Delay–Interleaved Cooperative Relay Networks

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***Abstract*—In this letter, we propose a novel system design for implementing distributed space–time codes (DSTCs) in order to improve the performance of the codes. The proposed method called delay and interleaved cooperative relay networks manages to force transmitted signals to experience different channel fading coefficients as much as possible, which increases the coding gain or even, in some cases, the diversity order of the codes. The only degradation to the conventional system is a small delay that is negligible in many communication applications. There are no extra computational complexities burdened to the relays, and only a simple permutation is performed at the relays and the destination. Simulation results also confirm the performance superiority of this innovative method over the conventional DSTC system.**

***Index Terms*—Cooperative network, distributed space-time coding, half-duplex antenna, quasi-static channels.**

I. INTRODUCTION

SINCE the late 90's, it has been well-known that the use of multiple antennas at the receiver i.e. single-input multiple-output (SIMO) can result in both diversity gain and array gain to the system [1], but merely employing too many transmit antennas at the receiver solely does not have any further effect on the system performance. In [2], space-time block coding (STBC) was introduced which could exploit maximum available spatial diversity at the transmitter by spreading the coding over space and time. Since then, multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) systems have been shown to be the best techniques to combat the channel fading in wireless communications.

Unfortunately, modern portable devices like mobile sets or tablets, cannot take advantage of spatial diversity due to the space limitations [3]. One of the best solutions to this challenging problem is that distributed devices cooperatively associate with each other as a communication system. This idea leads to virtual MIMO systems and introduces cooperative diversity.

Cooperative networks due to their large applications have motivated many researchers to work on new protocols and codes. In [3], efficient cooperation protocols were proposed and the most applicable ones i.e. amplify and forward (AAF) and decode and forward (DAF), were introduced. The outage probability analyses for these protocols were also provided. Furthermore, some code structures have been proposed in literatures in order to achieve the capacity of the channel and cooperative diversity offered in virtual MIMO systems. Linear dispersion distributed space-time block codes (DSTCs) were proposed in [4]. Also DSTCs based on orthogonal and quasi-orthogonal design were proposed in [5]. For the first time, authors in [6] proposed the use of the Golden code for DSTCs, and later in [7], its fast decoding was proposed. In addition, a variety of cooperative diversity algorithms were investigated that achieve the maximum available spatial diversity order also known as cooperative diversity. An example of this is the distributed space-time block coding (DSTBC) that has now been fully developed.

In this paper, a novel delay interleaved scheme is introduced that aims to enhance the performance of DSTCs. The proposed method is based on an acceptable delay and interleave of the received or transmitted vectors in each relay antenna. This technique does not affect the decoding complexity of DSTCs, whilst improving the performance. Also each relay needs very low complexity operations for constructing each column of the DSTC, which is very important in applications. This scheme can be utilized in any type of cooperative networks such as asynchronous cooperative network or cooperative networks with full-duplex relays [9]. Simulation results confirm that the proposed method improves the performance of DSTCs while it does not add complex calculations to relays nodes.

Notations: We use capital boldface letters for matrices, and boldface letters for vectors. Superscripts $(\cdot)^t, \bar{(\cdot)}$, and $(\cdot)^H$ denote transpose, conjugate and complex conjugation, respectively. Notations $\otimes$ stands for Tensor product. $\|.\|$ stands for the Frobenius norm. Notation $diag(a_1, a_2, \ldots, a_n)$ represents a diagonal $n \times n$ matrix whose diagonal entries are $a_1, a_2, \ldots, a_n$ C Stands for the complex field. Also, $\boldsymbol{I}_a$ represents an $a \times a$ identity matrix and e_i is a vector whose components are all zeros except ith element which is one.

II. PRELIMINARIES

Consider a wireless network with $R + 2$ nodes: one transmit antenna, one receive antenna and the remaining R nodes work as relays. Every node has a single half duplex antenna, which cannot transmit and receive at the same time, for both transmission and reception. Note that no direct link between the transmitter and the receiver is considered.

