Exploiting Cross-Layer Packet Overhearing for Opportunistic Distributed STC in Wireless Relay Networks

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***Abstract*—In this paper we propose a distributed Alamouti-based space-time code (STC) where opportunistic listening of packets from independent sources is exploited. Relays overhear broadcasted packets from multiple sources and acknowledge them dynamically. Acknowledgments are also overheard, allowing thus the relays to know the received packets at their neighbors. At each relay, the overheard data packets are multiplexed for generating in a distributed fashion the Alamouti STC that is broadcasted by the relays. Depending on the overheard packets the two relays may use dynamically the aforementioned multiplexed Alamouti STC scheme, or classic decode-and-forward (DF), or exploit transmit diversity with decode and joint forward (DJF). We perform extensive Monte Carlo simulations for testing the proposed protocol and the Alamouti-based STC under different channel conditions in the studied network topology.**

***Index Terms*—Cooperative protocol, Alamouti scheme, space-time block code, distributed space-time code (DSTC), opportunistic listening.**

I. Introduction

The Alamouti scheme [1] has been considered since its inception as the only orthogonal space-time block code (STBC) that can provide full rate and full diversity for a complex symbol constellation. After the original work, there was a significant amount of efforts that attempted to extend the Alamouti scheme from multi-antenna systems into relay-based cooperative systems. In this distributed form, relays first receive a noisy signal from the source. Then, these relays construct an Alamouti STC in a distributed fashion before relaying the signals to the final destination [2], [3]. More general distributed STCs we introduced in [4], [5]. Therefore, with the distributed STC (DSTC) techniques, orthogonal channels do not need to be allocated to various relay omni-directional transmitters, leading thus to better utilization of the spectrum. In order to successfully incorporate multiple relays in a DSTC scheme, the knowledge of the exact number of relays participating in cooperation as well as global channel knowledge is required. This problem is alleviated with a randomized distributed space time code (R-DSTC) [6]. All nodes transmit by forming random linear combinations of the received signal. Randomized distributed space-time coding generalizes other distributed cooperation schemes such as [7]. The basic disadvantage of R-DSTC is that the same symbol, although linearly coded with random coefficients, is transmitted simultaneously from the relays [8]. Therefore, time-diversity cannot be exploited to the fullest.

Antonios Argyriou would like to acknowledge the support from the European Commission through the Marie Curie Intra-European Fellowship WINIE-273041 and the STREP project CONECT (FP7ICT257616).

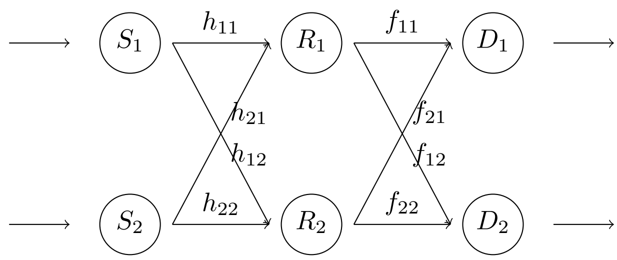


Fig. 1. System model for the distributed Alamouti-based scheme that supports multiplexing from two sources. In this parallel relay network model, the sources cannot communicate directly with their respective destinations.

In this paper we aim at creating an Alamouti-based DSTC so that multiple independent transmitting sources and two overhearing relays are accommodated. The goal is to exploit both spatial and time diversity to the fullest with a distributed STC. This is achieved with the proposed distributed and multiplexed Alamouti (DMX-Alamouti) STC since symbols that belong to different overheard packets are multiplexed and spread out in two successive slots the time domain. The contributions of the proposed system are two. It is independent of the MAC protocol and it does not require a specific channel access scheme, since the sources are allowed to transmit normally when they receive the channel. Therefore, complexity is shifted to the relays that may overhear random packets over the network but are responsible for identifying if they should construct the DSTC. Second, the DSTC is constructed and used dynamically depending on the available packets at the neighbors of a relay.

