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# A Virtual Full Duplex Distributed Spatial Modulation Technique for Relay Networks

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**Abstract**—Spatial modulation, a multiple-input multiple-output (MIMO) technology which uses the antenna *index* to transmit part of the incoming data, is an attractive way to reduce the energy cost and transceiver complexity in future wireless networks. In particular, the recently proposed technique of *distributed* spatial modulation (DSM) for relay networks can lead to better spectral efficiency, as it allows the relays to transmit their *own* data while simultaneously relaying the data of the source. A new distributed spatial modulation protocol is introduced in this paper which achieves *virtual full duplex* (VFD) communication. In this protocol, the source and relays transmit their own data in every time slot; thus, the spectral efficiency is significantly improved compared to conventional DSM. Simulation results indicate that at high signal-to-noise ratio (SNR), the proposed protocol has similar bit error rate (BER) performance versus SNR-per-bit compared to the standard full duplex relaying protocol of *successive relaying*; however, in contrast to successive relaying, the relays are simultaneously transmitting their own data, which is received at the destination with an error rate similar to that of the source's data.

**Index Terms**—Spatial modulation, virtual full duplex, relay networks.

## I. INTRODUCTION

Multiple-input multiple-output (MIMO) systems, which use multiple antennas for transmission and/or reception, represent a key technology for modern wireless communication systems. By using MIMO techniques, wireless systems can increase the system capacity and/or diversity gain [1]. In spite of the many advantages of MIMO systems which have been highlighted in the literature, however, there are some drawbacks for such systems, such as the issues of inter-channel interference (ICI) and inter-antenna synchronization (IAS), together with the requirement for multiple radio frequency (RF) chains. This latter requirement leads to an increase in energy consumption as well as an increased complexity of the transceiver design [2].

A technique which aims to overcome such problems, while retaining the principal benefits of MIMO systems, is spatial modulation (SM) [3]-[4]. In general, an SM system uses two key rules. The first is that during any time slot, only *one* antenna is active (i.e., transmitting); this means that the system avoids the problems of ICI and IAS. Furthermore, there is only one RF chain, which leads to a low-complexity transceiver

design. The second rule is that activation of any antenna depends on the incoming data [2].

SM requires the implementation of several antennas at the transmitter to achieve a high spectral efficiency. For the uplink, the assumption of many antennas is not practical, as the transmitting device is usually a mobile terminal. Fortunately however, the need for multiple antennas can be circumvented by exploiting distributed cooperating half-duplex relays to form a virtual MIMO system [5]. In spite of the many advantages of distributed cooperation, there are some drawbacks such as synchronization issues, the use of the relay's primary resources only for the source's benefit, and a delay in reception of the relays' own data due to their forwarding of the source's data.

The capability of SM for cooperative networks has been considered in [6]-[8]. In particular, distributed spatial modulation (DSM) is a recently proposed relaying protocol which increases the aggregate throughput of the network [7]-[8]. This throughput enhancement is achieved by allowing the relays to transmit their own data in addition to the demodulated source data during the relaying phase. More specifically, the source data is encoded into the *index* of the activated (i.e., transmitting) relay. The main disadvantage of this protocol, however, is that there is no increase in the throughput of the source; it remains the same as that of conventional relay networks, i.e.,  $1/2$  *spcu* (symbol per channel use).

Recently, full duplex communication has been considered in the context of relay networks [9]. These networks allow the relays to transmit and receive simultaneously, effectively doubling the system throughput compared to their half-duplex counterparts. Full duplex transmission at the relay is accomplished by equipping it with multiple antennas (one for transmission and one for reception). However, the significant amount of *self-interference* between transmitting and receiving RF chains means that the implementation of full duplex systems is still quite difficult to achieve [10]. However, we may instead consider a *distributed version* of a full duplex system, called *virtual full duplex* (VFD), where the transmit and receive antennas belong to geographically separate nodes. This idea inherits the benefits of the full duplex system while each relay requires only a single antenna, and thus the individual nodes operate in the conventional half-duplex mode [11].