At the receiver, information bits are modulated into groups of K symbols $\boldsymbol{s} = [s_1, \ldots, s_K]^t$ where $E\{\boldsymbol{s}^H \boldsymbol{s}\} = 1$ for normalization purposes. Now, considering the only possible two-hop protocol for half-duplex, first the vector $\sqrt{P_1 T_1}\boldsymbol{s}$ is sent to the relays within T_1 intervals where P_1 is the average power per transmission at the transmitter. Then the relays work as a distributive multi-antenna system and transmit a space-time-block code to the receiver during T_2 time slots. Note that since in the first hop each symbol is transmitted during one time slot the ratio $\frac{T_1}{T_2}$ is equal to the rate of the STBC used in the relays. Given that $T = T_1 + T_2$, it is clear that the overall symbol rate of the system which is equal to $\frac{K}{T}$ is always less than one. It is

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worth mentioning that the transmitter and the receiver, which in this paper are assumed to be equipped with only one antenna, in general can have multiple antennas.

The received vector at the ith relay for $i = 1, 2, \ldots, K$ can be formulated as:

$$\boldsymbol{r}^i = \sqrt{\frac{P_1}{T_1}} \boldsymbol{F}^i \boldsymbol{s} + \boldsymbol{z}^i, \tag{1}$$

where $\boldsymbol{z}^i \in C^{T_1 \times 1}$ is the additive white Gaussian noise (AWGN) vector and $\boldsymbol{F}^i \in C^{T_1 \times T_1}$ which is known as channel fading matrix (CFM) from the transmitter to the ith relay is:

$$\boldsymbol{F}^i = diag\left(f_1^i, f_2^i, \ldots, f_{T_1}^i\right), \tag{2}$$

In (2), f_l^i is the fading coefficient between source and the ith relay during the l_{th} time period for $l = 1, 2, \ldots, T_1$. Channel fading coefficients (FCs) are assumed to be i.i.d. zero-mean and unit-variance complex Gaussian and also independent in time and space from each other and random variable. It should be carefully noted that in quasi-static or mild-fast channels for a specific duration FCs are correlated, stated more precisely each τ_1 number of FCs are exactly similar. τ_1 is related to the coherent time interval, which itself is determined by the maximum Doppler frequency shift f_{s1} (in Hertz) with the following approximation:

$$\tau_1 = \frac{9}{16\pi f_{s1} T_S}, \tag{3}$$

where T_S is the duration of transmitting a symbol (in seconds) [8]. There is no need to express that Doppler frequency shift is one of the channels characteristics. To the best of our knowledge almost all of the STBCs and DSTBCs are designed for quasi-static channels, hence in this paper we also focus on this scenario. Keeping the above assumptions in mind we can rewrite (2) as:

$$\boldsymbol{F}^i = diag\left(f_1^i, f_1^i, \ldots, f_1^i, f_2^i, f_2^i, \ldots, f_2^i, f_{\frac{T_1}{\tau_1}}^i \ldots, f_{\frac{T_1}{\tau_1}}^i\right) \in C^{T_1 \times T_1}. \tag{4}$$

Up to here, r^i vectors are available at the relays, at this step the distributed coding is constructed. In a DSTBC system the transmitted signal from each relay is calculated from:

$$\boldsymbol{t}^i = \sqrt{\frac{P_2 T_2}{(P_1 + 1) T_1}} (\boldsymbol{A}^i \boldsymbol{r}^i + \boldsymbol{B}^i \bar{\boldsymbol{r}}^i) \in C^{T_2 \times 1} \tag{5}$$

for $i = 1, 2, \ldots, K$, where $\boldsymbol{A}^i$ and $\boldsymbol{B}^i$ are $T_2 \times T_1$ unitary matrices constructing the code structure of DSTBC and P_2 is the average power per transmission at each relay. It should be noted that the total transition power is considered as $P = P_1 + P_2$ and the optimum power allocation for P_1 and P_2 is calculated in [4] as: $P_1 = \frac{P}{2}$ and $P_2 = \frac{P}{2R}$.

