

OFDM-Based STBC with Low End-to-End Delay for Full-Duplex Asynchronous Cooperative Systems

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We propose a new space-time block coding (STBC) for asynchronous cooperative systems in full-duplex mode. The orthogonal frequency division multiplexing (OFDM) transmission technique is used to combat the timing errors from the relay nodes. At the relay nodes, only one OFDM time slot is required to delay for a pair-wise symbol swap operation. The decoding complexity is lower for this new STBC than for the traditional quasi-orthogonal STBC. Simulation results show that the proposed scheme achieves excellent performances.

Keywords: Space-time block coding (STBC), asynchronous cooperative, orthogonal frequency division multiplexing (OFDM), full-duplex, decoding complexity.

I. Introduction

The concept of relay network coding in a fading environment was proposed in [1], [2] to transmit information via multiple relay nodes instead of sending it directly, which can increase the capacity and reliability of a wireless network. Various relaying protocols have been proposed for relaying channels and operations. Among these, full-duplex cooperation is a spectrally efficient approach since it allows simultaneous transmission and reception on the same frequency [3]. However, different relay nodes have different oscillators and locations in asynchronous cooperative networks, the transmitted signals from different relay nodes may have different timing errors. This may cause difficulties in

recovering data at the destination node. To overcome this problem, the orthogonal frequency division multiplexing (OFDM) technique is applied. In [4], a simple Alamouti space-time block coding (STBC) transmission was implemented in the frequency domain by using time-reversion and complex conjugate methods. In [5], the OFDM-based STBC was studied for asynchronous relay networks. However, most previous works have only taken the half-duplex mode into account.

In general, full-duplex relay nodes must stack all the received OFDM symbols in terms of an STBC word before it processes and broadcasts, leading to a delay from the source node to the destination node. In this letter, we extend the Alamouti STBC transmission scheme to the case of four relay nodes in full-duplex mode and propose a new STBC transmission scheme with low end-to-end delay. This STBC, which is constructed based on the cyclotomic number theory [6], is practically a quasi-orthogonal STBC (QOSTBC). The maximum likelihood (ML) detection metrics of the STBC are simpler than that of the conventional QOSTBCs, resulting in lower decoding complexity. We emphasize that the reduction in both end-to-end delay and decoding complexity is not achieved at the expense of performance.

II. System Model

Consider that a relaying system wants to transmit information from a single-antenna source node to a single-antenna destination node through four relay nodes R_i , $i=1, \dots, 4$, as illustrated in Fig. 1. The relay nodes work in full-duplex mode. Every relay node is equipped with two antennas: one for reception and the other for simultaneous transmission. Thus, every relay node has a loop channel between the two antennas.

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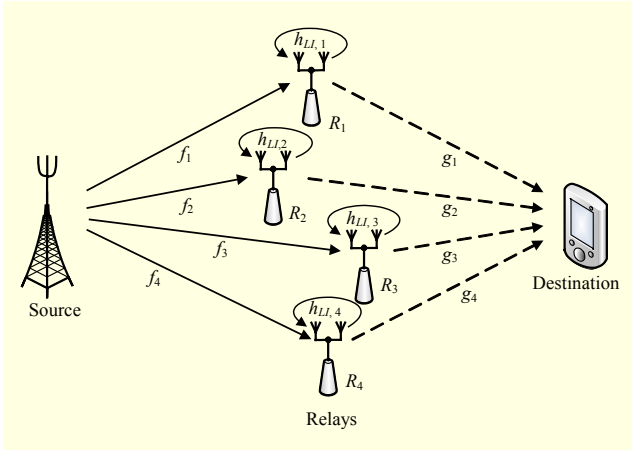


Fig. 1. Asynchronous cooperative system model.

