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# Virtual Full-Duplex Distributed Spatial Modulation with SER-Optimal and Suboptimal Detection

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**Abstract**—Spatial modulation, a multiple-input multiple-output (MIMO) technology which uses the antenna index as an additional means of conveying information, is an emerging technology for modern wireless communications. In this paper, a new distributed version of spatial modulation is proposed which achieves *virtual* full-duplex communication (VFD-DSM), allowing the source to transmit new data while the relay set forwards the source’s data in every time slot. Two maximum *a posteriori* (MAP) detection methods at the destination are proposed for this VFD-DSM protocol: one, called *local* MAP, is based on processing the signals received over each pair of consecutive time slots, while the other, called *global* MAP, is based on symbol-error-rate optimal detection over an entire frame of data. Simulation results for the proposed VFD-DSM protocol indicate that for source data detection at high signal-to-noise ratio (SNR), VFD-DSM with local MAP detection can provide a similar error rate performance to that of successive relaying, while providing a significant throughput advantage since the relays can forward the source transmissions while also transmitting their own data. Furthermore, the use of global MAP detection is shown to yield a further 1.8 dB improvement in source data error rate while still maintaining this throughput advantage.

## I. INTRODUCTION

The use of multiple antennas in wireless systems, popularly known as MIMO technology, has gained significant attention in the past two decades due to its powerful performance-enhancing capabilities [1]. However, in spite of the excellent advantages of MIMO communication such as increasing the system capacity and diversity, two major drawbacks of MIMO systems are related to the complexity and system cost. These problems arise naturally due to the need for multiple RF chains in a MIMO system, which causes issues related to inter-channel interference (ICI) and inter-antenna synchronization (IAS) [2], [3].

Among the methods which have been proposed to tackle these issues of MIMO, spatial modulation (SM) has been proposed as a new modulation concept for MIMO communication in order to reduce the cost and complexity of the system while still guaranteeing a good data rate [4]. An SM system operates by activating only *one* antenna for data transmission in any particular time slot, while the *index* of the active antenna conveys further information [2]–[4].

Implementation of SM in half-duplex cooperative networks has been considered in [5]–[8]. In particular, a distributed version of spatial modulation (DSM) was proposed in [7], [8] in which the source data is encoded into the *index* of the activated (i.e., transmitting) relay. The use of DSM increases the

aggregate throughput of the network, as the relays send their own data while the relay activation index conveys additional information regarding the source data. Another merit of using a DSM system is a solution for implementation problems of SM for uplink communication; in particular, the assumption of many transmit antennas is not practical when the transmitter is a mobile device. In such a scenario, a DSM system can compensate for this issue by exploiting distributed cooperating half-duplex relays to form a virtual MIMO system. However, despite the benefits of DSM over other distributed cooperation protocols, the problem of increasing the source data throughput is still open; this remains the same as that of conventional relay networks and is limited to  $1/2$  *spcu* (symbol per channel use).

Full-duplex communication in relay networks has been studied in [9] and [10], where the network permits the source and relays to transmit their data in every time slot, effectively doubling the throughput of the system compared to their half-duplex counterparts. In these networks, the relays can be equipped with multiple antennas, but the existence of *self-interference* is still a significant issue for such networks. One solution is to consider a distributed version of the half-duplex system, called *virtual full-duplex* (VFD), where the transmit and receive antennas belong to physically separated nodes [11], [12].

In this paper, a new virtual full-duplex protocol is proposed which works with DSM. In addition, two detection methods are proposed for the destination node. The first detection method, called *local* MAP detection, applies the MAP principle for detection over only two consecutive time slots and requires feedforward of previous decisions. The second detection method, called *global* MAP detection, is symbol-error-rate optimal and is based on the forward-backward algorithm (also known as the Bahl-Cocke-Jelinek-Raviv algorithm, after the authors of the first paper on this topic) [13].

Note that [14] also proposed a redesign of the DSM protocol for virtual full-duplex operation. This involved the introduction of an extra relay, called a *proxy relay*, which is activated if and only if it receives two successive equal symbols from the source. This protocol was shown in [14] to have a similar BER performance versus SNR-per-bit compared to the standard full-duplex protocol of *successive relaying* [15], [16]; however, the addition of the proxy relay increases the system’s complexity and cost. In contrast to that work, here the same data throughput is achieved without the need for an additional relay.