II. Distributed Alamouti STC with Multiplexed Sources

A. System Model

We study the parallel relay network model where a set of $\mathcal{S} = \{1, 2, ..., N\}$ sources want to communicate with a set of $\mathcal{D} = \{1, 2, ..., N\}$ destinations with the assistance of a set

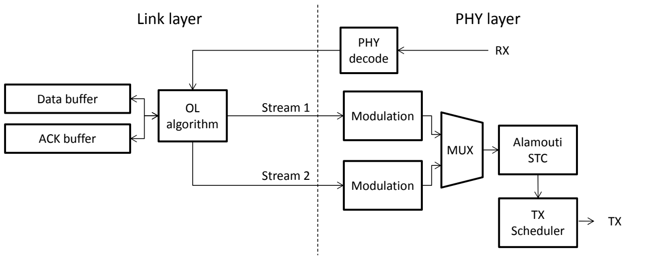


Fig. 2. System block diagram at the relay that depicts cross-layer interactions.

$\mathcal{R} = \{1, 2, ..., M\}$ relays. For our analysis in this paper we will assume $N = M = 2$. In Fig. 1 we present the topology that we study in this paper and it includes two sources, two relays, and two destinations/receivers. The transmission for a packet takes two hops since we assume that there is no direct link between the sources and the destinations. All of the channels, from sources to destinations, sources to relays, and relays to destinations are considered to be block-fading Rayleigh that stay constant for two symbol durations. Additive white Gaussian noise (AWGN) with zero mean and unit variance is assumed at the relays and the destinations. We also assume that all stations in the network are equipped with one antenna and have the same average power constraint.

The cooperative transmission of a packet occurs in two phases. In the first broadcasting phase, the source station S_1 transmits the packet to all its potential relay station(s) R_1, R_2. Each relay first tries to decode the packet by verifying the CRC and then its stores it locally. Subsequently, and when S_2 obtains the channel, it also broadcasts its packet to R_1, R_2 that act also as before. Depending on the status of the two transmissions each relay makes a decision regarding the action of the current relay in the next time slot. With the proposed scheme, the two relays may be allowed to transmit simultaneously in the forwarding phase under the DMX-Alamouti STC. If this is the case, then signals from all relays propagate to both destinations, where they are received by a single antenna at each destination.

B. DMX-Alamouti System Description

As it can already be understood, the core of the system functionality and the intelligence is located at the relays. The single-antenna relay employs a regular single-input and single output (SISO) decoder to decode the information sent by the source station in the first hop. The relay then re-encodes the information bits and passes them to the proposed encoder. The DMX-Alamouti encoder can be seen in the right side of Fig. 2. This encoding scheme basically exploits the existence of two independent correctly decoded streams named *Stream 1* and *Stream 2*. These two streams are manipulated at the bit-level. If the size of the packet is L bits then these two streams are multiplexed and we have the creation of a bitstream with length $2L$. This stream is fed to a standard 2x2 Alamouti STC encoder and the resulting bitstream is broadcasted synchronously with the bitstream from the other relay. We will explain next, with the help of mathematical notation, how the DMX-Alamouti scheme operates while we later describe how the complete cooperative protocol works and how synchronization is achieved. The receiver at the destination station employs a conventional STC decoder with one antenna. In the next subsection we will see in more detail what are the operations that occur during the transmissions from $\mathcal{S} \to \mathcal{R}$ and $\mathcal{R} \to \mathcal{D}$.

C. $\mathcal{S} \to \mathcal{R}$ Channel

Before we describe the system behavior in detail, we define some additional notation first. Every node has a single omni-directional antenna that can be used for both transmission and reception and they all have the same average power constraint. We denote the channel from the s-th transmitter to the r-th relay as $h_{s,r}$, and the channel from the r-th relay to the receiver k as $f_{r,k}$. We also use the notation $x_{s,t}$ with s denoting the id of the source, and t the time slot, in order to distinguish the transmitted symbols. Therefore, the transmitted symbols from the two sources in two consecutive symbol slots is described with the following array

$$\mathbf{X} = \begin{bmatrix} x_{1,1} & x_{2,1} \\ x_{2,1} & x_{2,2} \end{bmatrix},$$

where the vertical dimension corresponds to space while the horizontal to time. If the sources transmit with a symbol energy of E_S, then the received signal for example at relay R_1 during the first and second slots is

$$y_{R_{1,1}} = \sqrt{E_{S_1}} h_{1,1} x_{1,1} + w_{R_{1,1}}, \quad (1)$$

$$y_{R_{1,2}} = \sqrt{E_{S_2}} h_{2,1} x_{2,1} + w_{R_{1,2}}, \quad (2)$$

where $h_{1,1}$ is channel transfer function between the S_1 and relay R_1, and $w_{R_{1,1}}, w_{R_{1,2}}$ denote the AWGN at the relay R_1 during these two slots. Similar expressions apply for R_2.