The direct transmission link from source node to destination node is not considered. Assume the channels between the two terminal nodes and relay nodes are quasi-static flat Rayleigh fading. Denote the loop channel coefficient as $h_{LL,i}$ at the i -th relay node, the fading coefficient from the source node to the i -th relay nodes as f_i , and the fading coefficient from the i -th relay node to the destination node as g_i . These coefficients are assumed to be independent complex Gaussian random variables with zero mean and unit variance.

To combat the timing errors, we use the OFDM technique. The number of subcarriers is N . The knowledge of timing errors is assumed to be known at the destination node. The transmission delay of the signals from the i -th relay node is τ_i , which is a multiple of T_s , where T_s denotes the information symbol duration. The OFDM symbol blocks are denoted by $\mathbf{x}_j = [x_{j1}, x_{j2}, \dots, x_{jN}]^T$, $j = 1, \dots, 4$.

After an N -point inverse fast Fourier transform (IFFT) operation, each block is preceded by a cyclic prefix (CP) with length δ_{cp} . Due to the timing errors, the CP length δ_{cp} must be larger than the maximum delay $\max_i\{\tau_i\}$. Then, the corresponding OFDM symbols \bar{X}_j of length $N + \delta_{cp}$ are broadcasted to the relay nodes. In the j -th OFDM symbol duration, the received mixed signal $r_{i,j}$ at the i -th relay node and \bar{r}_j at the destination node are given respectively by

$$r_{i,j} = \sqrt{P_1} \bar{X}_j f_i + h_{LL,i} t_{i,j} + n_{i,j} \quad (1)$$

and

$$\bar{r}_j = \sqrt{\frac{P_2}{P_1+1}} \sum_{i=1}^4 [(t_{i,j} * \Gamma_i) g_i] + v_j, \quad (2)$$

where the elements are denoted as follows: $*$ is the circular convolution; $t_{i,j}$ is the symbol transmitted from the i -th relay node; Γ_i represents the timing errors, defined as the N -point vector whose (τ_i+1) th element is one and the others are zero;

$n_{i,j}$ and v_j are both additive white Gaussian noise with zero mean and unit variance at the i -th relay node and at the destination node, respectively, in the j -th OFDM symbol duration; P_1 and P_2 represent the transmit power at the source node and relay node, respectively. The total number of shifted samples is denoted by τ_i . Using the optimal power allocation strategy proposed in [1], we have $P_2 = P_1/4$ and obtain an optimal performance from the cooperative system.

We make the assumption that full loop channel information is available at the relay nodes such that the loop interference is perfectly canceled out. Thus, the signal from the source node can easily be estimated as

$$y_{i,j} = r_{i,j} - h_{LL,i} t_{i,j} = \sqrt{P_1} \bar{X}_j f_i + n_{i,j}. \quad (3)$$

As a result, the existing schemes for the half-duplex mode can be extended to the full-duplex mode.

III. Construction of STBC for Full-Duplex Cooperation

STBC is an effective approach to achieve full diversity in cooperative systems. It can improve the reliability of data transmission at the expense of extra consumption of time slots. In this section, we construct an STBC that has lower end-to-end delay and decoding complexity, without degrading performance. Assume $\mathbf{s}_j = [s_{j1}, s_{j2}, \dots, s_{jN}]^T$ ($j=1, \dots, 4$) are the independent complex "base" symbols drawn from a quadrature amplitude modulation (QAM) constellation. Then, the transmitted symbols $\mathbf{x}_j = [x_{j1}, x_{j2}, \dots, x_{jN}]^T$ ($j=1, \dots, 4$) are generated by $[x_{1,k}, x_{3,k}]^T = M[s_{1,k}, s_{3,k}]^T$ and $[x_{2,k}, x_{4,k}]^T = M[s_{2,k}, s_{4,k}]^T$ ($k=1, 2, \dots, N$), with M denoting the multidimensional signal constellation matrix of 2×2 . Matrix M is a Vandermonde matrix constructed based on the algebraic number theory; for more details, refer to [6]. In the case of our scheme, the 2×2 rotation matrix is given by

$$M = \frac{\sqrt{2}}{2} \begin{bmatrix} 1 & e^{i\pi/4} \\ 1 & e^{5i\pi/4} \end{bmatrix}. \quad (4)$$