## II. SYSTEM MODEL

### A. Brief Review of Distributed Spatial Modulation

In this section, a brief explanation of conventional half-duplex DSM [7], [8] is presented. In this protocol, a network topology with 1 source, 1 destination, and  $M = 2^q$  relays is considered. A fixed unique  $q$ -bit digital identifier (ID) is assigned to each relay. Two time slots are required for a complete transmission; in each odd time slot  $2k - 1$ , the source broadcasts an  $M$ -ary symbol and it is received by the destination as well as received and demodulated by all relays. In the next (even) time slot  $2k$ , if the demodulated source data at any relay matches that relay's ID, that relay will become active and transmit its own data to the destination (using a standard modulation format). An example is shown in Fig. 1 A) for the case  $M = 2$ . Thus, the signal received by the destination from the activated relay conveys information regarding the source data (through the relay-to-destination channel coefficient) as well as the relay's data. The destination's received signals for these two consecutive time slots are processed at the destination in order to perform joint MAP detection of the source data for time slot  $2k - 1$  and the relay data for time slot  $2k$ .

### B. Proposed Virtual Full-Duplex DSM Protocol

The basic DSM protocol described in the previous section can be extended to achieve virtual full-duplex communication as follows. First, the communication is *frame-based*; a frame of  $N + 1$  time slots is used to transmit  $N$  source symbols. The relay activation rule is as before; however, a new symbol is being transmitted by the source in every time slot  $k$ , where  $1 \leq k \leq N$ . In time slot  $N + 1$ , the source is silent, or equivalently transmits the constellation symbol 0 which is not "detected" by the destination. An illustration of the operation of the proposed virtual full-duplex DSM protocol is given in Fig. 1 B). The illustration is for the case  $N = 4$ ,  $M = 2$  and source data sequence  $\{b_s(1), b_s(2), b_s(3), b_s(4)\} = \{1, 0, 0, 1\}$ . Here we assume  $ID_{R_1} = 0$  and  $ID_{R_2} = 1$ . For simplicity, in the illustration it is assumed that demodulation at the relays is error-free.

At first glance, the continuous transmission by the source causes a potential problem regarding the destination's detection procedure. It will happen regularly that the source broadcasts two successive equal symbols, as occurs for example in time slots 2 and 3 in Fig. 1 B) (i.e.,  $b_s(2) = b_s(3) = 0$ ). This means that relay  $R_1$ , whose ID matches this symbol, will miss its activation in time slot 4, as it is active in the time slot 3 and therefore cannot detect the source symbol  $b_s(3)$ . However, the key observation here is that the resulting silence (inactivation) of all relays in time slot 4 *also conveys information*; therefore, this event does not cause any problem provided that the destination's MAP detector is aware of this event and takes it into account as one of the hypotheses during its MAP detection procedure. Explicit details regarding how this is achieved will be given in the next section.

