Physical Communication 1 (2008) 209–220

Contents lists available at ScienceDirect

Physical Communication

journal homepage: www.elsevier.com/locate/phycom

Full length article

Cooperative space–time block coding with amplify-and-forward strategy: Exact bit error probability and adaptive forwarding schemes

Jun He *, Pooi Yuen Kam

Department of Electrical and Computer Engineering, National University of Singapore, S117576, Republic of Singapore

ARTICLE INFO

Keywords:
Cooperative space–time block coding
Bit error probability
Amplify-and-forward

ABSTRACT

Cooperative space–time block coding (STBC) is a distributed way to exploit spatial diversity. Because of its simplicity, the amplify-and-forward (AF) strategy is often used at relays. However, the exact performance of this strategy is not available in the existing works. Therefore, in the first part of this paper, we analyze the performance of cooperative STBC with the AF strategy. Exact bit error probabilities (BEP) are derived in closed form for three existing protocols.

Since the AF strategy simply forwards the signals at the relays, the noise at the relay is also forwarded to the destination, and it degrades the received signals from both the relay and the source, due to the receiver structure of STBC. In the second part of this paper, we examine the effect of the forwarded noise and propose a condition under which the relay should stop forwarding the signals. Based on this condition, adaptive forwarding schemes for cooperative STBC are proposed. The performances of these schemes are studied and the exact BEP's are also obtained in closed form. Finally, the energy efficiencies of these adaptive schemes are discussed.

1. Introduction

Space–time coding (STC) [1] is a well known technique to exploit spatial diversity and mitigate the fading problem in wireless communication. However, it is usually difficult to install multiple antennas in one mobile communication node, due to its limited size. In such scenarios, we can exploit spatial diversity through the cooperation of neighboring nodes [2–4]. Therefore, STC can be cooperatively applied among several single antenna users, e.g. [5–8], by creating a "virtual array" of antennas.

More specifically, the transmission is completed in two phases. In the first phase, the source node sends information to relay nodes, and in the second phase, the relay nodes and the source node transmit together using STC. The relay nodes can either amplify and forward (AF), or decode and forward (DF) the received signal. The DF strategy can provide a better performance [9] compared with the AF strategy, but it has a higher complexity in decoding the signals. Therefore, the simpler AF strategy is also an attractive choice.

The performance of cooperative STC has been studied in many works. For example, [10–12] have studied the performance of cooperative STC with DF strategy. Recently, we have derived the exact bit error probability (BEP) for cooperative space–time block codes (CSTBC) with DF strategy, over nonidentical Ricean channels [13]. At the same time, many works, e.g. [14–17], have investigated CSTBC with AF strategy. Under a high SNR assumption, [14] obtained an upper bound on the pair-wise error probability; [15] derived asymptotic BEP results with both perfect and imperfect channel state information (CSI); [16] generalized the CSTBC to the case of an arbitrary number of relays and hops, and presented an asymptotic symbol error probability (SEP) result. Ref. [17] also derived the asymptotic SEP, which was used to optimize the power allocation.

However, none of the above mentioned works has obtained the exact error performance. Therefore, the first

* Corresponding author. Tel.: +65 65162122; fax: +65 67791103.
E-mail addresses: hejun@nus.edu.sg (J. He), elekampy@nus.edu.sg (P.Y. Kam).

1874-4907/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.phycom.2008.08.001

target of this paper is to analyze the exact bit error performance of CSTBC with AF strategy. Three existing transmission protocols are considered, and exact BEP results are obtained in closed form for all of these protocols. Based on the exact BEP, we compare our results with the existing asymptotic BEP in [15]. Then, we compare the performances of the protocols in different situations and examine the robustness of these protocols.

For the CSTBC with AF strategy, since the relay simply forwards the received signals, the additive noise at the relay is also forwarded. Due to the decoder structure of space–time block code, the forwarded noise degrades the received signals from both the relay and the source. Sometimes, when the forwarded noise is too large, the advantage of cooperative diversity vanishes, and even an error floor can be observed [9,15]. Therefore, in the second part of this paper, we address the key question of how the relay should decide whether to forward the signals and cooperate to form an STBC. We first examine the effect of the forwarded noise on the received SNR and find a critical condition, under which the forwarded signal from the relay will be deleterious. According to this condition, we propose adaptive forwarding schemes for CSTBC with full CSI, partial CSI and no CSI available at the relay. The exact BEP's of these adaptive CSTBC schemes, which are much better than that of the conventional CSTBC, are also obtained in closed form. Finally, the energy efficiencies of these adaptive schemes are also discussed.