Having the structure of STBCs in mind, (5) has actually the formulation of the ith column of an STBC, which is indeed the main idea of DSTBCs.

Finally, the received vector at the destination can be written as:

$$\boldsymbol{x} = \sum_{i=1}^{R} \boldsymbol{G}^i \boldsymbol{t}^i + \boldsymbol{w} \in C^{T_2 \times 1}, \tag{6}$$

where $\boldsymbol{w} \in C^{T_2} \times 1$ is the AWGN vector and $\boldsymbol{G}^i$ is the CFM from the ith relay to the destination. In general, all the explanations presented for $\boldsymbol{F}^i$ are also valid for $\boldsymbol{G}^i$ except for maximum Doppler frequency shift due to the channel characteristics which might be different. Therefore, considering the maximum Doppler frequency shift of the second hop as f_{s2}, we have: $\tau_2 = \frac{9}{16\pi f_{s2} T_S}$ and:

$$\boldsymbol{G}^i = diag\left(g_1^i, g_1^i, \ldots, g_1^i, g_2^i, g_2^i, \ldots, g_2^i, g_{\frac{T_2}{\tau_2}}^i, \ldots, g_{\frac{T_2}{\tau_2}}^i\right) \in C^{T_1 \times T_1}. \tag{7}$$

It is important to notice that the presented system model is a generalized version, for instance if $T_1 \leq \tau_1$ and $T_2 \leq \tau_2$ we obtain the model used in [5], and if also $T_2 = T_1$ we have the model used in [4].

In order to introduce the proposed method it is curtail to have the ordinary DSTBC in mind, therefore here we briefly explain how the conventional DSTBCs works [3]–[7]. For a given DSTBC $\boldsymbol{X}$, the rate of the code is $\frac{K_X}{T_X}$, vector s of size K_X is transmitted to the relays for $T_{1X} \leq \tau_1$. Distributed space time coding is then applied using $T_{2X} \times T_{1X}$ matrices $\boldsymbol{A}_X^i$ and $\boldsymbol{B}_X^i$ as in (5) where $T_{2X} \leq \tau_2$. One should notice that in this case $\boldsymbol{F}^i = f^i \boldsymbol{I}_{T_{1X}}$ and $\boldsymbol{G}^i = g^i \boldsymbol{I}_{T_{2X}}$.

III. Proposed DICRN Method

In this section, the proposed method i.e. the delay interleaved cooperative relay networks (DICRN) is investigated in detail.

Any DSTBC can be implemented with DICRN system and this leads to a significant performance improvement with the only expense of a paltry delay which is determined by the channel characteristics and because it is usually exceptionally short it is acceptable for many communication protocols.

The main goal of our proposed method is to force transmitted signals to undergo different FCs as much as possible because this phenomena can increase coding advantage and in some cases even diversity order of the codes [8]. The FCs of transmitter to relays and relays to destination do not change during τ_1 and τ_2 time slots respectively. Therefore, for the sake of the least possible delay in the proposed system we introduce two methods for DICRN.

For a given DSTBC $\boldsymbol{X}$, with the following characteristics: $K_X, T_{1X}, T_{2X}, \boldsymbol{A}_X^i$ and $\boldsymbol{B}_X^i$, the two methods of DICRN are investigated as follows.