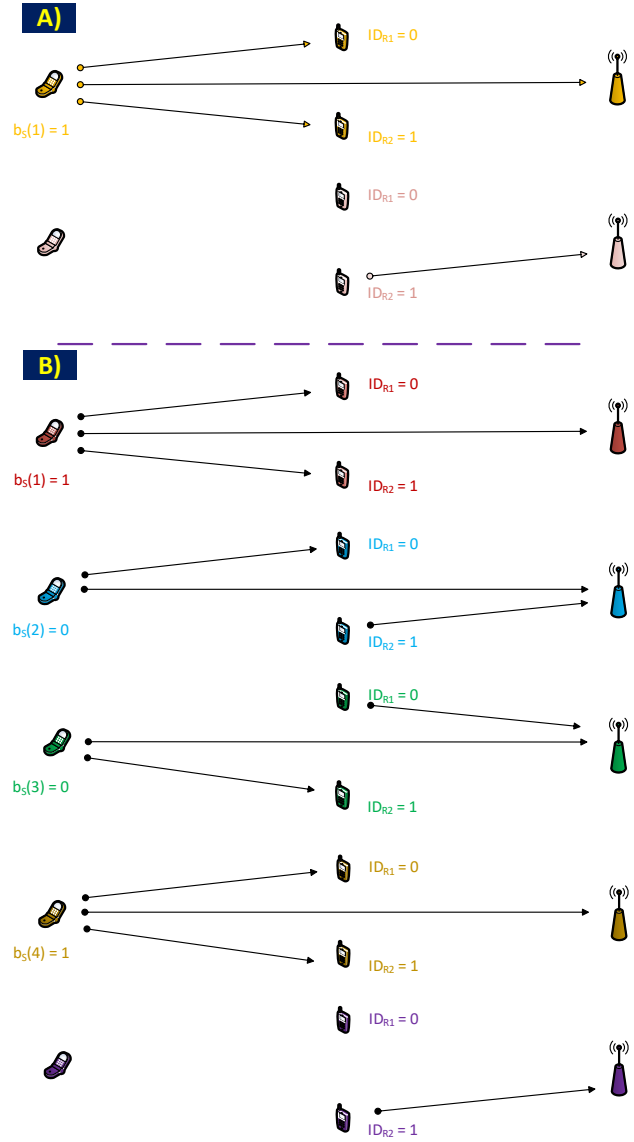


Fig. 1. A) Illustration of distributed spatial modulation in half-duplex mode. In the first time slot, the source broadcasts its data and in the second time slot, the relay whose ID matches with the received data will be active and transmit its own data to the destination. B) A full-duplex counterpart of DSM for the case  $N = 4$  and  $M = 2$ , with source data sequence  $\{b_s(1), b_s(2), b_s(3), b_s(4)\} = \{1, 0, 0, 1\}$  (terminated by a time slot during which the source is silent). For simplicity, it is assumed that demodulation at the relays is error-free.

### C. Definitions and Notations

The following definitions and notations are used throughout this paper. A multi-relay network topology with one source ( $S$ ), one destination ( $D$ ), and  $M = 2^q$  relays  $\{R_1, R_2, \dots, R_M\}$  is considered. All nodes are equipped with a single antenna, and all relays (as well as the source) have their own data to be delivered to the destination. The complex constellation used at the source, denoted by  $\mathcal{A}_s$ , is assumed to consist of phase shift keying (PSK) or quadrature amplitude

modulation (QAM) symbols. This constellation is normalized to have unit average energy, i.e.,  $\mathbb{E}_{x \in \mathcal{A}_s} \{|x|^2\} = 1$ . The symbol transmitted by the source in time slot  $k \geq 1$  is  $x_s(k) = \mathcal{M}_s(b_s(k))$ , where  $b_s(k)$  is the information bit sequence of length  $\log_2(M)$  and  $\mathcal{M}_s(\cdot)$  represents the bit-to-symbol mapping at the source. Similarly, each active relay  $F$  uses a unit-energy PSK/QAM constellation  $\mathcal{A}_r$  of size  $M'$  for transmitting its own data symbol  $x_F(k) = \mathcal{M}_r(b_F(k))$  in time slot  $k > 1$ , where  $b_F(k)$  is the information bit sequence of relay  $F$  having length  $\log_2(M')$ , and  $\mathcal{M}_r(\cdot)$  represents the bit-to-symbol mapping at relay  $F$ .

The received signal at any node  $B$  in time slot  $k$  is denoted by  $y_B(k)$ . Its noise component is denoted by  $n_B(k)$ , having zero mean and variance of  $\sigma^2 = N_0/2$  per dimension (here  $N_0$  is the power spectral density of the noise). The fading channel between nodes  $X$  and  $Y$  is represented by  $h_{XY}$  which is a circularly symmetric complex Gaussian random variable with zero mean and variance  $\sigma_{XY}^2$ . All fading parameters over different links and/or different time slots are assumed to be independent and identically distributed (i.i.d.). The set of active relays in time slot  $k \geq 1$  is denoted by  $\Phi_k \subseteq \{R_1, R_2, \dots, R_M\}$  and its complement  $\bar{\Phi}_k$  represents the set of inactive (or silent) relays – note that these relays will be in receive mode in time slot  $k$ . We have the initial condition  $\Phi_1 = \emptyset$  since no relay is active in the first time slot. Finally, each relay has a unique digital identifier  $\text{ID}_{R_r}$  for  $r = 1, 2, \dots, M$  which is a string of  $\log_2(M)$  bits. For example, if  $M = 4$  we may assign  $\text{ID}_{R_1} = 00$ ,  $\text{ID}_{R_2} = 01$ ,  $\text{ID}_{R_3} = 10$  and  $\text{ID}_{R_4} = 11$ . Throughout this paper, vectors are denoted by bold type.

