Enhancing Performance of Asynchronous Cooperative Relay Network with Partial Feedback

The-Nghiep Tran(✉)

Faculty of Radio-Electronics, Le Quy Don Technical University, Hanoi, Vietnam
nghiepsqtt@gmail.com
http://www.lqdtu.edu.vn

Abstract. Distributed close-loop extended orthogonal space-time block code (DCL EO-STBC) was demonstrated to achieve a significant improvement of performance for closed-loop cooperative relay network systems with limited feedback channel. This paper proposes a decode-and-forward (DF) cooperative strategy with using partial feedback in stead of DCL EO-STBC to obtain a distributed cooperative diversity gain. Based on the partial phase feedback technique, the new scheme has only previous inter-symbol interference (ISI) components in the received signals and obtains an enhancing system performance in term of signal-noise power ratio (SNR) at the destination node. Theoretical analysis and Monte-Carlo simulations confirm that the using near-optimum detection (NOD) at the destination can completely remove interference components before detection process. In comparison to previous DCL EO-STBC scheme, this work not only has simpler signal processing due to not using DCL EO-STBC endcoder and decoder, but also outperforms sytem performance without decrease transmission rate.

Keywords: Partial feedback · Near-optimum detection
Inter-symbol interference · Distributed space-time code
Asynchronous cooperative network

1 Introduction

Distributed space-time code (DSTC) is used in distributed relay networks, such as ad-hoc or wireless sensor networks, to achieve spatial diversity gain [1–3]. However, due to the different location of cooperative relay nodes and their distinct local oscillators, the received signals at the destination are not the same time in the symbol level. This imperfect synchronization results in inter-symbol interference (ISI) between the received symbols at the destination node, which damages the orthogonally of the DSTC and degrades the total system performance. Thus, the solutions of interference cancellation have attracted considerably attentions from the scientists in a few years ago [4–11].

In [2], the distributed close loop quasi-orthogonal space-time code (DCL QO-STBC) and sub-optimum detection (SOD) (called as DCL QO-STBC scheme)

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are proposed for the DF asynchronous cooperative networks. Although this scheme based on sub-optimum detection proves to be very effective to eliminate the ISI components with reducing detection complexity at the destination it relies mainly on the existence of a direct transmission (DT) link between the source node and the destination node. In [1], the DCL EO-STBC and near-optimum detection (NOD) (called as DCL EO-STBC scheme) is proposed for the same configuration network as Ref. [2] without the DT link between the source node and the destination node. The DCL EO-STBC scheme not only obtains a significant improving performance by canceling the interference components in the received signals, but also performs without the requirement of the DT link. However, both DCL EO-STBC scheme and DCL QO-STBC scheme are only the solution of interference cancellation at the destination node.

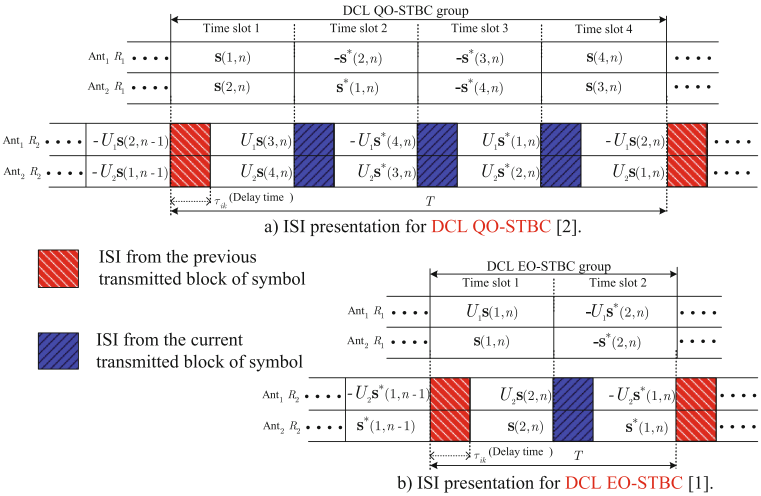

Fig. 1. The ISI representations in the DCL EO-STBC scheme [1] and DCL QO-STBC scheme [2].

