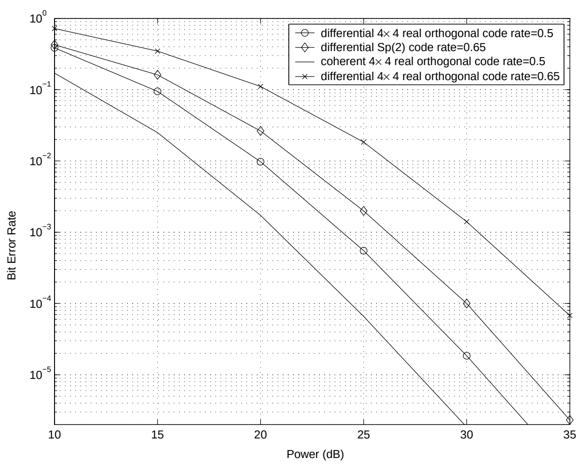

Fig. 3. Performance of 4-relay networks.

In Fig. 3, we show simulated performance of a wireless relay network with four relays using two 4×4 real orthogonal codes and a $Sp(2)$ code. For the first real orthogonal code, u_1, u_2, u_3, u_4 are chosen as BPSK. The bit rate is therefore 0.5. For the second one, u_1, u_2 are chosen as BPSK and u_3, u_4 are chosen as 3-PAM. The bit rate is therefore 0.6462. For the $Sp(2)$ code, a_1, b_1 are chosen as BPSK and a_2, b_2 are chosen as 3-PSK. The bit rate of the network is also 0.6462. We can see from Fig. 3 that all these codes achieve the same diversity, which approaches the maximum diversity four as the transmit power increases. Compared with the coherence code, the rate 0.5 distributed differential real orthogonal space-time code is about 3dB worse. The $Sp(2)$ code is about 4.5dB better than the real orthogonal code at rate 0.6462.

We should mention that similar, but different, differential schemes were proposed in [30] and [31] independently. The schemes in [30] and [31] are special cases of our scheme with $B_i = 0$. For example, the Alamouti and $Sp(2)$ codes cannot be included in [30] and [31].

VI. Conclusion

In this paper, we propose a differential transmission scheme for wireless relay networks using the ideas of distributed space-time coding and differential space-time coding. No channel information is needed at the transmitter, relays, or receiver. With this scheme, Alamouti, square real orthogonal, and $Sp(2)$ codes can be applied in networks with two, four, and eight relays. Both simulation and theoretical analysis show that compared with the corresponding coherent scheme, distributed differential space-time coding performs 3dB worse.

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