#### D. Signal transmission and relay activation

1) *Source broadcasting and relay detection*: In the proposed virtual full-duplex communication protocol, the source broadcasts a new data-bearing symbol in every time slot. Therefore, in each time slot  $k \geq 1$  every inactive relay  $F \in \bar{\Phi}_k$  receives from the source the signal

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

where  $E_s$  is the average transmit symbol energy at the source. Note that here inter-relay-interference (IRI) has been neglected. Each such relay then demodulates according to the MAP criterion, yielding the source symbol estimate

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

and the estimate of the source data at relay  $F \in \bar{\Phi}_k$  is then formed via  $\hat{b}_s^{(F)}(k) = \mathcal{M}_s^{-1}(\hat{x}_s^{(F)}(k))$ .

2) *Relay Activation Mechanism*: In each time slot, the SM encoding principle is applied to the set of  $M$  distributed relays in order to *implicitly* forward the estimate of the source data and to *explicitly* transmit the activated relay's own data. Each relay  $F$  which demodulated a symbol in a particular time slot  $k$  compares the estimated source data  $\hat{b}_s^{(F)}(k)$  with its own unique ID; if they match, the relay will be active in time slot  $k + 1$ . Of course, if relay  $F$  is active in time

slot  $k$ , it cannot receive any new data as it is in the process of transmitting, so it must be silent in time slot  $k + 1$ . The activation rule can therefore be summarized mathematically via

$$F \in \Phi_{k+1} \text{ if and only if } F \in \bar{\Phi}_k \text{ and } \hat{b}_s^{(F)}(k) = \text{ID}_F.$$

### III. DESTINATION PROCESSING: LOCAL MAP AND GLOBAL MAP DETECTION

In this section, two techniques are proposed for the destination's detection process. The first, called *local MAP detection*, works by processing a pair of consecutive received signals to make decisions, utilising feedforward of previous detection decisions. The second, called *global MAP detection*, uses the forward-backward algorithm to determine the exact *a posteriori* probabilities of the source symbols *and* the relay symbols conditioned on the *entire frame* of  $N + 1$  received signals. Thus, global MAP detection minimizes the achievable symbol error rate. Note that it may occur that more than one relay, or indeed no relay, might be active in a particular time slot, due to possible demodulation errors at the relay; however in this work, the *destination* will assume that the relays perform error-free demodulation of the source symbols. Both techniques proposed in this section can be extended to the case of erroneous demodulation at the relays, provided that the destination has prior knowledge regarding the pairwise error probabilities (PEPs)  $P(x_s(k) \rightarrow \hat{x}_s^{(R_r)}(k))$  at the relays.

#### A. Local MAP Detection

Denoting the average transmit symbol energy at each relay by  $E_r$ , the received signal at the destination in the previous time slot  $k - 1$  (which was stored at the destination for processing in the current time slot) may be written as

$$y_D(k-1) = \sqrt{E_s} h_{SD}(k-1) x_s(k-1) + \sum_{J \in \Phi_{k-1}} \sqrt{E_r} h_{JD}(k-1) x_J(k-1) + n_D(k-1), \quad (3)$$

while the received signal at the destination in the current time slot  $k$  may be written as

$$y_D(k) = \sqrt{E_s} h_{SD}(k) x_s(k) + \sum_{G \in \Phi_k} \sqrt{E_r} h_{GD}(k) x_G(k) + n_D(k). \quad (4)$$

According to the DSM principle, knowledge of the set of active relays  $\Phi_k$  (including the case where  $\Phi_k = \emptyset$ ), yields information regarding the source data in time slot  $k - 1$ . Therefore, joint MAP detection can be applied at the destination over the two time slots  $k$  and  $k - 1$  conditioned on the two received signals  $y_D(k)$  and  $y_D(k - 1)$  given by (3) and (4) respectively; here the MAP detector will consider all hypotheses regarding the previous and current source symbols  $x_s(k - 1)$  and  $x_s(k)$ , the current active relay set  $\Phi_k$ , and the corresponding relays'

data symbols. Therefore the destination's detection process for local MAP operates according to