The ISI components of the DCL EO-STBC and DCL QO-STBC schemes can be classified into two categories, one of them is due to the current transmitted symbol and the other is from the previous transmitted block of symbols as shown in Fig. 1 [3]. The SOD [2] and NOD [1] are proved that they can completely remove the previous ISI components if the detection process has been initialized properly. Whereas the current ISI components still exist in the received symbol vector after using either the SOD or NOD. Moreover, the number of current ISI components depends on the durations of between the second time slot and the last time slot in each DCL-STBC group. Hence, it is noticeable from the Fig. 1 that there are two and six current interference components at the received signals in DCL EO-STBC and DCL QO-STBC schemes respectively while their configuration networks are similar. Therefore, the using SOD or NOD does not work well in these schemes.

In this paper, we propose a new DF asynchronous cooperative relay network with partial feedback where there are only previous ISI components in received signals at the destination node. Although the proposed scheme is the similar configuration network in DCL EO-STBC scheme [1] and DCL QO-STBC scheme [2] it differs from those in the following points. Firstly, our proposed scheme uses the partial feedback technique [12] to ensure that there are only previous ISI components in the received symbols, and then near-optimum detection is utilized to remove completely them. Whereas, the solutions of interference cancellation in both DCL-QO STBC and DCL-EO STBC schemes are solved only at the destination node. Secondly, the previous works use the DCL-STBC encoding and decoding to achieve the distributed cooperative diversity, but the using partial feedback in new scheme is a better alternative in the term of received signal to noise ratio (SNR). Thirdly, the application NOD in this paper does not depend on the detection result of DT link while the performing sub-optimum detection [2] bases on the existence of that.

The rest of this paper is organized as follows: The DF asynchronous cooperative relay network with partial feedback is described in the Sect. 2. Near-optimum detection and feedback bit selection are presented in the Sect. 3. Simulation results and performance comparisons are provided in the Sect. 4. Finally, the Sect. 5 givens the conclusions of the paper.

In the remaining part of this paper, $[.]^T$, $[.]^*$ and $\|.\|^2$ denote transpose, complex conjugate, and Frobenius operation, respectively; $\Re$ and $\Im$ present to take the real and imaginary part of the complex variable, respectively; $\mathbb{E}[.]$ represents an expectational operation; and $\mathcal{A}$ indicates the signal constellation.

2 The Proposed Asynchronous Cooperative Relay Network with Partial Feedback

The proposed partial feedback scheme is depicted in Fig. 2 with the source node and destination node have a single antenna, relay nodes have two antennas. The DT link from the source node to the destination node is unavailable due to the effect of path loss and the limited transmitted power. All relay nodes operate in half-duplex mode and DF strategy. Let f_{ik} denotes the channel coefficient from the source node to the $i\,th$ antenna of the $k\,th$ relay node and g_{ik} is the channel coefficient from the $i\,th$ antenna of the $k\,th$ relay node to the destination node. We also assume that all channel coefficients f_{ik} and g_{ik} (for $i,\, k = \overline{1,2}$) are kept constant during two symbol intervals and varied randomly in the next two symbol intervals (i.e. a quasi-static fading). The noise terms of both the relay and destination node are assumed AWGN with distribution $\mathcal{CN}(0,1)$. If the total transmission power in the whole scheme is fixed as P (dB). The optimal power allocation is represented as follows [13]:

$$P_1 = \frac{P}{2},\ P_2 = \frac{P}{4}, \tag{1}$$

where, $P_1,\ P_2$ are the transmit power at the source and the each relay node, respectively.

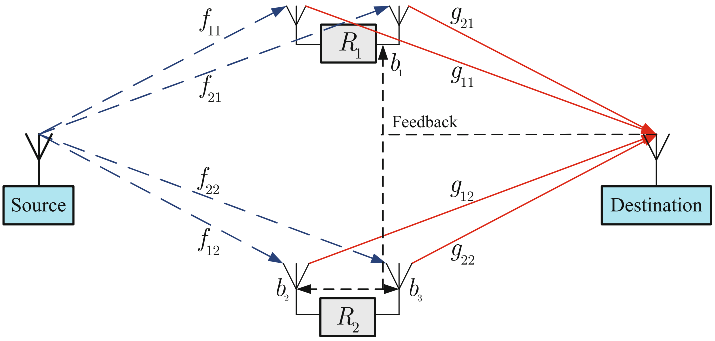

Fig. 2. The asynchronous cooperative relay network with partial feedback.