The four relay nodes perform signal processing on the received noisy signals, and the transmitted symbols $t_{i,j}$ ($1 \leq i, j \leq 4$) are given by

$$\begin{bmatrix} t_{1,1} & t_{1,2} & t_{1,3} & t_{1,4} \\ t_{2,1} & t_{2,2} & t_{2,3} & t_{2,4} \\ t_{3,1} & t_{3,2} & t_{3,3} & t_{3,4} \\ t_{4,1} & t_{4,2} & t_{4,3} & t_{4,4} \end{bmatrix} = \begin{bmatrix} y_{1,1} & -\zeta(y_{1,2}^*) & y_{1,3} & -\zeta(y_{1,4}^*) \\ y_{2,2} & \zeta(y_{2,1}^*) & y_{2,4} & \zeta(y_{2,3}^*) \\ y_{3,1} & -\zeta(y_{3,2}^*) & -y_{3,3} & \zeta(y_{3,4}^*) \\ y_{4,2} & \zeta(y_{4,1}^*) & -y_{4,4} & -\zeta(y_{4,3}^*) \end{bmatrix}, \quad (5)$$

where $*$ denotes the complex conjugation and $\zeta(\cdot)$ denotes the time-reversal of the signals, that is, $\zeta(y(0)) = y(0)$ and $\zeta(y(n)) = y(L_s - n)$, $N=1, \dots, L_s-1$. At the second and fourth relay nodes, the two successive OFDM symbols are switched.

Thus, all the relay nodes must stack every two OFDM symbols, inducing one OFDM time slot delay. Compared with the other QOSTBC schemes, such as the ABBA code and rotated QOSTBC (RQOSTBC) [2], [7], [8], which must stack all four OFDM symbols, our proposed scheme provides a transmission with much lower end-to-end delay.

We now exploit the received signal at the destination node after removing the CP. Since the time-reversal versions of the information symbols at the second and fourth relay nodes are required, we must shift the last δ_{cp} samples of the N -point vector as the first δ_{cp} samples for the second and fourth OFDM symbols. Length δ_{cp} is long enough to maintain the orthogonality between the subcarriers. Then, the symbols are fed to the OFDM demodulator with N -point FFT and transformed to $z_j = [z_{j,0}, z_{j,1}, \dots, z_{j,N-1}]^T, j=1, \dots, 4$ in the time domain. Since the FFT operation has the property that $FFT(\zeta(FFT(x))) = IFFT(FFT(x))$ and $(IFFT(x))^* = FFT(x^*)$, we can easily find the STBC structure on each subcarrier $k, 0 \leq k \leq N-1$ according to (6).

$$\underbrace{\begin{bmatrix} z_{1,k} \\ z_{2,k} \\ z_{3,k} \\ z_{4,k} \end{bmatrix}}_Z = \lambda \underbrace{\begin{bmatrix} x_{1,k} & x_{2,k} & x_{1,k} & x_{2,k} \\ -x_{2,k}^* & x_{1,k}^* & -x_{2,k}^* & x_{1,k}^* \\ x_{3,k} & x_{4,k} & -x_{3,k} & -x_{4,k} \\ -x_{4,k}^* & x_{3,k}^* & x_{4,k}^* & -x_{3,k}^* \end{bmatrix}}_X \underbrace{\begin{bmatrix} \mathbf{f}_k^{\tau_1} f_1 g_1 \\ \mathbf{f}_k^{\tau_2} f_2 g_2 \\ \mathbf{f}_k^{\tau_3} f_3 g_3 \\ \mathbf{f}_k^{\tau_4} f_4 g_4 \end{bmatrix}}_H + \underbrace{\frac{\lambda}{\sqrt{P_1}} \begin{bmatrix} N_{1,1,k} & N_{2,2,k} & N_{3,1,k} & N_{4,2,k} \\ -N_{1,2,k}^* & N_{2,1,k}^* & -N_{3,2,k}^* & N_{4,1,k}^* \\ N_{1,3,k} & N_{2,4,k} & -N_{3,3,k} & -N_{4,4,k} \\ -N_{1,4,k}^* & N_{2,3,k}^* & N_{3,4,k}^* & -N_{4,3,k}^* \end{bmatrix}}_W \underbrace{\begin{bmatrix} \mathbf{f}_k^{\tau_1} f_1 \\ \mathbf{f}_k^{\tau_2} f_2 \\ \mathbf{f}_k^{\tau_3} f_3 \\ \mathbf{f}_k^{\tau_4} f_4 \end{bmatrix}}_H + \underbrace{\begin{bmatrix} V_{1,k} \\ V_{2,k} \\ V_{3,k} \\ V_{4,k} \end{bmatrix}}_V. \quad (6)$$