$$\begin{aligned} \{\hat{x}_s(k-1), \hat{\Phi}_k, \{\hat{x}_G(k)\}\} = \arg \min \left\{ \begin{array}{l} \tilde{x}_s(k-1), \tilde{x}_s(k) \in \mathcal{A}_s \\ \tilde{x}_G(k) \in \mathcal{A}_r, \forall G \in \tilde{\Phi}_k \end{array} \right. \\ \left| y_D(k-1) - (\sqrt{E_s} h_{SD}(k-1) \tilde{x}_s(k-1) \right. \\ \left. + \sum_{J \in \tilde{\Phi}_{k-1}} \sqrt{E_r} h_{JD}(k-1) \tilde{x}_J(k-1)) \right|^2 + \\ \left| y_D(k) - (\sqrt{E_s} h_{SD}(k) \tilde{x}_s(k) + \sum_{G \in \tilde{\Phi}_k} \sqrt{E_r} h_{GD}(k) \tilde{x}_G(k)) \right|^2 \end{array} \right\} \quad (5)$$

and the detected data is obtained via  $\hat{b}_s(k-1) = \mathcal{M}_s^{-1}(\hat{x}_s(k-1))$  and  $\hat{b}_G(k) = \mathcal{M}_r^{-1}(\hat{x}_G(k))$  for every  $G \in \hat{\Phi}_k$ . Note that  $\tilde{x}_s(k-1)$  and  $\tilde{x}_s(k)$  represent hypotheses for the source data in time slots  $k-1$  and  $k$  respectively. In addition,  $\tilde{\Phi}_k$  denotes the hypothesized active relay set, while  $\tilde{x}_G(k)$  represents a hypothesis for the transmitted data of any relay  $G$  which is hypothesized to be active in time slot  $k$  (i.e.,  $G \in \tilde{\Phi}_k$ ). Finally, note that in order to ensure that the detection procedure yields a result consistent with the relay activation conditions of VFD-DSM, we impose the following constraint on the source symbol and active relay set hypotheses:  $F \in \tilde{\Phi}_k$  if and only if  $F \notin \hat{\Phi}_{k-1}$  and  $\tilde{b}_s^{(F)}(k-1) = \text{ID}_F$ ; we also initialize  $\hat{\Phi}_1 = \emptyset$ .

Note that this joint detection method yields the MAP solution conditioned on the two consecutive received signals  $y_D(k-1)$  and  $y_D(k)$ , and also conditioned on the assumption that the previous decisions are correct. Also note that the frame termination with a zero symbol ensures that the effect of any error propagation phenomenon is well-contained.

### B. Global MAP Detection

In this section, we describe the global MAP detector at the destination. This detector follows the general principle of efficiently computing the *a posteriori* probabilities (APPs) of the source and relay symbols. The first instance of this type of detector was proposed in the context of convolutional coding in [13], and is known as the BCJR algorithm after the initials of its inventors. A more general exposition followed in [17] where it was shown how to apply this principle to compute exact APPs for any context where the factor graph describing the global probability distribution is a tree.

Here we apply the principle of the forward-backward algorithm to the context of VFD-DSM, noting that APP computation over the transmission frame may be formulated as the problem of marginalizing a product of functions. The factor graph (tree) for the overall probability distribution relating to the detection problem is shown in Figure 2. The messages passed on the factor graph are also indicated in the figure; the message passed on each edge of the graph is a function of its associated variable node. Each variable node  $x_s(k)$  corresponds to the source symbol (in  $\mathcal{A}_s$ ) at time slot  $k$ , while each variable node  $\mathbf{x}_R(k) = [x_{R_1}(k) \ x_{R_2}(k) \ \dots \ x_{R_M}(k)]$

denotes the *relay transmission vector* (belonging to the Cartesian product  $\mathcal{A}_r^M$ ) in time slot  $k$ . Each factor node  $F_k$  (for  $1 \leq k \leq N$ ) represents the function given by

$$\begin{aligned} F_k(x_S(k), \mathbf{x}_R(k), \mathbf{x}_R(k+1)) = \\ p(y_D(k) | x_S(k), \mathbf{x}_R(k)) \cdot p(\mathbf{x}_R(k+1) | x_S(k), \mathbf{x}_R(k)) \end{aligned} \quad (6)$$

