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Network Coded Distributed Spatial Modulation for Relay Networks

Amir Shehni and Mark F. Flanagan
University College Dublin
Belfield, Dublin 4, Ireland
Email: amir.shehni@ucd.ie, mark.flanagan@ieee.org

***Abstract*—Distributed spatial modulation (DSM) is a cooperative diversity protocol for a wireless network, whereby communication from a source to a destination is aided by multiple intermediate relays. The main advantage of the DSM protocol is that it provides distributed diversity to the source's transmission, while simultaneously allowing the relays to efficiently transmit their own data to the destination. In this paper, network coding is combined with DSM in order to increase the data rate of the source-to-destination link while maintaining the same diversity order of 2 for this data. Two methods of detection are proposed for implementation at the destination node: an error-aware maximum likelihood (ML) demodulator which is robust to demodulation errors at the relays, and a low-complexity suboptimal demodulator which assumes correct demodulation at the relays. The system bit error rate (BER) performance is measured under two different relay geometries. Simulation results show that for the same overall system throughput, the proposed network coded DSM protocol can increase the source-to-destination data rate by approximately 33.3% compared to the conventional DSM system, while still guaranteeing a similar BER as for DSM for both of the considered channel geometries.**

I. Introduction

Multiple–input multiple–output (MIMO) communication has attracted a lot of attention in the last two decades as it has strong potential for achieving high throughput in modern wireless systems by achieving multiplexing, diversity, and antenna gains [1]. Since conventional MIMO systems assume the existence of multiple RF chains, this leads to issues such as inter-channel interference (ICI) which occurs due to the superposition of the signals to be transmitted by different transmit antennas, and/or inter-antenna synchronization (IAS) which is a key requirement of any space-time communication system. Taking these issues into account leads to a more complex transceiver design in MIMO communications [2]. Therefore, methods which can harvest the benefits of MIMO while avoiding its drawbacks are of high interest.

Following this ambitious research objective, spatial modulation (SM) has been proposed as a new modulation concept for MIMO systems, which aims to reduce the complexity and cost of multiple-antenna schemes without deteriorating the end-to-end system performance and still guaranteeing a high data rate [3]. An SM system operates by activating only *one* antenna for data transmission in any particular time slot, while the choice of active antenna conveys further information – thus, data is simultaneously modulated in the conventional *signal* domain and in the *spatial* (antenna index) domain. By this means, SM reduces hardware complexity by requiring only one transmit radio frequency (RF) chain, while maintaining many of the key benefits of a MIMO system [4].

Cooperative communication has been established as a promising technology for future wireless networks [5], [6]. Cooperative communication protocols usually employ single-antenna mobile terminals to reap the benefits of MIMO by forming a distributed antenna array. It has been shown that cooperation is an effective way to combat shadowing as well as multipath fading. However, employing cooperative networks with single-antenna devices which usually work in half-duplex mode leads to issues, such as: i) distributed cooperation needs extra bandwidth resources, which results in a loss of system throughput; ii) relays need to use their own resources (e.g., energy and signal processing) to forward the packets of the source; and iii) relays have to delay the transmission of their own data frames while they prioritize the retransmission of the source's data.

Several solutions have been proposed to overcome the aforementioned problems. For instance, in [7], [8] network coding is used in order to transmit simultaneously an algebraic combination of the source and relay data. Another solution, slightly similar but in the modulation domain, has been proposed in [9].

Spatial modulation requires the implementation of several antennas at the transmitter to achieve a high spectral efficiency. However, for the uplink, the assumption of many transmit antennas is not realistic as the transmitting device is usually a small mobile terminal. Fortunately, the necessity for multiple transmit antennas can be circumvented by exploiting distributed cooperating relays to form a virtual MIMO system. The application of SM to cooperative networks has been studied in [10]-[12]. In particular, distributed spatial modulation (DSM) is a recently-proposed relaying protocol which increases the aggregate throughput of the network [11], [12]; this throughput enhancement is achieved by allowing the relays to *explicitly* transmit their own data, while *implicitly* relaying the source data which 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).