In this paper, we propose a new relaying protocol based on distributed spatial modulation, which provides the benefits of virtual full duplex operation in order to enhance the throughput of the source as well as the overall network throughput. This means that the source broadcasts new data in every time slot, while the relays simultaneously transmit their own data as well as implicitly relaying the source data through their activation (as per the principle of DSM). Simulation results show that at the destination, the BER of the source data for the proposed protocol (measured with respect to SNR per bit) is close to that of successive relaying. On the other hand, the proposed protocol also allows the transmission of the relay's own data with similar error rate performance, thus approximately doubling the aggregate throughput with respect to successive relaying.

The remainder of this paper is organized as follows. In Section II, a summary of the existing half duplex DSM approach is given, and the necessity for re-designing this protocol for virtual full duplex operation is explained. A description of the system model for the new protocol is presented in Section III, together with a description of the associated signal processing at the relay and at the destination. Section IV presents simulation results, and Section V presents conclusions for this work.

## II. SUMMARY OF HALF-DUPLEX DSM AND THE NECESSITY FOR REDESIGN

In this section, the DSM protocol of [7], which was proposed for distributed networks with half-duplex relay nodes, is briefly overviewed. The extension of this protocol to a virtual full duplex system is also briefly discussed.

In conventional half duplex DSM, there is one source, one destination and  $M = 2^q$  relays. A unique  $q$ -bit identifier (or ID) is assigned to each relay before the start of transmission. In each odd time slot  $2k - 1$ , the source broadcasts an  $M$ -ary symbol which is received by the relays and the destination. All relay nodes immediately demodulate the source data (consisting of a  $q$ -bit vector  $x_s(2k - 1)$ ), while the destination saves the received signal  $y_D(2k - 1)$  for processing in the next time slot. In the next (even) time slot  $2k$ , if there is a match between the detected source data at any relay and that relay's ID, this relay is activated and transmits its own data-bearing symbol in time slot  $2k$ . Therefore, the activation of any relay conveys information regarding the source data, while the activated relay transmits its own data-bearing symbol. The destination receives the signal  $y_D(2k)$  at the destination in time slot  $2k$ , which conveys information regarding the data of the relay and the source. The destination then performs joint ML detection of the source and relay data using the received signals  $y_D(2k - 1)$  and  $y_D(2k)$ .

To extend this scheme to virtual full duplex operation, we require that the source broadcast a new data-bearing symbol in every time slot. As long as the source symbol for any time slot is different to that for the previous time slot, the system works similarly to the half duplex case, as every relay is then free from activation when receiving a symbol matching its ID.

However, a problem occurs when two successive equal symbols are transmitted from the source. This means that a relay which is activated by the first of these two successive equal symbols misses its re-activation by the second symbol (as it is actively in the process of transmitting during the source's transmission of the second symbol). It is therefore clear that the original DSM protocol requires a nontrivial improvement for extension to virtual full duplex communication. Such a redesign, which reaps the benefits of DSM while overcoming the half duplex constraint, is introduced in the next section.

## III. SYSTEM MODEL FOR NEW PROTOCOL

As explained in the previous section, a problem for the basic extension of half duplex DSM occurs when two successive equal symbols are transmitted from the source. To solve this problem, we propose the addition of a single extra relay  $R_p$ , called a *proxy relay*, to the set of existing relays, which we call *main relays* from now on. The task of the proxy relay is to perform the job of a main relay when such a main relay is in the process of transmitting and is therefore unable to receive a signal from the source. It becomes active therefore whenever it detects two successive equal symbols from the source.