The transmission between the source node and the destination node comprises two phases. In the first phase, the source node broadcasts information symbol $s(n)$ to the relay node during the first symbol period. As the similar previous works [1] and [2], the DF protocol is used by the relay nodes and the detection of relay node is supported a cyclic redundancy code (CRC) at the source. To limit focus of paper on the imperfect synchronization issue, the relaying nodes are assumed to detect the symbols correctly received signal from the source.

In the second phase, relay nodes cooperate together to transmit symbol to destination node by using partial feedback technique [12] before transmission, information symbols at the second antenna of the first relay, the first and second antenna of the second relay are multiplied by b_1, b_2, and b_3 respectively and which show in the Fig. 3. Thus, the transmitted symbol vector at the relay nodes is presented as follows:

$$E_B = \left[\, s(n)\ b_1 s(n)\ b_2 s(n)\ b_3 s(n) \,\right], \tag{2}$$

where b_i $(i = 1,\ 2,\ 3)$ gets value 1 or -1 depending on the feedback information from the destination node.

In this paper, the transmitted symbol from the relay nodes will undergo an asynchronous issue due to the different distances between the each delay node and the destination node. As the propagation delay of the distinct links is different which results in a inter-symbol interference at the destination node.

Without loss of generality, it is assumed that the received signals at the destination from both antenna of the first relay (denotes R_1) are fully synchronized (i.e. $\tau_1 = \tau_{11} = \tau_{12} = 0$). We also suppose that both antenna of the second relay node (denotes R_2) is not synchronized to the destination (i.e. $\tau_2 = \tau_{21} = \tau_{22} \neq 0$) [1]. Following that, the received symbol at the destination can be expressed as:

$$r(n) = \sqrt{\frac{P_2}{2}} h s(n) + I_{\text{int}}(n) + z(n), \tag{3}$$

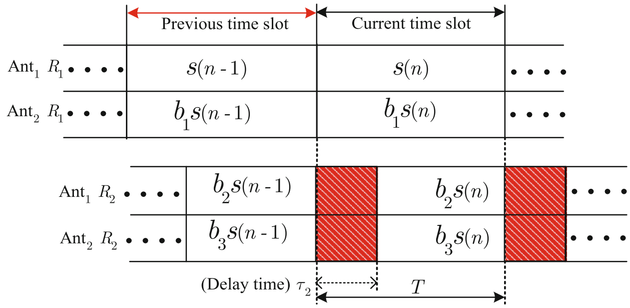

Fig. 3. The ISI presentations in the proposed asynchronous cooperative relay network.

where $h = g_{11} + b_1 g_{21} + b_2 g_{12} + b_3 g_{22}$ is the equivalent channel gain, $z(n)$ is the noise term at the destination node, and $I_{\text{int}}(n)$ is the ISI components:

$$I_{\text{int}}(n) = \sqrt{\frac{P_2}{2}} \left\{ b_2 g_{12}(-1) + b_3 g_{22}(-1) \right\} s(n-1). \tag{4}$$

The coefficients $g_{i2}(-1), (i = 1, 2)$ in Eq. (4) represent the complex channel gains from both antennas of the second relay to the destination due to the effect of asynchronous issue. In this paper, the value of $g_{i2}(-1)$ can be expressed as a ratio as [1]:

$$\beta = |g_{i2}(-1)|^2 / |g_{i2}|^2; \quad i = 1, 2 \tag{5}$$

Normally, $\beta = 0$ for $\tau = 0$ and $\beta = 1$ (i.e. 0 dB) for $\tau = 0.5T$ [1]. Note that, the coefficients $g_{i2}(-1), l = -2, -3...$ are ignored because they are small. The factor $\sqrt{P_2/2}$ in the Eq. (3) ensures that the total transmitted power of the each relay node is P_2. Figure 3 and Eq. (4) show that there are only two previous ISI components in the received symbols at the destination node. It is clear that the number of ISI components of the proposed scheme is reduced as compared with the DCL EO-STBC [1] and DCL QO-STBC scheme [2].