In this paper, we propose a new variant of DSM which incorporates network coding into the relay activation process. The use of an *index-domain network coding* operation at the relays allows for the destination's detection of the source data with a diversity order of 2, as is the case in conventional DSM; however, for the same overall system throughput, a higher source-to-destination data rate can be maintained. We also propose two demodulators for use at the destination: an error-aware maximum likelihood (ML) demodulator which is robust to demodulation errors at the relays, and a low-complexity sub-optimal demodulator which assumes that demodulation at the relays is always error-free. Our simulation results demonstrate that for both channel geometries considered, the the source-to-destination data rate is increased by approximately 33.3%, while the BER of the source and relay data for the proposed protocol is similar to that of conventional DSM.

II. System Model

This section begins by providing a brief review of DSM, and then explains how the new protocol employs network coding in conjunction with DSM. We also provide some relevant definitions and notation.

A. Review of DSM and explanation of NC-DSM

In DSM, in the first time slot the source broadcasts its data-bearing symbol, which is received by all relays as well as by the destination. The relays demodulate the data according to the ML criterion, while the destination reserves its received signal for later processing. Each relay possesses a unique (binary-vector) ID; any relay whose ID matches its demodulated data will be *activated*, and will correspondingly transmit its own data to the destination in the second time slot. This means that the system requires two time slots for the complete transmission of each source symbol. Also note that while the relay's transmission explicitly carries that relay's data (via straightforward signal modulation), it also *implicitly* carries a copy of the *source* data (through the *index* of the activated relay). The operation of the DSM protocol is illustrated in Fig. 1(a) for the case of two relays, where error-free demodulation has been assumed at the relays. Here the source data in time slot 1 is $x_S(1) = 1$, resulting in the activation of the relay with matching ID ($\mathrm{ID}_{R_2} = 1$) in time slot 2. Similarly, the source data in time slot 3 is $x_S(3) = 0$, resulting in the activation of the relay with matching ID ($\mathrm{ID}_{R_1} = 0$) in time slot 4.

In the proposed technique of *network coded DSM* (NC-DSM), three time slots are required for the transmission of two source symbols (compared to four time slots for DSM). In the first and second time slots, the source broadcasts its data to the relays and destination; each relay then has two detected bit-vectors for time slots 1 and 2. If the bitwise-XOR of these two bit-vectors match that relay's ID, the relay will become active and transmit its own data to the destination in time slot 3. The operation of the NC-DSM protocol is illustrated in Fig. 1(b) for the case of two relays, binary source data,