### A. Notation and Definitions

The following introduces some notations and definitions which will be used throughout this paper. Transmission takes place over a number of discrete *time slots*  $k \geq 1$ . The received signal at node  $Q$  in time slot  $k$  is denoted by  $y_Q(k)$ . The fading channel between nodes  $X$  and  $Y$  in time slot  $k$  is represented by a complex Gaussian random variable  $h_{XY}(k)$  having mean zero and variance  $\sigma_{XY}^2$  per dimension. All channel coefficients  $h_{XY}(k)$  are assumed to be independent random variables. The complex additive white Gaussian noise (AWGN) at node  $Q$  in time slot  $k$  is given by  $n_Q(k)$  having mean zero and variance  $\sigma^2 = N_0/2$  per dimension, where  $N_0$  is the one-sided noise power spectral density. Maximum likelihood (ML) detection is considered at the relays and at the destination.

A multi-relay protocol with one source ( $S$ ), one destination ( $D$ ) and  $N_r \geq 3$  relays is considered. The  $M$ -ary transmit constellation for the source, denoted by  $\mathcal{A}_s = \{p_1, p_2, \dots, p_M\}$ , is normalized to have unit average energy, i.e.,  $\mathbb{E}_{p \in \mathcal{A}_s} \{|p|^2\} = 1$ ; this is assumed to be a complex constellation such as  $M$ -ary phase-shift keying (PSK) or quadrature amplitude modulation (QAM). The total number of relays is determined by the source modulation order as  $N_r = M + 1$ . There are  $M$  "main" relays denoted by  $\{R_1, R_2, \dots, R_M\}$ , and one "proxy" relay denoted by  $R_p$ . The value of  $M$  is chosen to be a power of 2.

Each main relay  $R_r$ , where  $r \in \{1, 2, \dots, M\}$ , is assigned a unique identifier, denoted  $\text{ID}_{R_r}$ , of length  $\log_2(M)$  bits. For instance, if  $M = 4$ , the main relays  $R_1, R_2, R_3, R_4$  may be assigned the identifiers  $\text{ID}_{R_1} = 00$ ,  $\text{ID}_{R_2} = 01$ ,  $\text{ID}_{R_3} = 10$  and  $\text{ID}_{R_4} = 11$ , respectively. Let  $x_s(k)$  be the  $\log_2(M)$  bits to be transmitted by the source in time slot  $k$ . Then  $p_s(k) = \mathcal{M}_s(x_s(k))$  is the PSK/QAM complex symbol transmitted from the source, where  $\mathcal{M}_s(\cdot)$  denotes the bit to symbol modulation mapping at the source.

We define  $\Phi_k \subseteq \{R_1, R_2, \dots, R_M, R_p\}$  to be the set of active (transmitting) relays in time slot  $k \geq 1$ . Denote by  $\bar{\Phi}_k$  the complement of  $\Phi_k$  (this is then the set of relays in receive mode in time slot  $k$ ). Since no relay is active in the first time slot, we have the initial conditions  $\Phi_1 = \emptyset$  and  $\bar{\Phi}_1 = \{R_1, R_2, \dots, R_M, R_p\}$ . In each time slot  $k \geq 1$ , the source broadcasts a new complex symbol which is received by the destination  $D$  as well as by all relays in the *inactive* set  $\bar{\Phi}_k$ . Meanwhile, relays in the active set  $\Phi_k$  are busy transmitting their own data. Under normal operating conditions, exactly one relay will be active in time slot  $k$  ( $|\Phi_k| = 1$ ); however, this will not always be the case as we shall see in Subsection III-B.

### B. Relay processing and activation

Denote the average transmit symbol energy at the source by  $E_s$ . In each time slot  $k \geq 1$ , every inactive relay  $F \in \bar{\Phi}_k$  receives a signal

$$y_F(k) = \sqrt{E_s} h_{SF}(k) p_s(k) + n_F(k), \quad (1)$$

and demodulates according to the maximum likelihood criterion, giving the source symbol estimate

$$\hat{p}_s^{(F)}(k) = \arg \min_{\tilde{p}_s(k) \in \mathcal{A}_s} \{|y_F(k) - \sqrt{E_s} h_{SF}(k) \tilde{p}_s(k)|^2\}. \quad (2)$$

The source data is then estimated at this relay  $F \in \bar{\Phi}_k$  via  $\hat{x}_s^{(F)}(k) = \mathcal{M}_s^{-1}(\hat{p}_s^{(F)}(k))$ .