The components of (6) are denoted as follows: $\lambda = \sqrt{P_1 P_2 / (P_1 + 1)}$; $N_{i,j,k}$, \mathbf{f}_k , and $V_{i,k}$ are the k -th elements of $N_{i,j}$, \mathbf{f} , and V_i , respectively; $N_{i,j} = FFT(n_{i,j})$; $V_i = FFT(v_{i,j})$; $\mathbf{f} = [1, e^{-2\pi\sqrt{-1}/N}, \dots, e^{-2\pi\sqrt{-1}(N-1)/N}]^T$; and \mathbf{f}^{τ_i} represents the phase change in the frequency domain corresponding to the delay of τ_i sample in the time domain. Remarkably, the pairwise symbol ML decoding can be applied to the system.

IV. Decoding

QOSTBC relaxes the orthogonality constraint and achieves full rate and full spatial diversity, at the expense of a considerable additional decoding complexity. In this section, we focus on reducing the decoding complexity. Though joint ML detection of two symbols is required for our scheme, the ML metrics are simplified. We rewrite (6) as

$$Z = \lambda XH + W, \quad (7)$$

where Z , H , X , and W are the corresponding terms of (6). For simplicity, we assume that $Z = [z_1, z_2, z_3, z_4]^T$, $H = [h_1, h_2, h_3, h_4]^T$, and the STBC code is given by

$$X = \begin{bmatrix} x_1 & x_2 & x_1 & x_2 \\ -x_2^* & x_1^* & -x_2^* & x_1^* \\ x_3 & x_4 & -x_3 & -x_4 \\ -x_4^* & x_3^* & x_4^* & -x_3^* \end{bmatrix}. \quad (8)$$

We assume the destination node knows the channel static information. Then, the optimal decision rule with ML detection is

$$\min_x [\lambda H^H X^H XH - 2Re(Z^H XH)], \quad (9)$$

where $Re(\cdot)$ is the real part of a complex. Due to the quasi-orthogonal structure, it is easy to decompose x into two disjointed groups of symbols $x_1 = [x_1, x_3]^T$ and $x_2 = [x_2, x_4]^T$ for respective independent ML decoding. This method is useful for reducing the complexity of decoding without sacrificing the performance. The two independent ML metrics are calculated as:

$$\min_{(x_1, x_3)} \{ (|\bar{h}_1|^2 + |\bar{h}_2|^2) |x_1|^2 + (|\bar{h}_3|^2 + |\bar{h}_4|^2) |x_3|^2 - 2Re[(\bar{h}_1 z_1^* + \bar{h}_2 z_2^*)x_1 + (\bar{h}_3 z_3^* + \bar{h}_4 z_4^*)x_3] \} \quad (10)$$

and

$$\min_{(x_2, x_4)} \{ (|\bar{h}_1|^2 + |\bar{h}_2|^2) |x_2|^2 + (|\bar{h}_3|^2 + |\bar{h}_4|^2) |x_4|^2 - 2Re[(\bar{h}_1 z_2^* - \bar{h}_2 z_1^*)x_2 + (\bar{h}_3 z_4^* - \bar{h}_4 z_3^*)x_4] \}, \quad (11)$$

where

$$\bar{h}_1 = h_1 + h_3, \quad \bar{h}_2 = h_2 + h_4, \quad \bar{h}_3 = h_1 - h_3, \quad \bar{h}_4 = h_2 - h_4.$$