where

$$\begin{aligned} p(y_D(k) | x_S(k), \mathbf{x}_R(k)) = \frac{1}{\pi N_0} \cdot \\ \exp \left[ -\frac{|y_D(k) - \sqrt{E_s} h_{SD}(k) x_S(k) - \sqrt{E_r} \mathbf{h}_{RD}^T(k) \mathbf{x}_R(k)|^2}{N_0} \right] \end{aligned} \quad (7)$$

and  $\mathbf{h}_{RD}(k) = [h_{R_1D}(k) \ h_{R_2D}(k) \ \dots \ h_{R_MD}(k)]$ . Note that the term  $p(\mathbf{x}_R(k+1) | x_S(k), \mathbf{x}_R(k))$  expresses the probabilistic dependency of the next relay transmission vector on the current relay transmission vector and the current source symbol (due to the relay activation principle of the proposed VFD-DSM protocol). This coupling is what creates the tree structure in the factor graph in Figure 2.

The forward-backward algorithm then begins with the (simultaneous) recursive computation of the forward metrics  $\alpha_k$  and the backward metrics  $\beta_k$  [17]. For the forward recursion, the initialization for the forward metrics is given by

$$\alpha_0(\mathbf{x}_R(1)) = F_0 = p(\mathbf{x}_R(1)) = \begin{cases} 1 & \text{if } \mathbf{x}_R(1) = \mathbf{0} \\ 0 & \text{otherwise} \end{cases}, \quad (8)$$

and the recursion operates as: for every  $k = 1, 2, \dots, N$ ,

$$\begin{aligned} \alpha_k(\mathbf{x}_R(k+1)) = \\ \sum_{x_s(k)} \sum_{\mathbf{x}_R(k)} F_k(x_S(k), \mathbf{x}_R(k), \mathbf{x}_R(k+1)) \cdot \alpha_{k-1}(\mathbf{x}_R(k)). \end{aligned} \quad (9)$$

The initialization for the backward metrics is given by

$$\begin{aligned} \beta_{N+1}(\mathbf{x}_R(N+1)) = F_{N+1} \\ = p(y_D(N+1) | \mathbf{x}_R(N+1)) \\ = \frac{1}{\pi N_0} \exp \left[ -\frac{|y_D(N+1) - \sqrt{E_r} \mathbf{h}_{RD}^T(N+1) \mathbf{x}_R(N+1)|^2}{N_0} \right] \end{aligned} \quad (10)$$

and the recursion operates as: for every  $k = N, N-1, \dots, 1$ ,

$$\begin{aligned} \beta_k(\mathbf{x}_R(k)) = \\ \sum_{x_s(k)} \sum_{\mathbf{x}_R(k+1)} F_k(x_S(k), \mathbf{x}_R(k), \mathbf{x}_R(k+1)) \cdot \beta_{k+1}(\mathbf{x}_R(k+1)). \end{aligned} \quad (11)$$

Finally, the metrics  $\gamma_k$  are computed for every  $k = 1, 2, \dots, N$  via

$$\begin{aligned} \gamma_k(x_S(k)) = \sum_{\mathbf{x}_R(k)} \sum_{\mathbf{x}_R(k+1)} F_k(x_S(k), \mathbf{x}_R(k), \mathbf{x}_R(k+1)) \\ \cdot \alpha_{k-1}(\mathbf{x}_R(k)) \cdot \beta_{k+1}(\mathbf{x}_R(k+1)). \end{aligned} \quad (12)$$