The rules governing the activation of the relays are then as follows. First, each main relay  $R_r \in \bar{\Phi}_k$  (i.e., each main relay which is *not* active in time slot  $k$ ) will detect the source data  $\hat{x}_s^{(R_r)}(k)$  in time slot  $k$ . If the detected data matches that relay's ID, relay  $R_r$  will be active in the next time slot  $k+1$ . In other words, for each  $k \geq 1$  and  $r \in \{1, 2, \dots, M\}$ , if  $R_r \in \bar{\Phi}_k$  then

$$R_r \in \Phi_{k+1} \text{ if and only if } \hat{x}_s^{(R_r)}(k) = \text{ID}_{R_r}.$$

If the main relay  $R_r$  is *active* in time slot  $k$ , then it cannot estimate the source symbol  $x_s(k)$  and thus it cannot be activated in this way. Therefore, if  $R_r \in \Phi_k$  then  $R_r \notin \Phi_{k+1}$ .

In the case that the source broadcasts two successive equal symbols, i.e.,  $x_s(k-1) = x_s(k)$ , the main relay  $R_r$  with matching ID is unable to receive the second symbol  $x_s(k)$ , as it has been activated by detection of the first symbol  $x_s(k-1)$ . Therefore, the role of the proxy relay  $R_p$  is to be activated on behalf of this busy relay. Thus, rather than having its own specific ID, the proxy relay will be activated when it detects two successive equal symbols from the source. Note that to do this, it cannot be active during either of these source transmissions. In summary,  $R_p \notin \Phi_1$  and  $R_p \notin \Phi_2$ , and for  $k \geq 3$ ,

$$R_p \in \Phi_k \text{ if } R_p \in \bar{\Phi}_{k-1}, R_p \in \bar{\Phi}_{k-2} \text{ and } \hat{x}_s^{(R_p)}(k-1) = \hat{x}_s^{(R_p)}(k-2).$$