D. $\mathcal{R} \to \mathcal{D}$ Channel

Now at the relay the symbols are decoded and the result is denoted with $\hat{x}$. If the relays determine that they should transmit the decoded symbols with the DMX-Alamouti scheme, we can express the forwarded signal from the relay at the first and second forwarding symbol time slots as follows. In this case it will be that R_1 and R_2 transmit in the first forwarding slot

$$z_{R_1} = \sqrt{E_{R_1}} \hat{x}_{1,1} \text{ and } z_{R_2} = -\sqrt{E_{R_2}} \hat{x}^*_{2,1}.$$

In the second forwarding time slot similarly

$$z_{R_1} = \sqrt{E_{R_1}} \hat{x}_{2,1} \text{ and } z_{R_2} = \sqrt{E_{R_2}} \hat{x}^*_{1,1}.$$

The received signal at D_1 for one symbol can then be written as follows for the two forwarding slots

$$y_1 = \sqrt{E_{R_1}} f_{1,1} \hat{x}_{1,1} - \sqrt{E_{R_2}} f_{2,1} \hat{x}^*_{2,1} + w_{D_{1,1}}, \quad (3)$$

$$y_2 = \sqrt{E_{R_1}} f_{1,1} \hat{x}_{2,1} + \sqrt{E_{R_2}} f_{2,1} \hat{x}^*_{1,1} + w_{D_{1,2}}. \quad (4)$$

If we assume coherent detection and by using the orthogonality property of the STC, a sufficient statistics to estimate each transmitted symbol, can be expressed as [9]

$$\tilde{x}_1 = \sqrt{E_{R_1}} f^*_{1,1} y_1 + \sqrt{E_{R_2}} f_{2,1} y^*_2. \quad (5)$$

```
proc_ovhd_pkt_relay()
1: if rx_phy() == DATA then
2:    k = DATA.dst
3:    if k == me then
4:       store(DATA.id, data)
5:       wait(T_SIFS), tx_phy(ACK)
6:    else
7:       //Packet not for me (overheard)
8:       store(DATA.id, ovhd)
9:       wait(2T_SIFS + ACK.length)
10:   end if
11: end if
12: if rx_phy() == ACK then
13:    j = ACK.snd, l = ACK.DATA.id
14:    store(l, ovhd_acks)
15: end if
tx_pkt_R1(l, m)
1: if (data.l && ovhd.m)!=NULL  then
2:    if ACKs for l, m in ovhd_acks then
3:       //Other relay received l, m
4:       DMX-Alamouti()
5:    end if
6: end if
7: if (data.l!=NULL && R1==DATA.l.dst then
8:    //Pkt for R1 always TXed in the 3rd slot
9:    tx_phy(DATA.l)
10: end if
11: if (ovhd.m!=NULL && R2==DATA.m.dst then
12:    wait(T_SIFS + DATA.m.length)
13:    tx_phy(DATA.m)
14: end if
```

Fig. 3. The adaptive cooperative protocol for the DMX-Alamouti STC.

III. Cooperative Protocol for DMX-Alamouti

In Fig. 2 we present the behavior of the cooperative protocol that utilizes the previously described distributed and multiplexed Alamouti STC. The basic protocol can be described as follows: During the broadcast phase, S_1 broadcasts and R_1, R_2 decode. During a second broadcast phase, S_2 broadcasts and R_1, R_2 decode. Next, R_1, R_2 forward the coded packet concurrently according to the adaptive cooperative protocol that we describe next. An additional forwarding phase is used when the two relays do not broadcast concurrently.

Now we elaborate a little more on the protocol operation for which a pseudo-algorithm can be seen in Fig. 3. First we focus on the process named $proc\_ovhd\_pkt\_relay()$ that is responsible for opportunistic listening/overhearing. Lines 1-10 in the algorithm of Fig. 3 show this opportunistic listening functionality where even if a relay is not the intended receiver, it still decodes and stores a packet in the **ovhd** data structure [10]. When a relay is the target destination of packet transmission, it responds with this ACK after a specific guard period (e.g. like the short inter-frame space (SIFS) in IEEE 802.11), while if it is the relay that employs opportunistic listening it takes an additional time slot (line 9 in the algorithm of Fig. 3). This ensures that ACKs are not colliding, while both relays know if the other relay decoded successfully the broadcasted packet [10]. This last information is stored in the **ovhd_acks** data structure.

