DIFFERENTIAL MODULATION SCHEMES FOR DECODE-AND-FORWARD COOPERATIVE DIVERSITY

Yimin Zhang

Center for Advanced Communications
Villanova University, Villanova, PA 19085, USA
E-mail: yimin@ieee.org

ABSTRACT

In this paper, we develop a cooperative diversity scheme that supports decode-and-forward cooperative diversity in the absence of channel state information (CSI) at either user or destination terminals. The proposed scheme employs differential modulation in the broadcast phase, whereas in the relay phase, the information is retransmitted from relay terminals using differential space-time codes. The proposed scheme has a simple structure. In forming a differential space-time code in the relay phase, in addition to the information to be relayed, a relay terminal requires only the portion of the previous codeword transmitted from the same terminal. When different users have different channel quality to the destination, it is pointed out that unitary codes remain the optimum in high signal-to-noise ratio (SNR) scenarios.

1. INTRODUCTION

The cooperative diversity techniques have attracted considerable and increasing attentions over the past several years [1, 2]. In responding to the increasing needs of effective and reliable wireless networks in various applications, the development of cooperative diversity techniques has benefitted from the recent advances of space-time codes, transmit diversity, and multi-input-multi-output (MIMO) technologies. Recent research work has shown the feasibility of cooperative operation and provided various capacity and performance analyses of cooperative diversity systems (see for example, [3]–[5] and references therein).

All the aforementioned methods assume that the channel state information (CSI) is available at the receivers, although few assume the CSI knowledge at the transmitters. For ordinary decode-and-forward relaying schemes, it also implies that the CSI has to be obtained at all relay terminals. The CSI knowledge at the receivers is usually obtained through channel estimation, either using training (pilot) signals or utilizing blind methods. However, the use of training signals reduces the transmission efficiency. In addition, channel estimation becomes unreliable and even impractical if the channels experience fast fading [6].

Differential modulation schemes have been considered useful when the CSI is unavailable at the receivers. The concept has been extended to MIMO systems, where differentially coded space-time codes can be decoded at the receiver without the knowledge of the propagation channels [6]–[11].

As the cooperative diversity schemes involve both broadcast and relay phases, multiple cooperative terminals should be considered and the respective channels are more complicated than those encountered in MIMO scenarios. The consideration of system design without assuming the knowledge of CSI at the receiver, therefore, becomes more demanding.

In spite of the importance, little attention has been paid to the cooperative diversity operations in the absence of CSI knowledge at the receivers. In [12], the authors proposed a cooperative diversity protocol which provides simple implementation of amplify-and-forward cooperative diversity in such a situation. In this paper, we develop a distributed space-time modulation scheme for decode-and-forward cooperative systems where no knowledge of the CSI is required at both transmitters and receivers. The proposed scheme employs differential modulation in the broadcast phase, whereas in the relay phase, the information is retransmitted from relay terminals using differential space-time codes. The proposed scheme has a simple structure. In forming a differential space-time code in the relay phase, a relay terminal does not require the information transmitted from other relay terminals. In addition to the information it receives from the source terminal, only the transmitted signal transmitted from the same terminal during the previous codeword interval is needed.

MIMO differential space-time schemes assume independent and identically distributed (i.i.d.) channels and usually use unitary codes to achieve high coding gain. In a typical cooperative diversity system, different users have different channel quality to the destination. However, it is pointed out that, when the signal-to-noise ratio (SNR) is high, unitary codes remain the optimum in such scenarios.

2. SYSTEM MODEL

To illustrate the concept of cooperative diversity in a wireless network, consider the system model depicted in Fig. 1. U users cooperate with each other. It is assumed that each user is equipped with a single antenna for semi-duplex operation, i.e., it cannot transmit and receive signals at the same time. Each user transmits its own information whereas it also serves as a relay terminal for other users. Therefore, each terminal receives an attenuated and noisy version of the signals transmitted from other users and relays them to the destination or other relays. The destination terminal receives a noisy version of the sum of the attenuated signals

This work is supported in part by the ONR under Grant No. N00014-04-1-0617.