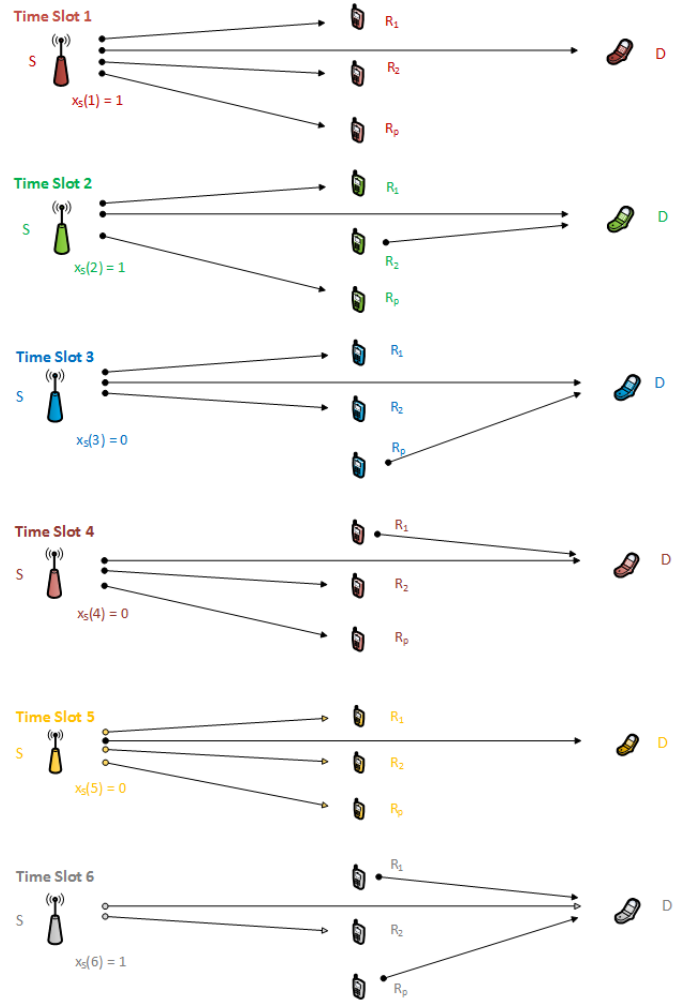


Fig. 1. Illustration of the proposed virtual full duplex DSM protocol for the example source data sequence  $\{x_s(1), x_s(2), x_s(3), \dots\} = \{1, 1, 0, 0, 0, 1, \dots\}$  and the constellation size  $M = 2$ . The system uses  $N_r = M + 1 = 3$  relays. For the main relays, we have  $\text{ID}_{R_1} = 0$  and  $\text{ID}_{R_2} = 1$ . For simplicity, it is assumed that demodulation at the relays is error-free.

An illustration of the operation of the proposed virtual full duplex DSM protocol is given in Fig. 1. The illustration is for a source constellation size  $M = 2$  (i.e.,  $M + 1 = 3$  relays) and the example source data sequence  $\{x_s(1), x_s(2), x_s(3), \dots\} = \{1, 1, 0, 0, 0, 1, \dots\}$ . Here we assume  $\text{ID}_{R_1} = 0$  and  $\text{ID}_{R_2} = 1$ . For simplicity, it is assumed that demodulation at the relays is error-free. In time slot 1, no relay is active, so that all relays receive the symbol of the source. In this time slot, the main relay  $R_2$  detects a match of the demodulated source symbol with its own ID ( $\hat{x}_s^{(R_2)}(1) = 1$ ); therefore it becomes active in time slot 2. In time slot 2, a second equal symbol is transmitted by the source ( $x_s(2) = x_s(1) = 1$ ); however, relay  $R_2$  is busy transmitting and misses its detection. However, activation of a relay still occurs in this case; the proxy relay  $R_p$  detects two successive equal source symbols  $\hat{x}_s^{(R_p)}(1) = \hat{x}_s^{(R_p)}(2) = 1$ , so that  $R_p$  becomes active in time slot 3 on behalf on relay  $R_2$ .

The example also illustrates some irregular activation se-

quences which may arise during operation of the protocol. In time slot 4, relay  $R_1$  is active, having demodulated a symbol matching its ID in the previous time slot ( $\hat{x}_s^{(R_1)}(3) = 0$ ). In the same time slot, a second equal symbol is transmitted by the source ( $x_s(4) = 0$ ), which is not detected by the busy relay  $R_1$ ; however the proxy relay also misses being activated in time slot 5 as it was active and hence unable to receive in time slot 3. Therefore, no relay is activated in time slot 5. Meanwhile, in time slot 5 the symbol  $x_s(5) = 0$  is transmitted by the source, which causes both relays  $R_1$  and  $R_p$  to be active in time slot 6. As we shall see in Section III-C, these irregular activation patterns of the protocol will not pose a problem, as the destination will be capable of tracking the sequence of active relay sets  $\{\Phi_k\}$  throughout the transmission process, and hence detecting such instances of non-activation and double-activation.

Note that a key characteristic of this protocol is the requirement of only one additional proxy relay, regardless of the number of main relays and of the constellation sizes used at source and relays.

### C. Destination Processing

Each activated relay  $F \in \Phi_k$  will transmit its own data  $x_F(k)$  in time slot  $k \geq 1$ . The PSK/QAM complex symbol transmitted from relay  $F$  is denoted  $q_F(k) = \mathcal{M}_r(x_F(k))$ , where  $\mathcal{M}_r$  denotes the bit to symbol mapping at the relays. Each relay uses the same transmit constellation  $\mathcal{A}_r = \{q_1, q_2, \dots, q_N\}$  of size  $N$  which is normalized to unit average energy, i.e.,  $\mathbb{E}_{q \in \mathcal{A}_r} \{|q|^2\} = 1$ .