3 Near-Optimum Detection and Feedback Bit Selection

3.1 Feedback Bits

From Eq. (3), the signal-to-noise ratio (SNR) of received signal $r(n)$ is

$$\gamma = \frac{P_2 \lambda}{2} \tag{6}$$

where $\lambda = h^* h = \alpha_B + \beta_B$ is the total performance gain. α_B and β_B are given as:

$$\alpha_B = |g_{11}|^2 + |g_{21}|^2 + |g_{12}|^2 + |g_{22}|^2; \tag{7}$$

$$\beta_B = 2b_1\Re\left(g_{11}g_{21}^*\right) + 2b_2\Re\left(g_{11}g_{12}^* + b_1g_{21}g_{12}^*\right) + 2b_3\Re\left(g_{11}g_{22}^* + b_1g_{21}g_{22}^* + b_2g_{12}g_{22}^*\right). \quad (8)$$

The total gain of the proposed scheme includes the conventional diversity gain α_B, that is always a positive value and the addition array performance gain β_B, which is depended on the value of three feedback bits. In order to enhance the system performance, an exhaustive search algorithm can be used to select feedback bits as following:

$$b_1, b_2, b_3 = \arg \max_{b_1,b_2,b_3\in\{-1,1\}} \beta_B \quad (9)$$

As an alternative approach, the 3 bits for feedback may be selected according to the inductive algorithm follows to ensure a positive α_B value:

Step 1: $b_1 = \begin{cases} 1 & \text{if} \quad \Re\left(g_{11}g_{21}^*\right) \geq 0 \\ -1 & \text{if} \quad \Re\left(g_{11}g_{21}^*\right) < 0 \end{cases}$

Step 2: $b_2 = \begin{cases} 1 & \text{if} \quad \Re\left(g_{11}g_{12}^* + b_1g_{21}g_{12}^*\right) \geq 0 \\ -1 & \text{if} \quad \Re\left(g_{11}g_{12}^* + b_1g_{21}g_{12}^*\right) < 0 \end{cases}$

Step 3: $b_3 = \begin{cases} 1 & \text{if} \quad \Re\left(g_{11}g_{22}^* + b_1g_{21}g_{22}^* + b_2g_{12}g_{22}^*\right) \geq 0 \\ -1 & \text{if} \quad \Re\left(g_{11}g_{22}^* + b_1g_{21}g_{22}^* + b_2g_{12}g_{22}^*\right) < 0 \end{cases}$

The exhaustive search will provide the larger array gain but at additional computational complexity than the inductive search. It is clear that the addition array performance gain of the proposed scheme β_B is better than conventional array performance gain λ_a as compared with previous DCL EO-STBC scheme (see λ_a in Eq. (13) [1]). Therefore, the system performance of the new scheme is enhanced in the term of the received SNR to compare with former one.

3.2 Near-Optimum Detection

It is evident from the Eq. (4) that the number of ISI components of the new scheme is less than amount of those in the previous works [1,2]. However, the existence of interference components in the received signals can still degrade the system performance in the asynchronous channel assumptions. This subsection presents a detector which can completely remove ISI components and improve the total system performance in this case. Fortunately, there are only two previous interference components in the received signals of the proposed scheme. Therefore, the application of NOD scheme at the destination node can completely remove the ISI components $I_{\text{int}}(n)$ in (3) before the information detection process. In fact, $s(n-1)$ is already known if the detection process has been initialized properly (e.g. through the use of pilot symbols at the start of the packet). Hence, the interference components $I_{\text{int}}(n) = \sqrt{P_2/2}\left\{b_2g_{12}(-1) + b_3g_{22}(-1)\right\}s(n-1)$ in the Eq. (3) can completely removed as the following steps:

Step 1: Remove the ISI component $I_{\text{int}}(n)$ in the Eq. (3):

$$r'(n) = r(n) - I_{\text{int}}(n) = \sqrt{\frac{P_2}{2}}hs(n) + z(n). \quad (10)$$

Step 2: Apply the Least Square (LS) at the destination:

$$\tilde{s}(n) = \arg\min_{s_m \in \mathcal{A}} \left| r'(n) - \sqrt{\frac{P_2}{2}} h s_m \right|^2, \tag{11}$$

where $\mathcal{A}$ denotes the signal constellation.