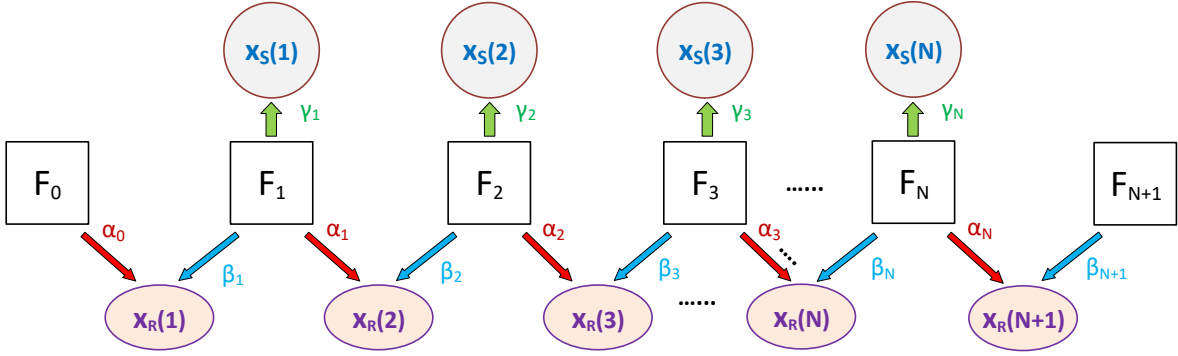


Fig. 2. Factor graph, together with illustration of the forward-backward algorithm, for virtual full-duplex DSM. The red arrows show the propagation of the forward recursion ( $\alpha$  metrics), and the blue arrows indicate the backward recursion ( $\beta$  metrics).

Note that for fixed  $k$ , the values of  $\gamma_k(x_S(k))$  form a probability distribution over the discrete random variable  $x_S(k)$  and correspond to the exact source symbol APPs. These are then used to make decisions on the source symbols via

$$\hat{x}_s^{(D)}(k) = \arg \max_{x_S(k)} \gamma_k(x_S(k)). \quad (13)$$

Simultaneously with the  $\gamma_k$  metric computation, the relay symbol vector APPs are computed via

$$\delta_k(\mathbf{x}_R(k)) = \alpha_{k-1}(\mathbf{x}_R(k)) \beta_k(\mathbf{x}_R(k)) \quad (14)$$

for each  $k = 2, 3, \dots, N + 1$ . Note that here only a single multiplication is required for each value of  $\mathbf{x}_R(k)$ . Note that for fixed  $k$ , the values of  $\delta_k(\mathbf{x}_R(k))$  form a probability distribution over the discrete random vector  $\mathbf{x}_R(k)$  and correspond to the exact relay symbol vector APPs. The detection of the relay data will then proceed according to

$$\hat{\mathbf{x}}_R(k) = \arg \max_{\mathbf{x}_R(k)} \delta_k(\mathbf{x}_R(k)). \quad (15)$$

Note that here the frame termination with a zero symbol is what allows for initialization of the backward recursion (via (10)). Also, as with implementations of the standard BCJR algorithm of [13], computation of all metrics in the log-domain is preferred. In this implementation, all metrics are replaced by their real logarithms; multiplication is replaced by addition, and addition is replaced by the well-known Jacobian logarithm ( $\max^*$ ) [18] which is defined by

$$\max^*\{x, y\} = \log(e^x + e^y) \quad (16)$$

$$= \max\{x, y\} + \log(1 + e^{-|x-y|}). \quad (17)$$

Since  $\max\{x, y\} \gg \log(1 + e^{-|x-y|})$  for a reasonable range of  $x, y \in \mathbb{R}$ , the Jacobian logarithm can be approximated with the first term in (17) with a minor loss in performance.

#### IV. SIMULATION RESULTS AND DISCUSSION

In this section, simulation results are presented for the proposed VFD-DSM protocol. The case of 2 relays ( $M = 2$ ) is considered in our simulations, with BPSK transmission at source and relays. Two different node geometries are

considered. In the first geometry (called G1), an equal distance between all pairs of nodes is assumed i.e.,  $\sigma_{SD}^2 = \sigma_{SR_r}^2 = \sigma_{R_rD}^2 = 1$  for  $r = 1, 2$ . In the second case, both relay nodes lie at the centre point between the source and destination (although unrealizable in practice, this is a common test case for cooperative protocols). Our model assumes a path loss exponent of 2, so that for the second geometry (called G2),  $\sigma_{SD}^2 = 1$  while  $\sigma_{SR_r}^2 = \sigma_{R_rD}^2 = 4$  for  $r = 1, 2$ . Note that the probability of no relay transmission in any time slot is  $1/2$ . Also, it was shown in [8] that one relay is active on average in DSM, even when there are demodulation errors at the relays. Thus the *total average transmit energy per information* (source or relay) bit is  $E_b = (E_s + \frac{1}{2}E_r)/(1 + \frac{1}{2})$ . In our simulations we assume  $E_r = E_s$ , so that  $E_b = E_s$ .