As the system is virtual full duplex, the destination receives in each time slot the superposition of the signal from the source with the signals from all active relays. In normal operation, only one relay is active, but in practice no relay may be active, or indeed more than one relay may be simultaneously active, due either to relay demodulation error(s) or due to occurrence of the conditions illustrated in time slots 5 and 6 in the example of Figure 1. Therefore, denoting the average transmit symbol energy at any relay by  $E_r$ , the received signal at the destination in the current time slot  $k$  may be written as

$$y_D(k) = \sqrt{E_s} h_{SD}(k) p_s(k) + \sum_{F \in \Phi_k} \sqrt{E_r} h_{FD}(k) q_F(k) + n_D(k) \quad (3)$$

while the received signal at the destination in the previous time slot  $k-1$  (which was stored at the destination for use in the current time slot) may be written as

$$y_D(k-1) = \sqrt{E_s} h_{SD}(k-1) p_s(k-1) + \sum_{G \in \Phi_{k-1}} \sqrt{E_r} h_{GD}(k-1) q_G(k-1) + n_D(k-1). \quad (4)$$

Note that by the principle of DSM, knowledge of the set of active relays  $\Phi_k$  for time slot  $k$  yields information regarding the source data in time slot  $k-1$ . Therefore, in time slot  $k$  the destination performs joint ML detection of the previous source symbol  $x_s(k-1)$ , the current active relay set  $\Phi_k$ , and

the corresponding relays' data symbols (i.e.,  $x_F(k)$  for all  $F \in \Phi_k$ ), based on the two received signals  $y_D(k)$  and  $y_D(k-1)$  given by (3) and (4) respectively. In the detection process, it will use the estimate  $\hat{x}_s(k-2)$  of the source symbol in time slot  $k-2$ , as well as the estimate  $\hat{\Phi}_{k-1}$  of the set of active relays in time slot  $k-1$ , together with the associated transmit symbols  $\hat{q}_G(k-1) = \mathcal{M}_r(\hat{x}_G(k-1))$  for every relay  $G \in \hat{\Phi}_{k-1}$ . These estimates are available from the ML detection process applied in previous time slots. The destination's joint ML detection therefore operates according to

$$\begin{aligned} \{\hat{p}_s(k-1), \hat{\Phi}_k, \{\hat{q}_F(k)\}\} = & \arg \min_{\substack{\tilde{p}_s(k-1), \tilde{p}_s(k) \in \mathcal{A}_s \\ \tilde{q}_F(k) \in \mathcal{A}_r, \forall F \in \tilde{\Phi}_k}} \left\{ |y_D(k) \right. \\ & - (\sqrt{E_s} h_{SD}(k) \tilde{p}_s(k) + \sum_{F \in \tilde{\Phi}_k} \sqrt{E_r} h_{FD}(k) \tilde{q}_F(k)) \left. \right|^2 \\ & + \left| y_D(k-1) - (\sqrt{E_s} h_{SD}(k-1) \tilde{p}_s(k-1) \right. \\ & \left. + \sum_{G \in \tilde{\Phi}_{k-1}} \sqrt{E_r} h_{GD}(k-1) \tilde{q}_G(k-1)) \right|^2 \left. \right\} \quad (5) \end{aligned}$$

The estimated data is then obtained via  $\hat{x}_s(k-1) = \mathcal{M}_s^{-1}(\hat{p}_s(k-1))$  and  $\hat{x}_F(k) = \mathcal{M}_r^{-1}(\hat{q}_F(k))$ .

Note that in the joint detection problem,  $\tilde{p}_s(k-1)$  and  $\tilde{p}_s(k)$  represent hypotheses regarding the source symbols in time slots  $k-1$  and  $k$ ,  $\tilde{\Phi}_k$  represents the hypothesized active relay set, and  $\tilde{q}_F(k)$  represent a hypothesis regarding the transmitted symbol of any relay  $F$  which is active in time slots  $k$  (so that the detection algorithm hypothesizes over possible active relay sets as well as all possible symbols transmitted by the relays in that set). Note that while the minimization in (5) will correspond to a particular value of  $\tilde{p}_s(k)$ , the decision on this symbol will be reserved until the next time slot.