Now when a relay desires to forward to the destination the packets that it may have received during the first two slots, three cases can occur and they are presented in the process $tx\_pkt\_R1(l,m)$. The first case, where DMX-Alamouti encoding is used, occurs when both R_1, R_2 have decoded successfully the packets from S_1 and S_2. R_1 is in a position to determine the above by checking first the data structures **data** and **ovhd** in order to see if itself received them. Then it checks in **ovhd_acks** to find if an ACK was overheard from R_2 for both of these packets. If both conditions happen, the relay proceeds with the use of DMX-Alamouti scheme.

Now the second case occurs when one of the relays decodes one packet and the other relay decodes two packets (regardless of the intended destination). If this case is identified (after the conditions for the DMX-Alamouti encoding fail) then the packet that is received by both relays is transmitted concurrently. To minimize complexity and message passing we adopt a trick: A packet that has as the intended destination the relay R_1, it will always be transmitted in the first forwarding time slot regardless of which node received it, while a packet that has as the intended relay destination R_2 it will always be transmitted in the second forwarding time slot. To illustrate this with an example, consider that R_1 decodes both S_1 and S_2 bitstreams, and R_2 only S_2. Then R_1 knows that it should not multiplex with the proposed DMX-Alamouti scheme the two bitstreams. Instead it broadcasts the two packets in the first and fourth forwarding time slots. At the same time, R_2 has not received S_1 and so it broadcasts the received S_2 in the second forwarding slot. Therefore, in this example R_1, R_2 would essentially apply during the second forwarding slot decode-and-joint forward (DJF). The performance of the S_2 transmission in this way will be enhanced because of transmitter diversity. This control functionality is located in lines 7-14 of the $tx\_pkt\_R1(l,m)$ process.

The third case occurs if both nodes have not received at at least one of the two transmitted packets (either their own or the overheard). In this case they apply classic decode-and-forward (DF) in the pre-determined slots similarly with the previous paragraph.

IV. Performance Analysis

For the first hop, we can model the impact of DMX-Alamouti scheme transmissions as a SISO transmission. Now if M-quadrature amplitude modulation (QAM) is used as the modulation scheme, the exact closed-form BER conditioned on the instantaneous channel SNR γ is

$$P_{e,M} = \frac{2}{\sqrt{M}\log M} \sum_{j=1}^{\log_2 M} \Big[\sum_{i=0}^{(1-2^{-j})\sqrt{M}-1} C_{j,i}(M) \times Q\Big((2i+1)\sqrt{\frac{3\gamma}{M-1}}\Big)\Big], \quad (6)$$

where the coefficient $C_{j,i}(M)$ can be obtained from

$$C_{j,i}(M) = (-1)^{\lfloor 2^{j-1}i/M \rfloor}\Big(2^{j-1} - \Big\lfloor \frac{2^{j-1}i}{\sqrt{M}} + \frac{1}{2} \Big\rfloor\Big). \quad (7)$$

Now in order to calculate the average BER P_e, we take the expectation of (6), and since (7) is a constant we have that

$$\begin{aligned} P_{e,M} &= \frac{2}{\sqrt{M}\log M} \sum_{j=1}^{\log_2 M} \Bigg\{ \sum_{i=0}^{(1-2^{-j})\sqrt{M}-1} C_{j,i}(M) \\ &\times \quad E\Big[Q\Big((2i+1)\sqrt{\frac{3\gamma}{M-1}}\Big)\Big]\Bigg\}. \end{aligned} \quad (8)$$

The packet error rate (PER) for packets of length L is

$$P_{p,M} = 1 - (1 - P_{e,M})^L \quad (9)$$

A. Transmission mode selection probabilities

The previous analysis provides the BER for one hop. Before we proceed further we must calculate the probability that packets originating from certain source nodes are received at certain relays. This will help us calculate the probability that a certain transmission mode is selected from the relays. The first case we have to consider is that no packet is received by any relay node. This happens with probability

$$P[no\_tx] = P_p(S_1,R_1)P_p(S_1,R_2)P_p(S_2,R_1)P_p(S_2,R_2),$$

where it means that each of the point-to-point transmissions has to fail. For the DMX-Alamouti to be used, two independent transmissions from the two sources have to be received at both relays. Therefore, the probability that this happens is:

$$\begin{aligned} P[dmx] &= [1 - P_p(S_1,R_1)] \times [1 - P_p(S_1,R_2)] \\ &\times [1 - P_p(S_2,R_1)] \times [1 - P_p(S_2,R_2)] \end{aligned}$$