Its clear that, the received symbol $r'(n)$ in (10) will has no ISI component if the initialized signals have no decision feedback error. More details about the effect of initialized signals are illustrated clearly by Monte-Carlo method in the following section. Since the received symbol $r'(n)$ has no interference component, the LS detection in (11) has been improved.

4 Performance Comparisons and Time Delay Experimental Results

4.1 Comparison Results

This subsection provides some comparisons between the BER performance of the proposed partial feedback scheme and the DCL EO-STBC scheme [1] under the channel conditions such as perfect synchronous or imperfect synchronous. The QPSK modulation is used in all simulations. The BER system performances are shown as function of total transmit power in the whole network.

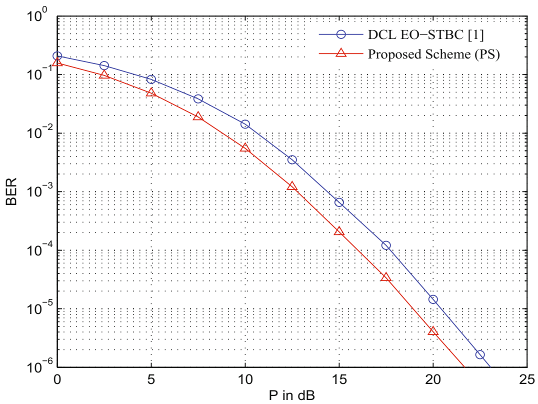

Fig. 4. BER performance comparisons between the proposed scheme and DCL EO-STBC scheme [1] under perfect synchronization condition.

Figures 4 and 5 represents simulation results are corresponding to synchronous and asynchronous channel conditions. From these simulation results, we can have several observations. Firstly, in the perfect synchronous channels, the proposed partial feedback scheme can obtain a SNR gain of 2.3 dB at BER of 10^{-3} in comparison to the DCL EO-STBC scheme [1]. Secondly, the degradation of BER performance of the proposed scheme under asynchronous channels is very small when compared with perfect synchronous channel, i.e., it is robust against asynchronous channels. Thirdly, by decreasing the β factor (i.e., more loss of synchronization), the proposed scheme becomes superior to the DCL EO-STBC scheme (for example, an improvement of 2.5 dB, 5.0 dB and 8.2 dB at BER of 10^{-3} correspond to β factors of -6 dB, -3 dB and 0 dB).

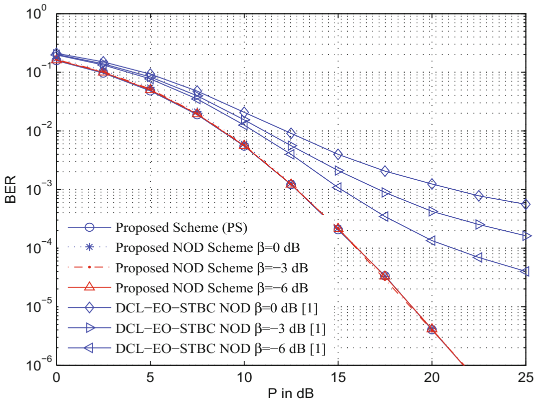

Fig. 5. The comparison of BER performance proposed scheme.

As previous discussion in Sect. 3, the interference cancellation is dependent on the initialized signal $\tilde{s}(n-1)$. It could be detected either correctly or incorrectly. To determine the effect of error propagation to system performance, we perform simulation for two cases, one has error propagation (EP), i.e., $\tilde{s}(n-1)$ hence gets the value of previous detection and can different from information symbol $s(n-1)$, the other has no EP, i.e., $\tilde{s}(n-1)$ gets the value of true information symbol $s(n-1)$. The simulation results in Fig. 6 demonstrate that the effect of error propagation in the proposed scheme is very small and acceptable.