To achieve low-complexity ML detection as well as to ensure that detection yields a source symbol sequence and an active relay set sequence which are consistent with each other, the set  $\tilde{\Phi}_k$  is constrained to contain only those relays which are consistent with the source data hypothesis  $\tilde{p}_s(k)$  and previous decisions regarding active relay sets and data. Therefore, for  $r \in \{1, 2, \dots, M\}$ , if  $R_r \in \tilde{\Phi}_{k-1}$  then  $R_r \notin \tilde{\Phi}_k$ , while if  $R_r \notin \tilde{\Phi}_{k-1}$  then  $R_r \in \tilde{\Phi}_k$  provided  $\tilde{x}_s(k) = \text{ID}_{R_r}$ . We mention here the initial condition  $\tilde{\Phi}_1 = \emptyset$ . Also,  $R_p \notin \tilde{\Phi}_1$  and  $R_p \notin \tilde{\Phi}_2$ , while for  $k \geq 3$  we have that  $R_p \in \tilde{\Phi}_k$  provided  $R_p \notin \tilde{\Phi}_{k-1}$ ,  $R_p \notin \tilde{\Phi}_{k-2}$  and  $\tilde{x}_s(k-1) = \hat{x}_s(k-2)$ . Using these rules,  $\tilde{\Phi}_k$  is not an independent variable in (5) but is completely determined by the other variables (hypotheses and previous decisions).

Another prominent full duplex relaying protocol, called *successive relaying* [12]-[14], is considered as a baseline for performance comparison in this paper. The successive relaying protocol, which uses two relays, is illustrated in Fig. 2. At every odd time slot  $2k-1$ , relay  $R_1$  forwards the symbol received from the source in the previous time slot while relay  $R_2$  receives the current transmission of the source. In the next (even) time slot  $2k$ , the relays interchange their roles:

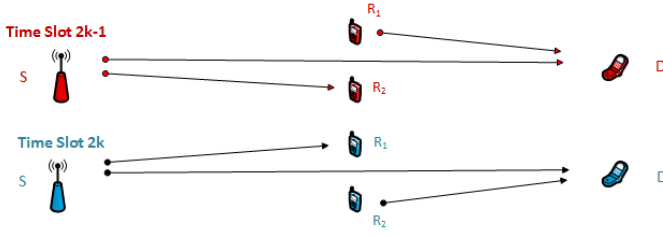


Fig. 2. Illustration of the successive relaying protocol.

$R_2$  forwards the previous source symbol while  $R_1$  receives. Therefore, successive relaying allows the relays to transmit and receive alternately while the source is transmitting data continuously. The destination performs ML detection of the source data over the two time slots  $2k - 1$  and  $2k$ .

#### IV. SIMULATION RESULTS AND DISCUSSION

In this section, simulation results are presented for the proposed protocol, and a comparison is made with the performance of successive relaying. The following setup has been assumed: *i*) all wireless links are assumed to be of identical average quality, i.e.,  $\sigma_{XY}^2 = 1/2$  for all wireless links  $XY$ ; *ii*) the average transmit symbol energy at the relays is double that at the source, i.e.,  $E_r = 2E_s$ , both for successive relaying and for the proposed VFD DSM scheme; *iii*) BPSK is used at all transmitting nodes in both protocols (i.e.,  $M = N = 2$ ); *iv*) it is assumed for both protocols that no inter-relay interference is present.

A comparison of the BER of the detected source data for the proposed virtual full duplex DSM system and for successive relaying is shown in Fig. 3. It can be seen that at high SNR, the source data BER of the proposed virtual full duplex DSM system appears to be approximately 3 dB worse than that for successive relaying. However, note that for the same value of  $E_s$ , the VFD DSM system is using half the average transmit energy per *bit* compared with successive relaying; therefore, the BER performance of the two systems, when measured against SNR per *bit*, are almost identical.