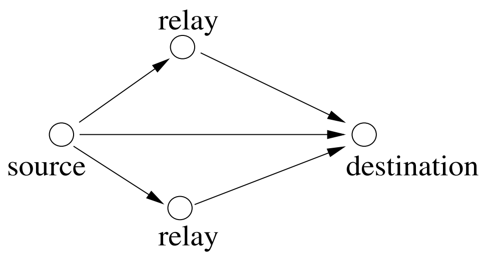

Figure 1: System model.

from all users.

The cooperation process can be divided into two phases. In the first phase (broadcast phase), the information is transmitted from a source user to the relay terminals, and the destination may also receive a copy of the same information. In the second phase (relay phase), the relay terminals transmit the signal to the destination.

Depending on how the relay terminals process the received signals, there are two major algorithms, namely, amplify-and-forward and decode-and-forward. In the amplify-and-forward algorithm, a relay terminal amplifies the attenuated and noisy signals it receives and retransmits them to the destination and other possible relay terminals. The operation at a relay terminal is limited to amplification and, in some cases, some simple computations such as complex conjugation. On the other hand, when the decode-and-forward algorithm is used, the information is first decoded at the relay terminals, and then retransmitted after proper coding. At the expense of higher complexity at relay terminals, the decode-and-forward algorithm allows the removal of relay noise, and provides the flexibility of encoding the information at the relay phase in a spectrum efficient manner [3, 4].

In a decode-and-forward cooperative diversity system, when some of the relay terminals make erroneous data detection, the terminals may choose either to continue relaying the erroneous symbols or not to relay them. The former is referred to as fixed relaying scheme, whereas the latter is called selection relaying scheme. It is shown in [3] that the latter provides better performance.

3. PROPOSED SCHEME

Consider a time frame where information stream I is to be transmitted from a source terminal to the destination. Without loss of generality, we assume that each user has a dedicated channel resource, and user 1 is considered as the source terminal. In the broadcast phase of the proposed scheme, the source terminal transmits differentially encoded information to the relay and destination terminals, whereas in the relay phase, a differential space-time block code is formed to effectively relay the information.

3.1. Broadcast Phase

In the broadcast phase, the source terminal transmits information to other terminals. The received signal at the ith relay terminal, $i = 2, \cdots, U$, during the lth symbol period, is expressed as

$$y_i(l) = \gamma_i h_i(l) x_1(l) + n_i(l), \tag{1}$$

where $x_1(l)$ is the signal transmitted from user 1, γ_i and $h_i(l)$ respectively represent the long-term attenuation factor and the unit-variance short-term time-varying statistics of the channel between user 1 and the ith relay terminal, and $n_i(l)$ is the additive channel noise at the i terminal.

Similarly, at the $(l-1)$th symbol period, the received signal is

$$y_i(l-1) = \gamma_i h_i(l-1) x_1(l-1) + n_i(l-1). \tag{2}$$

We assume that the channel variation during two symbol periods is negligible, i.e., $h_i(l) = h_i(l-1)$, $i = 2, \cdots, U$. To detect the information without the CSI knowledge at the relay and destination receivers, differential phase modulations (e.g., M-ary DPSK) are used in transmitting the information at the source terminal. That is, the information stream I is mapped into a sequence of $\mathbf{g}(l) = [g(l), \cdots, g(l+L-1)]$ where each symbol $g(l)$ is modulated using the M-ary DPSK schemes. For data symbol denoted by $g(l)$, the transmitted symbol is

$$x(l) = x(l-1)g(l) = x(0) \prod_{\tau=1}^{l} g(\tau), \tag{3}$$

where $x(0)$ denotes the initial symbol data which does not carry information but is transmitted for reference purpose. Therefore, the L-symbol sequence $\mathbf{g}(l)$ is transmitted through $L+1$ symbol period and the information transmitted is $L \log_2 M$ bits. When the selection relaying scheme is used, to detect erroneous data decision, additional error correction codes should be added, resulting in some capacity loss.