A. First Method—DICRN—$\tau_1 > \tau_2$

If $\tau_1 < \tau_2$:

Symbol vector $\boldsymbol{s}$ of size MK_X, is transmitted through R independent channels in $T_1 = MT_{1X}$ timeslots to R distributed relays where M is an adaptive parameter determining the delay of the system and must only satisfy the condition $M \geq \tau_1$. The symbol vectors $\boldsymbol{r}^i$ are received at each of the relays (1). Now, first we define a permuted version of $\boldsymbol{r}^i$ as:

$$\widetilde{\boldsymbol{r}}^i = \boldsymbol{P}_1 \boldsymbol{r}^i, \tag{8}$$

where,

$$\boldsymbol{P}_1 = \left[\boldsymbol{U}_1^t \boldsymbol{U}_2^t \boldsymbol{U}_3^t \ldots \boldsymbol{U}_M^t\right]^t \tag{9}$$

and

$$\boldsymbol{U}_t = \left[\boldsymbol{e}^t_{t}\boldsymbol{e}^t_{M+t}\ \boldsymbol{e}^t_{2M+t}\ \ldots \boldsymbol{e}^t_{K_X-1M+t}\right]^t, \quad t = 1, 2, 3, \ldots, M. \tag{10}$$

Now, it suffices to determine the structure of $\boldsymbol{A}^i$ and $\boldsymbol{B}^i$:

$$\boldsymbol{A}^i = \boldsymbol{A}^i_X \otimes \boldsymbol{I}_M, \boldsymbol{B}^i = \boldsymbol{B}^i_X \otimes \boldsymbol{I}_M. \tag{11}$$

Then during $T_2 = MT_{2X}$ timeslots, R relays simultaneously transmit $\boldsymbol{t}^i$ to the destination. At the destination, the vector $\boldsymbol{x} \in C^{MT_{2X}1}$ is received as in (6). Since the matrices $\boldsymbol{F}^i$ and $\boldsymbol{G}^i$ are assumed to be estimated, the maximum-likelihood (ML) decoder can be easily used. It is important to notice that the complexity of the decoder is not increased.

Although the received vector consists of M different DSTBCs, they can be separately decoded. Each successive T_{2X} rows of $\boldsymbol{x}$ are in accordance to one DSTBC block of $\boldsymbol{X}$. Decoding K_X symbols from each T_{2X} rows of x and concatenating them we obtain vector $\widetilde{\boldsymbol{s}}$. Now, using the same permutation as (8) the decoded symbol vector $\hat{\boldsymbol{s}}$ is:

$$\hat{\boldsymbol{s}} = \boldsymbol{P}_1\widetilde{\boldsymbol{s}}. \tag{12}$$

B. Second Method—DICRN—$\tau_1 > \tau_2$

If $\tau_1 > \tau_2$:

At the transmitter nothing is changed from the first method except for the parameter M which must now satisfy $M \geq \tau_2$. The received vectors at each relay are then used to construct t_i using (5) and (10). In this scenario the permutation is applied to the t_i vectors as:

$$\widetilde{\boldsymbol{t}}_i = \boldsymbol{P}_2\boldsymbol{t}_i \tag{13}$$

where

$$\boldsymbol{P}_2 = \left[\boldsymbol{U}^t_1\boldsymbol{U}^t_2\boldsymbol{U}^t_3 \ldots \boldsymbol{U}^t_{T_{2X}}\right]^t \tag{14}$$

and

$$\boldsymbol{U}_t = \left[\boldsymbol{e}^t_{t}\boldsymbol{e}^t_{T_{2X}+t}\ \boldsymbol{e}^t_{2T_{2X}+t}\ \ldots \boldsymbol{e}^t_{M-1T_{2X}+t}\right]^t \tag{15}$$

for $t = 1, 2, 3, \ldots, T_{2X}$.

Then, the vectors $\widetilde{\boldsymbol{t}}_i$ are transmitted simultaneously during $T_2 = MT_{2X}$ timeslots from R relays.

At the destination, using (6) the received vector can be formulated as: $\boldsymbol{x} = \sum_{i=1}^{R} \boldsymbol{G}^i\widetilde{\boldsymbol{t}}_i + \boldsymbol{w} \in C^{T_2\times 1}$. Here, in order to make it possible to decode each of M blocks of DSTBC separately we need to perform the same permutation as (14):

$$\widetilde{\boldsymbol{x}} = \boldsymbol{P}_2\boldsymbol{x}. \tag{16}$$

Now each successive T_{2X} rows of $\widetilde{\boldsymbol{x}}$ are distinct DSTBCs which can be easily decoded using the ML decoder of the given DSTBC.