Note however that in successive relaying, the relays do not transmit their own data, so that the proposed scheme has an aggregate throughput advantage of approximately 100% (taken together, the relays have a data rate slightly worse than that of the source). This is the key benefit of DSM-based systems compared to conventional relaying protocols. The cost of this increased throughput is the addition of the proxy relay.

Fig. 4 compares the BER for the detected source and relay data. It can be seen that the BER for the main relays is close to that of the source, while the data of the proxy relay has a less favorable BER. One reason for this difference is the irregular behavior of the protocol as shown in time slots 5 and 6 in Fig. 1.

#### V. CONCLUSION

In this paper, a new protocol for virtual full duplex relaying was proposed, based on distributed spatial modulation. A joint

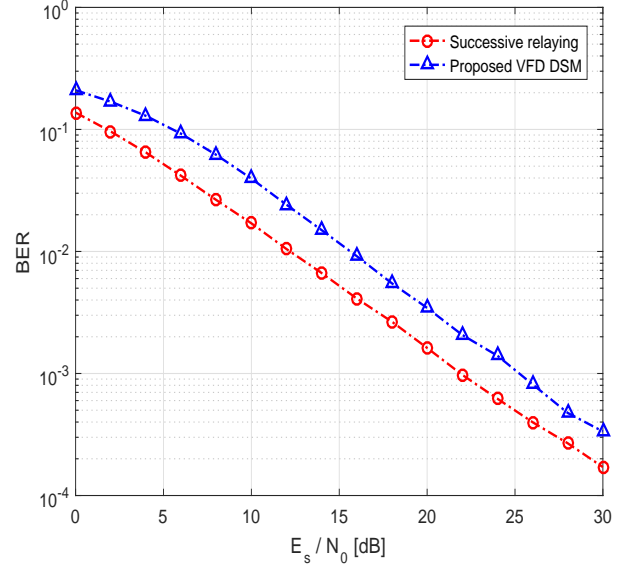


Fig. 3. Comparison of BER of source data for the proposed virtual full duplex DSM scheme with that of successive relaying.

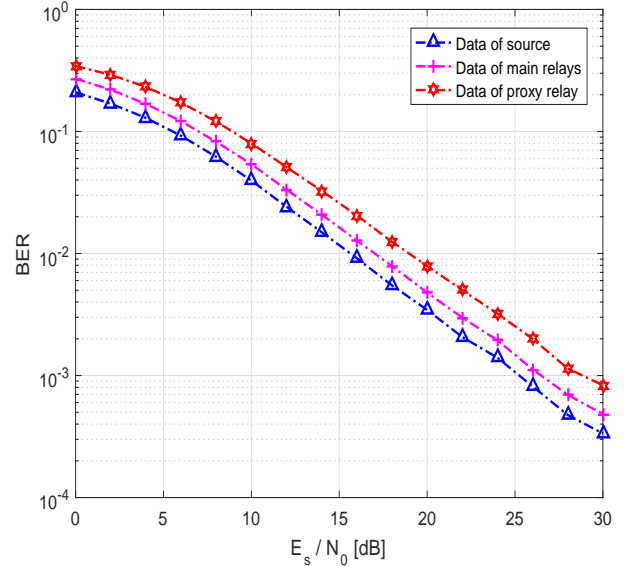


Fig. 4. Comparison of the BER of the different relays for the proposed virtual full duplex DSM scheme.

ML detection method was proposed for implementation at the destination, taking into account the received signals over two time slots. The error rate performance of the proposed system was compared to that of successive relaying. Simulation results confirm that regarding the detection of the source data, the performance of the proposed protocol is very close to that of successive relaying, while the VFD DSM protocol allows also the transmission of the relay's own data with a similar error rate performance. The aggregate throughput of the proposed

protocol is approximately double that of successive relaying, at the cost of adding a single additional relay to the system.

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