4.2 Time Delay Experimental Results

This subsection presents the performance analysis of time delay based on both impact of imperfect synchronization and decoding complexity. As previous mention, the communication between the source and destination node is performed over two phase. The relays are assumed to detect the correctly received signals from the source. Hence, time delay is depended on the process at relay nodes, multipath channel coefficients and decoding time [14]. Time delay between transmission from the antennas on the relays to destination was presented by factor value reflecting of imperfect synchronous β. The process complexity of the relays and destination was shown in the number of operation requirement.

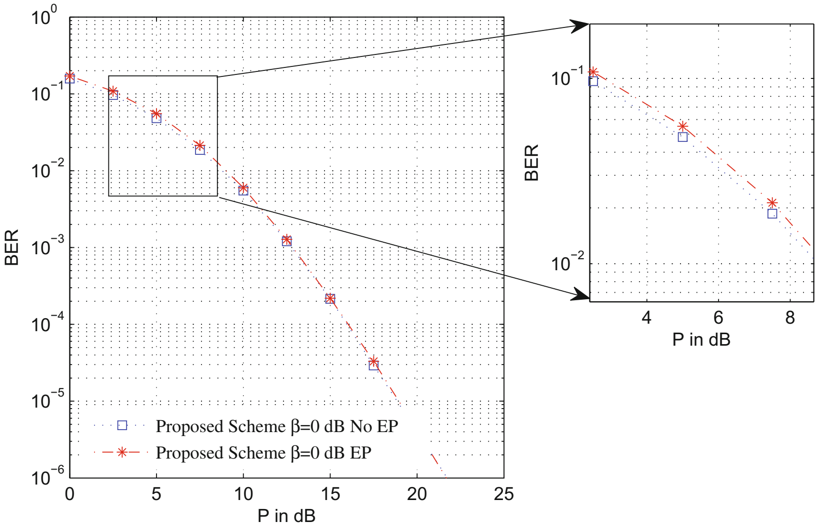

Fig. 6. The impact of error propagation (EP) on the BER performance.

This paper utilizes and adopts all notation and definition as representation in [15]. We denote the complexity of the proposed scheme by C_{New} and $C_{DCLEO-STBC}$ for DCL EO-STBC scheme [1], respectively. The complexity formula was split into two parts in order to represent C_M, that is a real multiplication and C_A, which means a real addition operation independently. The total decoding complexity of the proposed scheme can be written as (see the Appendix A for more details):

$$C_{New} = 36C_M + 20C_A + (90C_M + 74C_A)\, M. \tag{12}$$

Similarly, the DCL EO-STBC scheme has the total processes as follows (see the Appendix B for more details):

$$C_{DCL\,EO-STBC} = 102C_M + 56C_A + (170C_M + 134C_A)\, M. \tag{13}$$

From Eqs. (12) and (13), it could be noticeable that process time requirement of DCL EO-STBC scheme is higher than its proposed scheme. In order to make it more clearly, we provide the experimental results of the performance by using Monte-Carlo method to get the average transmission time delays between the relays and destination, which are as function of size constellation M (4, 8, 16, 32, 64, 128 and 256-QAM constellations) with $\beta = -3$ dB. In the simulation, the delay time (second) of one symbol includes required time of feedback process, encoding process and decoding operation. Figure 7 shows simulation results by using the computer with CPU dual-core i5 3230M, clock rate of 2.60 GHz and