Compared to coherent detection schemes, the use of differential detection results in a 3dB noise enhancement for $M \geq 4$. For DPSK modulation using binary constellations, the effect of noise is less than 3dB because the receiver is only affected by the the real part of the noise [13].

3.2. Relay Phase

A. Differential Space-Time Coding

Consider the selection relaying scheme and assume that the first M active users make correct decision and are selected from the U users to participate in the relay retransmission, where $M \leq U$. Define the following $M \times M$ space-time code matrix

$$\mathbf{C} = \begin{bmatrix} c_{11} & c_{12} & \ldots & c_{1M} \\ c_{21} & c_{22} & \ldots & c_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ c_{M1} & c_{M2} & \ldots & c_{MM} \end{bmatrix}, \tag{4}$$

and denote $\mathcal{G}$ as a set of K different unitary matrices used for differential coding, $k = 1, \cdots, K$, i.e.,

$$\mathcal{G} = \{\mathbf{U}_k, k = 1, \cdots, K\}. \tag{5}$$

The information steam is mapped to one of the K space-time codewords $\mathbf{U}_k$ in $\mathcal{G}$. To send the message $\mathbf{G}(t) \in \mathcal{G}$ at codeword period t, the transmitter sends $\mathbf{C}(t)$ where

$$\mathbf{C}(t) = \mathbf{C}(t-1)\mathbf{G}(t) = \mathbf{C}(0) \prod_{\tau=1}^{t} \mathbf{G}(\tau). \tag{6}$$

To achieve full diversity gain, it is necessary that $\mathbf{C}(t)$ be full rank. When the channels are independent and identically distributed (i.i.d.), $\mathbf{C}(t)$ is often designed to take the form of unitary matrices for improved system capacity [7, 8]. A massage matrix $\mathbf{G}(t)$ carries information of $\log_2 K$ bits. When $L' + 1$ codewords are transmitted in a time frame, the total information is $L' \log_2 K$ bits.

B. Coding Implementation in Cooperative Systems

In a cooperation diversity system, each row of a space-time code is transmitted from different terminals. Therefore, a relay terminal is responsible to generate the codeword row it transmits. For example, the ith terminal generates and transmits the ith row of a codeword, i.e., $c_{i1}(t), \cdots, c_{iM}(t)$ for the tth codeword.

To generate the ith row of the tth codeword, we notice the following relationship

$$[c_{i1}(t), \cdots, c_{iM}(t)] = [c_{i1}(t-1), \cdots, c_{iM}(t-1)]\mathbf{G}(t). \quad (7)$$

Therefore, in the process of generating the ith row, the ith terminal only requires the same ith row of the previous code that was generated and sent from itself, whereas the other rows of the previous code transmitted from other terminals (i.e., $c_{j1}(t-1), \cdots, c_{jM}(t-1), j \neq i$) are not required. As a result, when comparing to the cooperative diversity schemes with known CSI information at the receivers, the differential cooperation diversity scheme does not require additional communication flow (except the transmission of the reference codeword $\mathbf{C}(0)$ for each block).

C. Detection of Differentially Coded Information

Denote $\tilde{\mathbf{h}}(t) = \mathbf{h}(t)\mathbf{\Gamma} = [\gamma_{1D}h_{1D}(t), \cdots, \gamma_{MD}h_{MD}(t)]$ as the $1 \times M$ channel row vector, where the elements of the $M \times M$ diagonal matrix $\mathbf{\Gamma}$ denote the long-term attenuation gain factors, whereas the elements of $M \times 1$ vector $\mathbf{h}(t)$ are the unit-variance time-varying channel coefficients. It is assumed that $\mathbf{h}(t)$ are pairwise-constant, that is, it remains constant for any two adjacent codewords (i.e., $\mathbf{h}(t) = \mathbf{h}(t-1)$) and its elements are independent and stationary ergodic stochastic processes over time. Then, the received signal row vector at the destination terminal is expressed as