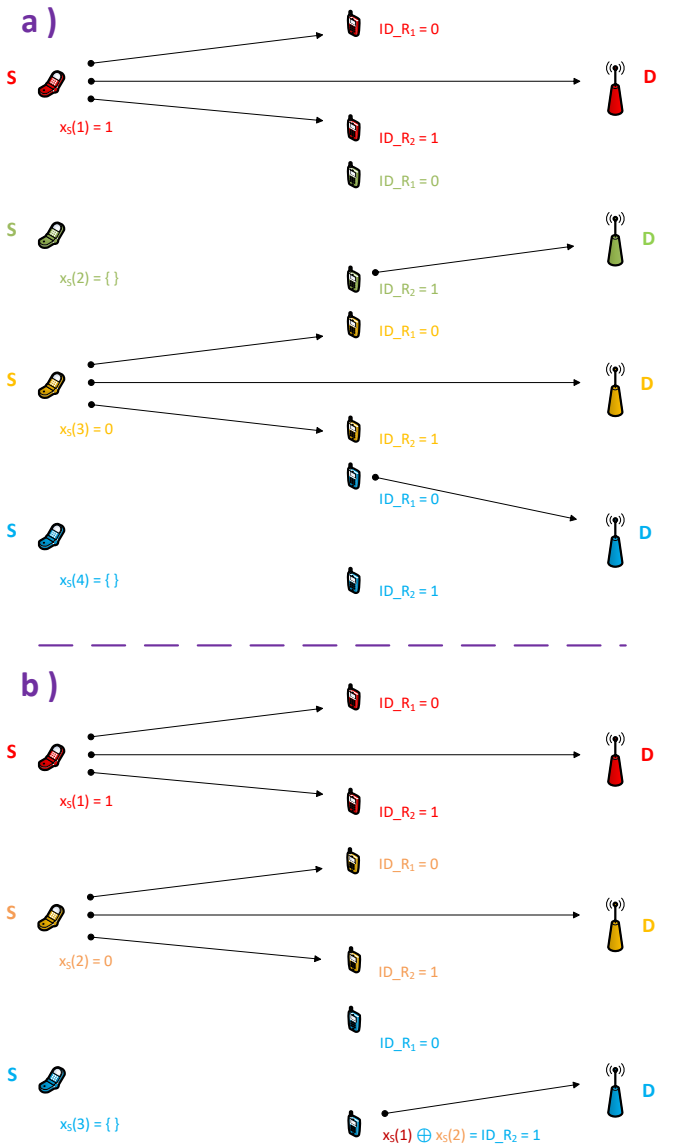

Fig. 1. a) Illustration of distributed spatial modulation for the source symbols $\{1, 0\}$. b) Illustration of the proposed network-coded distributed spatial modulation with the same source symbols. In the "red" and "orange" time slots, the source broadcasts new data symbols. Here BPSK modulation is assumed, and for simplicity it is assumed that demodulation at the relays is error-free.

and error-free demodulation at the relays. The source data in time slots 1 and 2 are $x_S(1) = 1$ and $x_S(2) = 0$ respectively. Each relay will demodulate this data and compute the XOR $x_S(1) \oplus x_S(2) = 1$; since this matches the ID of relay R_2, this relay will be activated (and transmit its own data) in time slot 3. Note that the destination therefore receives $x_S(1)$, $x_S(2)$ *and* $x_S(1) \oplus x_S(2)$, the final symbol being conveyed by the *index* of the activated relay in time slot 3; any two of these symbols is sufficient for reconstruction of the complete source data. A more detailed mathematical explanation of the NC-DSM protocol will be given in Sections III and IV.

B. Notation and definitions

A multi–relay network with one source (S), one destination (D) and $M = 2^q$ relays (comprising the set $\Phi = \{R_1, R_2, \ldots, R_M\}$) is considered. It is assumed that all nodes are half-duplex and equipped with a single antenna. The received signal at node B in time slot t is denoted by $y_B(t)$. The fading gain between nodes X and Y in time slot t is a complex Gaussian random variable $h_{XY}(t)$ with zero mean and variance σ^2_{XY}. All the channel coefficients $h_{XY}(t)$ are independent random variables from one node pair (X, Y) to another and from one time slot to another. The complex additive white Gaussian noise (AWGN) at node B in time slot t is given by $n_B(t)$ having mean zero and variance $\sigma^2 = N_0/2$ per dimension, where N_0 is the noise power spectral density.

The source transmits complex modulated symbols, by using either phase shift keying (PSK) or quadrature amplitude modulation (QAM) from a constellation $\mathcal{A}_s$ of size M. We denote by $\mathbf{x}_S(t)$ the bit vector of length $\log_2(M)$ to be transmitted by the source in time slot t, and by $p_S(t) = \mathcal{M}_S(\mathbf{x}_S(t))$ the corresponding complex PSK/QAM symbol for transmission by the source, where $\mathcal{M}_S(.)$ denotes the bit to symbol modulation mapping at the source. Similarly, any active relay uses a PSK/QAM modulation constellation $\mathcal{A}_r$ of size N to transmit its own data symbol $p_F(t) = \mathcal{M}_F(\mathbf{x}_F(t))$ to the destination; here $\mathbf{x}_F(t)$ is the data vector of active relay F in time slot t, and $\mathcal{M}_F(.)$ denotes the bit to symbol modulation mapping at relay F. Each relay F is assigned a unique digital identifier, ID_F, of $\log_2(M)$ bits. For example, if $M = 4$ the relays R_1, R_2, R_3, R_4 could be assigned identifiers according to $\mathrm{ID}_{R_1} = 00$, $\mathrm{ID}_{R_2} = 01$, $\mathrm{ID}_{R_3} = 10$, $\mathrm{ID}_{R_1} = 11$, respectively. Throughout this paper, vectors are denoted by bold type.