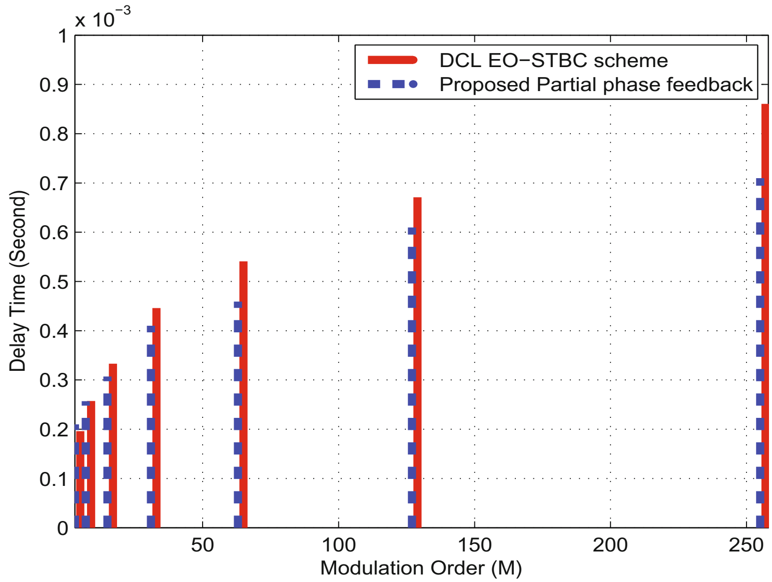

Fig. 7. Comparison time delay between the proposed scheme and DCL EO-STBC [1].

4 Gb random-access memory. These experimental results confirm that our proposed scheme is more efficient than the DCL EO-STBC in terms of time delay.

5 Conclusion

In this paper, a partial feedback scheme for asynchronous cooperative DF relay networks is considered. The proposed partial feedback technique allows to obtain more additional received SNR gain than the DCL EO-STBC scheme and has only previous ISI components at the received symbols. Different from the DCL EO-STBC scheme [1], the proposed scheme does not use DSTC encoding at relay nodes and DSTC decoding at destination node, so it is simpler than the DCL EO-STBC scheme in practical signal processing. The analysis and simulation results demonstrated that the proposed scheme improves the performance of cooperative relay network in both the perfect synchronous and asynchronous channel conditions as compared with existing DCL-STBC works. Moreover, the partial feedback technique is able to extended general cooperative relay network where each relay node has larger than two antennas without an extra study. With these advantages, we believe the proposed scheme can become a prospective candidate for practical cooperative relay networks.

Appendix

A The Processional Requirement of the Proposed Scheme

Firstly, from the step 1 to step 3 at the Subsect. 3.2 in Sect. 3 we can calculate the number of operation for choosing three feedback bits as follows:

$$C_{new\_feedback} = 30C_M + 20C_A. \tag{14}$$

Then, transmitted symbols at the relays are multiplied by these three feedback bits as shown in the Eq. (2) which require the processional complexity as follows:

$$C_{new\_relay} = 6C_M. \tag{15}$$

The decoding complexity of the proposed NOD scheme depends on both the Eqs. (10) and (11) as following:

$$\begin{aligned} C_{new\_NOD} &= C_{new\_eq10} + C_{new\_eq11} \\ &= (32C_M + 22C_A)\,M + (58C_M + 52C_A)\,M \\ &= (90C_M + 74C_A)\,M \end{aligned} \tag{16}$$

where, M is the size of constellation $\mathcal{A}$ (e.g. M-QAM or M-PSK). Therefore, the total processional requirement of the proposed scheme can be written as:

$$\begin{aligned} C_{New} &= C_{new\_feedback} + C_{new\_relay} + C_{new\_NOD} \\ &= 30C_M + 20C_A + 6C_M + (90C_M + 74C_A)\,M \\ &= 36C_M + 20C_A + (90C_M + 74C_A)\,M. \end{aligned} \tag{17}$$

B The Processional Requirement of the DCL EO-STBC Scheme

From the Eqs. (15) and (16) in [1], the requirement of feedback process can be written as:

$$C_{DCL\,EO-STBC\_feedback} = 96C_M + 48C_A. \tag{18}$$

The process of the relays is used to encode the DCL EO-STBC as shown in Eq. (5) [1] and requires the number of operations as follow:

$$C_{DCL\,EO-STBC\_relay} = 16C_M + 8C_A. \tag{19}$$

The complexity of DCL EO-STBC detection is the number of operations from the Eqs. (20) to (24) in [1] and can be written as following:

$$C_{DCL\,EO-STBC\_detection} = (170C_M + 134C_A)\,M. \tag{20}$$

Then, the total processional requirement of the DCL EO-STBC scheme is written as:

$$\begin{aligned} C_{DCL\,EO-STBC} &= C_{DCL\,EO-STBC\_feedback} + C_{DCL\,EO-STBC\_relay} \\ &\quad + C_{DCL\,EO-STBC\_detection} \\ &= 96C_M + 48C_A + 16C_M + 8C_A + (170C_M + 134C_A)\,M \\ &= 102C_M + 56C_A + (170C_M + 134C_A)\,M. \end{aligned} \tag{21}$$