$$\begin{aligned} \mathbf{y}(t) &= \tilde{\mathbf{h}}(t)\mathbf{C}(t) + \mathbf{n}(t) \\ &= \tilde{\mathbf{h}}(t-1)\mathbf{C}(t-1)\mathbf{G}(t) + \mathbf{n}(t) \\ &= \mathbf{y}(t-1)\mathbf{G}(t) + \mathbf{n}(t) - \mathbf{n}(t-1)\mathbf{G}(t), \end{aligned} \quad (8)$$

where $\mathbf{n}(t)$ is the additive noise vector. Because $\mathbf{G}(t)$ is unitary, it is clear that the differential detection scheme converts the problem to one with known channel coefficients $\mathbf{y}(t-1)$ with twice the noise power.

The maximum likelihood differential detection of $\mathbf{G}(t)$ becomes

$$\begin{aligned} \hat{\mathbf{G}}(t) &= \arg\min_{\mathbf{G}} \mathrm{tr}\left\{[\mathbf{y}(t) - \mathbf{y}(t-1)\mathbf{G}]\,[\mathbf{y}(t) - \mathbf{y}(t-1)\mathbf{G}]^H\right\} \\ &= \arg\max_{\mathbf{G}} \mathrm{Re}\ \mathrm{tr}\left\{\mathbf{G}\mathbf{y}^H(t)\mathbf{y}(t-1)\right\}, \end{aligned} \quad (9)$$

where "tr" denotes the trace of a matrix and "Re" denotes the real part operator.

4. PERFORMANCE ANALYSIS

Now we consider the performance of the relay phase where $M \times M$ differential space-time codes are transmitted from M different users. The effect of the broadcast signal at the destination is not considered. While it is analogous to most MIMO problems using differential space-time codes, we emphasize the uniqueness of this work by noting that the channels in general have different variances and, therefore, are no longer i.i.d. in general in the underlying cooperative diversity systems.

To consider the optimum power allocation in transmitting the space-time codewords, we now consider a more general form of $\mathbf{C}$ in which the following codeword is transmitted,

$$\mathbf{C}' = \mathbf{P}^{1/2}\mathbf{C} = \begin{bmatrix} \sqrt{P_1}c_{11} & \sqrt{P_1}c_{12} & \ldots & \sqrt{P_1}c_{1M} \\ \sqrt{P_2}c_{21} & \sqrt{P_2}c_{22} & \ldots & \sqrt{P_2}c_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \sqrt{P_M}c_{M1} & \sqrt{P_M}c_{M2} & \ldots & \sqrt{P_M}c_{MM} \end{bmatrix}, \quad (10)$$

where the elements of $\mathbf{P} = diag[P_1, \cdots, P_M]$ determine the power transmitted from each antenna. Because $\mathbf{C}'(\mathbf{C}')^H = \mathbf{P}$, $\mathbf{C}'$ is unitary only when all the terminals transmit the same power. Note that, because $\mathbf{G}(t)$ is unitary, the power of $\mathbf{C}'(t)$ is unchanged for different values of t, and the coding system remains stable, irrespective to the selection of $\mathbf{P}$.

While the performance accurate of a differentially coded system requires the consideration of the quadratic receiving structure [6, 7], it can be well approximated in high SNR situations by using an equivalent coherent receiver model (8) with known channel vector $\mathbf{y}(t-1)$ and enhanced noise power [9].

Assume that $\mathbf{h}^T(t) \sim \mathcal{CN}(0, \mathbf{I}_M)$, where $\mathbf{I}_M$ is the $M \times M$ identity matrix. The channel is reflected in $\mathbf{\Gamma}$, which is assumed unchanged during the entire period of interest.