The rest of this paper is organized as follows: Section 2 describes the system model. The exact BEP results of the conventional CSTBC are derived in Section 3. A comparison of different protocols is also provided in this section. Section 4 proposes and analyzes the adaptive CSTBC schemes, together with numerical examples and discussion. A summary is given in Section 5.

2. System model

We consider a cooperative transmission scenario with three nodes, where each node only has one antenna. The source S transmits information to the destination D, with the assistance from the relay R. We assume all the nodes are half duplex, such that they cannot transmit and receive simultaneously. Therefore, we use a time-division multiple-access strategy here, and the transmission is completed in two phases. According to different settings of the source and the destination, three existing protocols are listed in Table 1.

Table 1
List of three protocols

Phase	Protocol I	Protocol II	Protocol III
1	$S \rightarrow R, D$	$S \rightarrow R, D$	$S \rightarrow R$
2	$S \rightarrow D, R \rightarrow D$	$R \rightarrow D$	$S \rightarrow D, R \rightarrow D$

Protocol I: The source broadcasts the information to the relay and the destination in the first phase. In the second phase, the source and the relay transmit together to the destination using STBC. The destination combines the signals from the first and second phases before decoding.

Protocol II: The source only transmits in the first phase, and the relay transmits in the second phase. The destination listens in both phases and combines the signals.

Protocol III: Similar to protocol I, the source transmits in both phases and the relay forwards the signals in the second phase. But, the destination only listens in the second phase.

Notice that the settings of the relay are the same in all of the three protocols, such that it listens in the first phase and forwards in the second phase. However, the source/destination can choose to transmit/listen in one or both phases. These protocols are essentially the same as they all try to exploit spatial diversity through relays. The different settings for the source and the destination can be viewed as adaptation to different scenarios. For example, if the channel between the source and the destination varies fast, protocol I should be preferred, since the destination listens to the source in both phases and enjoys greater orders of diversity. Protocols II and III free the source/destination in the second/first phase, so that the latter can be involved in other transmissions, which is an advantage in multi-hop transmission. The further comparison of protocols will be detailed later in Section 3.3.2. In Section 3, we will first focus on the performance of protocol III. The results will be extended to protocols I and II later.

We denote the link from A to B as $A \rightarrow B$. And the channel gains of $S \rightarrow D$, $S \rightarrow R$ and $R \rightarrow D$ links are denoted as h_{SD}, h_{SR} and h_{RD}, respectively. They are independent, complex, Gaussian random variables with means of zero and variances of $2\sigma_{SD}^2$, $2\sigma_{SR}^2$ and $2\sigma_{RD}^2$, respectively. Here, the channel variances can be different due to the different propagation environments and the different distances between nodes. The channels are block fading such that they remain constant for at least one space–time block. The CSI is perfectly known at the receivers of the relay and the destination.

For this scenario with one relay, we apply Alamouti's code [18] for two transmit antennas, which is given by

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}, \tag{1}$$

where s_1 and s_2 are from a certain complex signal constellation. Here, we assume M-PSK modulation such that each s_i, $i = 1, 2$, can be written as $s_i = \mathrm{e}^{j\phi_i}$, where ϕ_i takes on, with equal probabilities, the values in the set $\{2n\pi/M\}_{n=0}^{M-1}$.

For protocol III, the source transmits the first column of the code matrix to the relay in the first phase. The received signal at the relay, r_{Ri}, is given by

$$r_{Ri} = \sqrt{E_{SR}} h_{SR} x_i + n_{R,i}, \quad i = 1, 2 \tag{2}$$

where $x_1 = s_1$ and $x_2 = -s_2^*$ are transmitted with power $\sqrt{E_{SR}}$, and the noise $n_{R,i}$ is the additive white Gaussian noise (AWGN) with mean zero and variance N_o. In the second phase, the relay amplifies and forwards the received signals to the destination, while the source transmits the second column of the code matrix. Therefore, the received signals at the destination are given by

$$\begin{aligned} r_1 &= \sqrt{E_{RD}}\sqrt{E_{SR}} h_{RD} h_{SR} s_1 + \sqrt{E_{SD}} h_{SD} s_2 \\ &\quad + \sqrt{E_{RD}} h_{RD} n_{R,1} + n_{D,1}, \end{aligned} \tag{3}$$

$$\begin{aligned} r_2 &= -\sqrt{E_{RD}}\sqrt{E_{SR}} h_{RD} h_{SR} s_2^* + \sqrt{E_{SD}} h_{SD} s_1^* \\ &\quad + \sqrt{E_{RD}} h_{RD} n_{R,2} + n_{D,2} \end{aligned} \tag{4}$$