Note that these two ML metrics can share the calculation result of the first and second terms of (10) or (11). Besides, the ML metrics of RQOSTBCs are clearly similar to (10) and (11), except for an additional term involving $x_1 x_3^*$ (or $x_2 x_4^*$). For the M -QAM constellation, the number of floating point operations required for detection is $21M^2$ for RQOSTBCs and $19M^2$ for the proposed STBC. The complexity reduction of the proposed STBC over the traditional RQOSTBC is about 9.5%.

V. Simulation Results

We assume that the length of OFDM subcarriers is $N=64$. The timing errors τ_i are randomly chosen from 0 to 15 with a uniform distribution. The length of CP is $\delta_{cp}=16$. We fix the transmit power at the source node P_1 , which is measured in

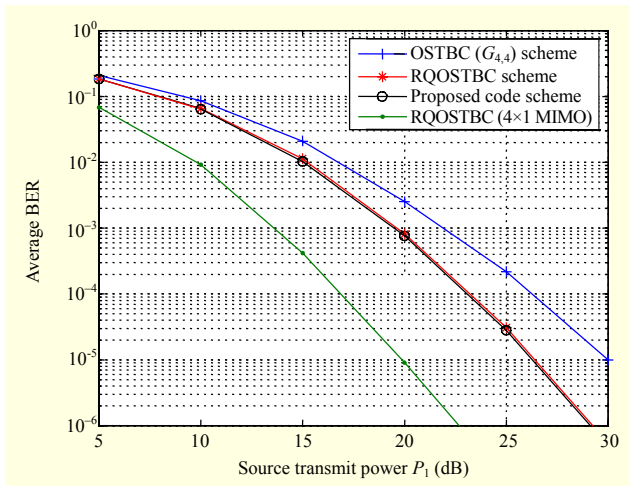


Fig. 2. BER performance vs. source transmit power P_1 at 2 bit/s/Hz.

decibels. To compare the achieved spatial diversity, the performances of the RQOSTBC for a multiple-input multiple-output (MIMO) system are also given. We use $\pi/4$ [7] as the optimal rotation angle for RQOSTBC for QAM modulation.

In Fig. 2, we show the decoding performance of the networks at the transmission rate of 2 bit/s/Hz. The 4-QAM modulation is adopted for our scheme. For the sake of comparison, we also show the performances of the rate 1/2 OSTBC $G_{4,4}$ scheme [8], which uses a 16-QAM constellation to maintain the same transmission rate. From the figure, we observe that the slope of the bit error rate (BER) curve of our proposed scheme approaches the slope of the RQOSTBC MIMO curve when the source transmit power P_1 increases. This indicates that the new scheme can achieve full diversity when P_1 is large. In terms of coding gain, the new code has a gain of about 4 dB over $G_{4,4}$ at a BER of 10^{-5} , which implies a quantified gain proportional to the information loss. In addition, the new code scheme and the RQOSTBC scheme have similar performances. In fact, they have reached the performance limit of all known codes in their class. However, our scheme has a comparative advantage in both end-to-end delay and decoding complexity, as demonstrated by the above analysis.

VI. Conclusion

In this letter, we proposed a novel quasi-orthogonal STBC for asynchronous cooperative relay networks. The OFDM technique was implemented at the source node to combat timing errors. There was no knowledge of the transmitted signal symbols and channel information at the relay nodes. We reduced the transmission delay induced at the relay nodes by symbol switching. Furthermore, we demonstrated that the new code achieves lower ML decoding complexity compared with RQOSTBC, without sacrificing the performance.

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