The pairwise codeword error probability (CER), i.e., the probability of transmitting $\mathbf{G}$ and deciding in favor of another $\mathbf{E}$ at the detector, conditioned by equivalent channel vector $\mathbf{y}(t-1)$, is given by

$$\begin{aligned} P(\mathbf{G} \to \mathbf{E}|\mathbf{y}(t-1)) &= Q\left(\sqrt{E_s d^2(\mathbf{G}, \mathbf{E})/(2\sigma_n^2)}\right) \\ &\leq \exp\left[-E_s d^2(\mathbf{G}, \mathbf{E}) E_s/(4\sigma_n^2)\right], \end{aligned} \quad (11)$$

where E_s is the averaged power transmitted from all the antennas per symbol period, and

$$d^2(\mathbf{G}, \mathbf{E}) = \mathbf{y}(t-1)\mathbf{A}\mathbf{y}^H(t-1), \quad (12)$$

$$\mathbf{A} = [\mathbf{G}(t) - \mathbf{E}(t)]\,[\mathbf{G}(t) - \mathbf{E}(t)]^H. \quad (13)$$

We make the following approximation for high SNR scenarios

$$\mathbf{y}(t) \approx \mathbf{h}(t)\mathbf{\Gamma}\mathbf{C}'(t). \quad (14)$$

Then, (12) can be approximated by

$$\begin{aligned} d^2(\mathbf{G}, \mathbf{E}) &\approx \mathbf{h}(t)\mathbf{\Gamma}\mathbf{C}'(t-1)\mathbf{A}(\mathbf{C}'(t-1))^H\mathbf{\Gamma}\mathbf{h}^H(t) \\ &= \mathbf{h}(t)\mathbf{\Gamma}\mathbf{P}^{1/2}\mathbf{C}(t-1)\mathbf{A}\mathbf{C}^H(t-1)\mathbf{P}^{1/2}\mathbf{\Gamma}\mathbf{h}^H(t). \end{aligned} \quad (15)$$

Because $\mathbf{y}(t)$ is approximated as a linear combination of $\mathbf{h}(t)$ and therefore constitutes a set of dependent channel coefficients, averaging the above bound with respect to $\mathbf{y}(t-1)$ results in [9]

$$P(\mathbf{G} \to \mathbf{E}) \leq \prod_{i=1}^{M} \left(1 + \frac{E_s}{4\sigma_n^2} d_i\right)^{-1}, \qquad (16)$$

where d_i, $i = 1, \cdots, M$, are the M eigenvalues of $\mathbf{K} = \mathbf{\Gamma}\mathbf{C}'(t)\mathbf{A}(\mathbf{C}'(t))^H\mathbf{\Gamma}$. At high SNR scenarios, we have

$$P(\mathbf{G} \to \mathbf{E}) \leq \prod_{i=1}^{M} \left(\frac{E_s}{4\sigma_n^2} d_i\right)^{-1} = \left(\frac{E_s}{4\sigma_n^2}\right)^{-M} [\det(\mathbf{K})]^{-1}. \qquad (17)$$

It is clear that, in this case, the system achieves full diversity gain of M, and the coding gain (diversity product) is determined by the minimum determinant of $\mathbf{K}$. Because

$$\begin{aligned} \min\det(\mathbf{K}) &= \min\det(\mathbf{A})\det\left(\mathbf{\Gamma}\mathbf{C}'(t)(\mathbf{C}'(t))^H\mathbf{\Gamma}\right) \\ &= \min\det(\mathbf{A})[\det(\mathbf{\Gamma})]^2\det(\mathbf{P}). \end{aligned} \qquad (18)$$

Therefore, the transmission power should be equally distributed over different user terminals, irrespective to the code and channel characteristics. Note that, however, this conclusion is derived in high SNR scenarios. Allocating higher power to good channels may result in improved performance during the transition range of SNR values.