As a baseline for performance comparison, another prominent full-duplex relaying protocol, called *successive relaying* [15], [16], is considered. This protocol operates as follows: in every odd time slot  $2k - 1$ , relay  $R_1$  forwards the symbol received from the source in the previous time slot while the other relay  $R_2$  receives the current transmission of the source. In the next (even) time slot  $2k$ , the relays interchange their roles:  $R_2$  forwards the previous source symbol while  $R_1$  receives. A direct link also exists from source to destination. It should be noted that in successive relaying, the relays do not have their own data and only retransmit the source data to the destination. The destination performs MAP detection over two consecutive time slots in a fashion similar to the local MAP detector.

A comparison of the bit error rate (BER) for the source data at the destination for the proposed VFD-DSM and successive relaying is shown in Fig. 3. It can be seen that for the system with geometry G1, VFD-DSM with local MAP detection yields a similar error rate performance to successive relaying. 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 50%. This is the key benefit of DSM-based systems compared to conventional relaying protocols. It can also be seen that at a BER of  $10^{-3}$ , the proposed global MAP detection algorithm shows a gain of

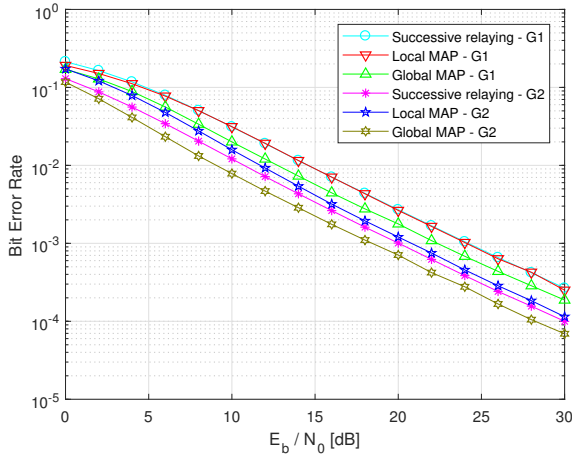


Fig. 3. Comparison of BER of source data at the destination for the proposed VFD-DSM scheme (using local and global MAP detection) with that of successive relaying. The two different node geometries G1 and G2 are considered.

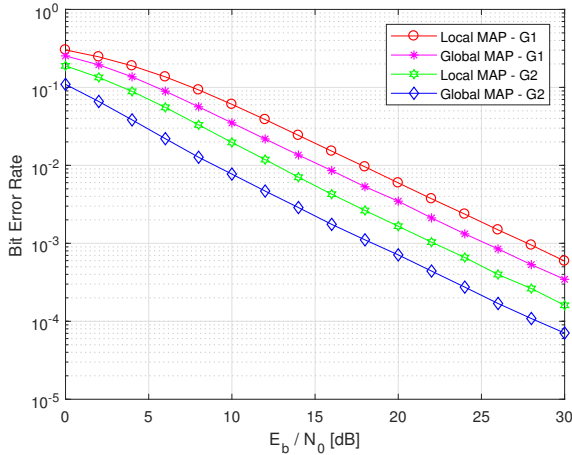


Fig. 4. Comparison of BER of relay data at the destination for the proposed VFD-DSM scheme (using local and global MAP detection) with that of successive relaying. The two different node geometries G1 and G2 are considered.

1.8 dB over successive relaying in addition to this throughput advantage. In the linear geometry G2, successive relaying has a gain in source data error rate of 0.8 dB over VFD-DSM with local MAP detection, but with global MAP detection, VFD-DSM shows a gain of 1.6 dB over successive relaying, while maintaining the significant increase in throughput. Finally, Fig. 4 compares the BER for the relay data at the destination in the proposed VFD-DSM protocol for both node geometries. The performance gain at a BER of  $10^{-3}$  between local and global MAP detection in this case is 2.2 dB for geometry G1, and rises to 3.8 dB for geometry G2.

## V. CONCLUSION

In this work, a new protocol for virtual full-duplex relaying based on distributed spatial modulation has been introduced.

Two detection methods at the destination were proposed, using a local and a global application of the MAP principle for data detection. The global MAP detector has an efficient implementation in this context, using the forward-backward algorithm traditionally employed in the decoding of turbo codes. Simulation results demonstrate that for a realistic co-operation geometry, the source data error rate performance of the proposed protocol with local MAP detection is quite close to that of successive relaying, while global MAP detection yields a gain of 1.8 dB over successive relaying. The system throughput is also significantly improved using the proposed VFD-DSM protocol due to the simultaneous transmission of the data of the source and of the active relay.

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