Now we also calculate the probability that the DJF scheme is used. In this case the packet from S_1 has to be received by both nodes or if this does not happen, the packet from S_2 has to be received by both nodes. Therefore, we have:

$$\begin{aligned} P[djf] &= (1 - P_p(S_1,R_1))(1 - P_p(S_1,R_2)) \\ &+ [1 - (1 - P_p(S_1,R_1))(1 - P_p(S_1,R_2))] \\ &\times (1 - P_p(S_2,R_1))(1 - P_p(S_2,R_2)) \end{aligned}$$

The final case is that none of the above three cases occur, which means that at least one packet or two different packets are available at each of the relays. In this case the packets have to be transmitted with point-to-point transmission from the relays to the destinations. This event occurs with probability

$$P[p2p] = 1 - (P[djf] + P[dmx] + P[no\_tx]).$$

B. Packet error probability for the second hop

In this section we provide an analysis for estimating the packet loss probability of our scheme in the second hop when the Alamouti code is employed in the multiplexed stream at the relays. From the literature we know the performance of the Alamouti scheme. We average over the different realizations of the related channels to obtain the average BER P_e for an M-QAM modulation scheme (p.p. 77 [9]):

$$P_{e,M,dmx} \approx 2\binom{4N_r - 1}{2N_r}\Big(\frac{1}{2sin^2(\pi/M)}\Big)^2\Big(\frac{1}{\gamma}\Big)^{2N_r} \quad (10)$$

In the above γ is the SNR as defined in the previous subsection and $N_r = 2$ since two relays transmit. When the same two packets are transmitted from the two relays then MRC combining is used at the destinations to enhance the SNR of the received packet. We have that the BER is

$$P_{e,M,djf} = \Big(\frac{1-\Gamma}{2}\Big)^{N_r} \sum_{l=0}^{N_r-1} \binom{N_r - 1 + l}{l}\Big(\frac{1}{2}(1+\Gamma)\Big)^l \quad (11)$$

where $\Gamma = \sqrt{\gamma/(\gamma+1)}$. When in the second hop the relays select the point-to-point direct transmission mode, then the $P_{e,M}$ derivation we performed in the start of this section can be readily used. The previous two BER expressions can be used with the formula in (9) for obtaining the PER.

C. End-to-end packet loss rate

The above analyses are used for calculating the final desired quantity that is the average packet loss rate for the complete system. Therefore, when this scheme is used the end-to-end packet loss rate for one destination is

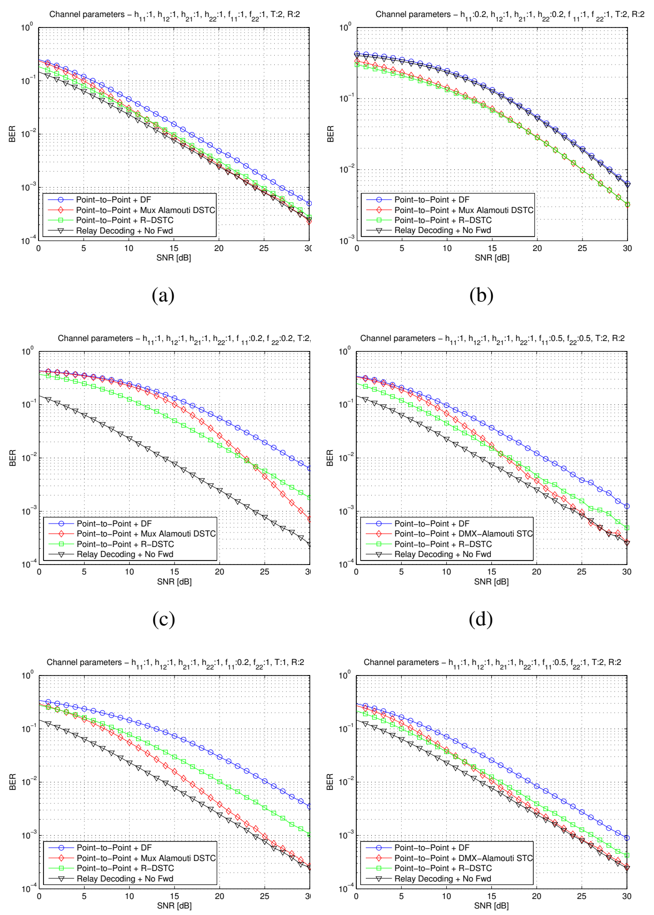
$$\begin{aligned} P_{e2e} &\approx P[p2p] \times P_{p,M} + P[djf] \times P_{p,M,djf} \\ &+ P[dmx] \times P_{p,dmx} \end{aligned} \quad (12)$$