References

1. Qaja, W.M., Elazreg, A.M., Chambers, J.A.: Near-optimum detection scheme with relay selection technique for asynchronous cooperative relay networks. IET Commun. **8**(8), 1347–1354 (2014)
2. Elazreg, A., Kharaz, A.: Sub-Optimum detection scheme for distributed closed-loop quasi orthogonal space time block coding in asynchronous cooperative two dual-antenna relay networks. In: Mumtaz, S., Rodriguez, J., Katz, M., Wang, C., Nascimento, A. (eds.) WICON 2014. LNICST, vol. 146, pp. 217–228. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-18802-7_30
3. Astal, M.T.O.E., Olivier, J.C.: Distributed closed-loop extended orthogonal STBC: improved performance in imperfect synchronization. In: Proceedings of the Personal Indoor and Mobile Radio Communications (PIMRC), England, pp. 1941–1945 (2013)
4. Elazreg, A.M., Abdurahman, F.M., Chambers, J.A.: Distributed closed-loop quasi-orthogonal space time block coding with four relay nodes: overcoming imperfect synchronization. In: Proceedings of the IEEE International Conference on Wireless and Mobile Computing, Networking and Communication, WIMOB, pp. 320–325 (2009)
5. Desouky, A., El-Mahdy, A.: Asynchronous down-link cooperative communication scheme in Rayleigh fading wireless environment. In: Proceedings of the Signal Processing: Algorithms, Architectures, Arrangements, and Applications, pp. 142–146 (2016)
6. Elazreg, A., Chambers, J.: Closed-loop extended orthogonal space time block coding for four relay nodes under imperfect synchronization. In: Proceedings of the Workshop on Statistical Signal Processing, pp. 545–548 (2009)
7. Zheng, F.-C., Burr, A.G., Olafsson, S.: Signal detection for distributed space-time block coding: 4 relay nodes under quasi-synchronisation. IEEE Trans. Commun. **57**(5), 1250–1255 (2009)
8. Elazreg, A.M., Chambers, J.A.: Sub-optimum detection scheme for asynchronous cooperative relay networks. IET Commun. **5**(15), 2250–2255 (2011)
9. Guangxiang, L., Zhuo, W.: Signal detection for cooperative cellular systems with 4 relay nodes under imperfect synchronization. In: Proceedings of the Signal Processing, Communication and Computing (ICSPCC), KunMing, China, pp. 1–6 (2013)
10. Zheng, F.C., Burr, A.G., Olafsson, S.: Near-optimum detection for distributed space-time block coding under imperfect synchronization. IEEE Trans. Commun. **56**(11), 1795–1799 (2008)
11. Astal, M.-T.E., Abu-Hudrouss, A.M., Olivier, J.C.: Improved signal detection of wireless relaying networks employing space-time block codes under imperfect synchronization. Wireless Pers. Commun. **82**(1), 533–550 (2015)

12. Van Bien, P., Son, P.T., Thap, P.H.: Enhancing performance of four transmit antennas and one receive antenna system with partial feedback. In: Proceedings of the International Conference on Advanced Technologies for Communications, pp. 259–262 (2012)
13. Jing, Y.: Combination of MRC and distributed space-time coding in networks with multiple-antenna relays. IEEE Trans. Wireless Commun. **9**, 2550–2559 (2010)
14. Celik, G., Celebi, H.: G-CRLB analysis of time delay based localization for decode-and-forward cooperative relay networks in multipath environments. In: Proceedings of the International Wireless Communications and Mobile Computing, pp. 454–459 (2015)
15. Pham, V.-B.: Spacetime block code design for LTE-advanced systems. Trans. Emerg. Telecommun. Technol. **26**(5), 918–928 (2013)