5. NUMERICAL RESULTS

We consider a two-user scenario where $\gamma_{1D} = 1$ and $\gamma_{2D} = 0.5$. The Differential codewords are generated based on Alamouti's codes with QPSK constellations. Fig. 2 shows the bit error rate (BER) performance with two different power allocations conditioned unit total power at each symbol period. In the first curve the power is equally distributed to different users, whereas in the second the power is divided proportional to the average channel strength. The former shows lower BER in high SNR range, and the latter provides slightly better BER in low SNR scenarios.

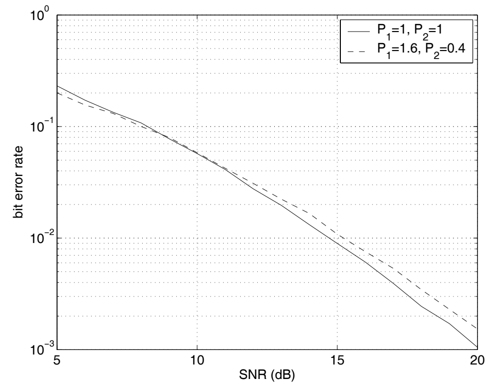

Figure 2: BER performance comparison.

6. CONCLUSION

A novel space-time cooperation scheme using differential modulation and differential space-time coding has been developed for effective cooperative diversity where the CSI are unavailable at the receivers. The performance analysis shows that, at high SNR scenarios, distributing transmit power equally to all users in forming the differential space-time code results in optimum coding gain, irrespective to the used codes and the channel characteristics.

ACKNOWLEDGMENT

The author would like to thank Dr. Moeness Amin and Dr. Genyuan Wang for their valuable discussions.

REFERENCES

[1] A. Sendonaris, E. Erkip, and B. Aazhang, "Increasing uplink capacity via user cooperation diversity," *Proc. IEEE Int. Symp. Info. Theory*, Cambridge, MA, p. 156, Aug. 1998.

[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperative diversity – Part I and Part II," *IEEE Trans. Commun.*, vol. 51, no. 11, pp. 1927–1948, Nov. 2003.

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: effective protocols and outage behavior," *IEEE Trans. Inform. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[4] J. N. Laneman and G. W. Wornell, "Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks", *IEEE Trans. Inform. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[5] Y. Hua, Y. Mei, and Y. Chang, "Parallel wireless mobile relays with space-time modulations," *IEEE Workshop on Statistical Signal Processing*, St. Louis, MO, Sept. 2003.

[6] B. L. Hughes, "Differential space-time modulation," *IEEE Trans. Inform. Theory*, vol. 46, pp. 2567–2578, Nov. 2000.

[7] B. M. Hochwald and T. L. Marzetta, "Unitary space-time modulation for multiple-antenna communications in Rayleigh flat fading," *IEEE Trans. Inform. Theory*, vol. 46, pp. 543–564, March 2000.

[8] B. M. Hochwald and W. Sweldens, "Differential unitary space-time modulation," *IEEE Trans. Commun.*, vol. 48, pp. 2041–2052, Dec. 2000.

[9] V. Tarokh and H. Jafarkhani, "A differential detection scheme for transmit diversity," *IEEE J. Select. Areas Commun.*, vol. 18, pp. 1169–1174, July 2000.

[10] Z. Liu, G. B. Giannakis, and B. L. Hughes, "Double differential space-time block coding for time-selective fading channels," *IEEE Trans. Commun.*, vol. 49, pp. 1529–1539, Sept. 2001.

[11] H. Li and J. Li, "Differential and coherent decorrelating multiuser receivers for space-time-coded CDMA systems," *IEEE Trans. Signal Processing*, vol. 50, no. 10, pp. 2529–2537, Oct. 2002.

[12] G. Wang, Y. Zhang, and M. Amin, "Cooperation diversity using differential distributed space-time codes," *Joint Conf. of Asia-Pacific Conf. on Commun. and Int. Symp. on Multi-Dimensional Mobile Commun.*, Beijing, China, Aug. 2004.

[13] J. G. Proakis, *Digital Communications*, 3rd Ed., McGraw-Hill, 1995.