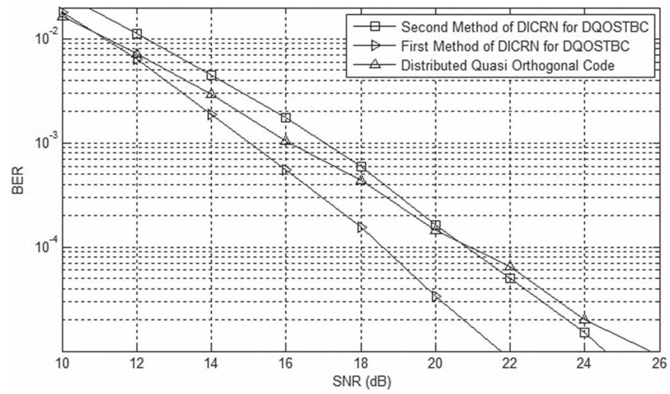

Fig. 1. BER vs. SNR for slow frequency non-selective channel with 4 relays; BPSK modulation.

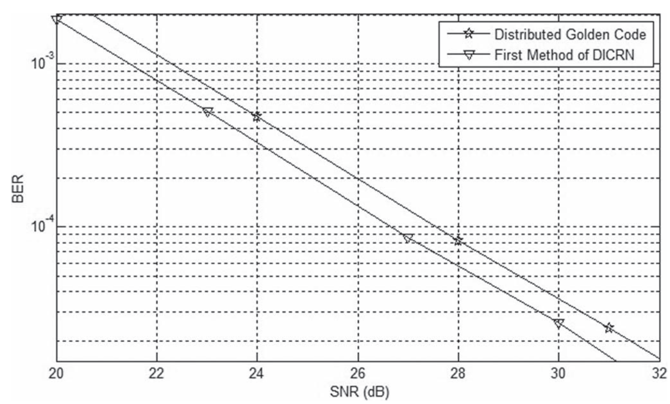

Fig. 2. BER vs. SNR for slow frequency non-selective channel with 2 relays; BPSK modulation.

IV. Simulation Results

In this section, simulation results for conventional DSTBC and DICRN is presented. In the simulations we ran, a cooperative network with one transmitter antenna and one receiver antenna was considered and the number of active relays depended on the chosen DSTBC. Also, without loss of generality, in order to evaluate the proposed method regardless of the channel characteristics M is chosen randomly for all the simulation operations. We evaluated the performances of the two proposed methods by plotting average bit-error-rate (BER) versus average signal-to-noise-ratio (SNR). Although we have indicated the total power of P, SNR is used for the horizontal axis instead of the total power of P due to the prevalent use of SNR. We applied the proposed methods to the distributed quasi-orthogonal space-time code (DQOSTC) [5] and distributed Golden code (DGC) [6], and compared the performances of our methods against those of the ordinary DQOSTC and DGC. Also, it is clear that the number of active relays for the DQOSTC and DGC are equal to four and two, respectively. As illustrated in Figs. 1 and 2 the proposed methods improves the performances of both the DQOSTC and the DGC. For instance, at $BER = 10^{-5}$, the proposed methods achieve more than 3.5 dB and up to 2 dB gains over the DQOSTC. Also, from Fig. 2, it is easy to see a gain of 1 dB for the first proposed method against the DGC. Finally, in [10] and [11] a complete series of simulation results are presented for different DSTBCs.

V. Conclusion

In this paper, we presented a novel delay interleaved cooperative relay network method which could be used to implement all of the existing DSTBCs resulting in an improvement in the coding gain and diversity order of the codes which enhances the system efficiency. The proposed method only adds a paltry delay to the system which is negligible in many applications.

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