V. Performance Evaluation

We implemented the proposed protocol, that is named DMX-Alamouti in all the result figures, and we evaluated its the performance in terms of BER under different channel conditions through Monte Carlo simulations. The proposed protocol is compared against a system named DF, where each relay receives the bitstream of interest, decodes it and then forwards it by transmitting orthogonally with the other relay to the respective destination. Also the system named NoFwd presents the performance only at each relay after it decodes the bitstream in order to act as a reference result. The final tested protocol is named R-DSTC. With this protocol again each relay decodes all the received bitstreams, and then in the same time slot both relays forward the same signal but each symbol is multiplied with a random Gaussian coefficient [8]. Furthermore, we consider the transmission of packets with a length of L bits (is shown in all the figures). We present the averaged results of 10,000 packet transmissions. The channel bandwidth is 20 MHz, while the AWGN has variance 10^{-9} W/Hz at every node. We also used a Rayleigh fading wireless channel model. The channel transfer functions between the nodes vary independently but they have the same average SNR.

A. Results

Results for a symmetric network in terms of channel SNR can be seen in Fig. 4(a). The results have minor differences in the low SNR regime and the R-DSTC is the optimal choice in this range. For improving channel conditions the performance



(a) (b) (c) (d) (e) (f)

Fig. 4. BER vs. channel SNR.

of the DMX-Alamouti outperforms all the other schemes including the R-DSTC and reaches the optimal which is the NoFwd case. Now we evaluate the first important characteristic of the complete system, that is opportunistic listening. When the primary links from $S_1 \rightarrow R_1$ and $S_2 \rightarrow R_2$ have poor average channel quality of $|\mathrm{h}_{11}| = |\mathrm{h}_{22}| = 0.2$ relative to the rest of the network, the results can be seen in Fig. 4(b). This scenario demonstrates that when the overhearing is jointly employed with the R-DSTC and DMX-Alamouti protocols the poor performance of the primary links can be alleviated.

Now we test the performance for the more interesting links $\mathcal{R} \rightarrow \mathcal{D}$ where they can actually allow us to test the performance of the STC schemes. Higher performance differences can be seen in Fig. 4(c) for very low quality $\mathcal{R} \rightarrow \mathcal{D}$ links, while the performance also differentiates for slightly better conditions in Fig. 4(d). As expected all the cooperative protocols have significant performance differences when compared with the NoFwd system that provides the upper bound. Nevertheless, the DMX-Alamouti scheme is superior again in the high SNR regime when compared to R-DSTC. However, the main advantage of the proposed scheme is when one of the overhearing $\mathcal{R} \rightarrow \mathcal{D}$ links suffers from poor performance and the other one does not. The related results are presented in Fig. 4(e,f). This is the case where the diversity gain can be collected better than R-DSTC. The proposed scheme is able to exploit better spatial and time diversity in this case as the results of very poor channel conditions indicate in Fig. 4(e). When the quality of the direct link f_{11} is improved to $|\mathrm{f}_{11}| = 0.5$, the results in Fig. 4(f) demonstrate that Alamouti-DMX still performs best while the other schemes do not suffer significantly.

VI. Conclusions

In this paper we proposed a distributed Alamouti STC that is based on exploiting opportunistically overheard packets that originate from independent sources. The system model considers two relays that overhear broadcasted packets from the multiple sources and acknowledge them dynamically. The acknowledgments are also overheard so as to allow the relays to know each other's received packets. Depending on the overheard packets the two relays dynamically select the forwarding mode to the final destination that is either the distributed Alamouti scheme, a classic transmit diversity scheme, or direct transmission. We performed extensive Monte Carlo simulations under different channel conditions and we showed that the proposed scheme can outperform a more complex distributed STC schemes under in certain channel conditions. In the future we plan to generalize our scheme to operate with general OSTBCs.

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