III. Transmission Process

In this section, signal processing in the broadcasting and relaying phases are described in detail, and equations describing the destination's received signals are presented. The entire transmission process takes place over three time slots: $t = 1, 2, 3$.

A. Source broadcasting phases

In each time slot $t = 1, 2$, the source broadcasts its symbol $p_S(t) = \mathcal{M}_S(\mathbf{x}_S(t))$, where $\mathbf{x}_S(t)$ denotes the bit vector of length $\log_2(M)$ for transmission at the source in time slot t. For every $F \in \Phi = \{R_1, R_2, ..., R_M\}$, the received signal at relay F in time slot $t \in \{1, 2\}$ is given by

$$y_F(t) = \sqrt{E_s}\ h_{SF}(t)\ p_S(t) + n_F(t)\ , \tag{1}$$

where E_s is the average transmit symbol energy at the source.

Applying the ML criterion, the demodulated source symbol at the relay in time slot $t \in \{1, 2\}$ is

$$\hat{p}_S^{(F)}(t) = \underset{\tilde{p}_S(t) \in \mathcal{A}_s}{\arg\min} \{|y_F(t) - \sqrt{E_s}\ h_{SF}(t)\ \tilde{p}_S(t)|^2\} \tag{2}$$

and the source data at the relay F is estimated via $\hat{\mathbf{x}}_S^{(F)}(t) = \mathcal{M}_S^{-1}(\hat{p}_S^{(F)}(t))$. In the same time slot, the destination receives a signal from the source given by

$$y_D(t) = \sqrt{E_s}\ h_{SD}(t)\ p_S(t) + n_D(t)\ . \tag{3}$$

The destination stores this signal for joint signal processing whcih will be performed in time slot 3. The nature of this processing will be discussed in the next section.

B. Relay assisting phase

In this section, the relay activation strategy for network coded DSM is presented. For vectors $\mathbf{x}$ and $\mathbf{y}$, let $\mathbf{x} \oplus \mathbf{y}$ denote the bitwise exclusive-or (XOR) of the two vectors, *e.g.* $[1011] \oplus [1110] = [0101]$. The new activation strategy for the relay is defined in such a way that the relay will be active in time slot 3 *if and only if* there is a match between that relays' ID and the element-wise XOR of the two demodulated bit vectors $\hat{\mathbf{x}}_F(1) \oplus \hat{\mathbf{x}}_F(2)$. Formally,

$$p_F(3) = \begin{cases} \mathcal{M}_F\big(\mathbf{x}_F(3)\big) & \text{if} \quad \mathrm{ID}_F = \hat{\mathbf{x}}_S^{(F)}(1) \oplus \hat{\mathbf{x}}_S^{(F)}(2) \\ 0 & \text{otherwise,} \end{cases} \tag{4}$$

where $\mathbf{x}_F(3)$ denotes the relays' own data vector to be transmitted to the destination.

Thus, the signal received at the destination from the relaying phase can be written as

$$y_D(3) = \sum_{F \in \Phi} \sqrt{E_r}\ h_{FD}(3)\ p_F(3) + n_D(3) \tag{5}$$

where E_r denotes the average transmit energy per symbol at the relay.

Thus, assuming no demodulation errors occur at the relays, the index of the active relay contains information regarding *both* source symbols $\mathbf{x}_S(1)$ and $\mathbf{x}_S(2)$, according to the spatial modulation concept; this enhances the achievable diversity gain of the destination's detector. Note that there is the possibility of more than one non-zero term (or indeed, no non-zero term) in (4) due to demodulation errors at the relays. Taking this situation into the account allows for the design of a more robust (albeit more complex) demodulator which will be discussed in detail in Section IV-A.

IV. Detection Process at the Destination

In this section, we derive the optimal ML detector, called the *error-aware* demodulator, as well as a simplified suboptimal detector, called the *low-complexity* demodulator, which perform demodulation of the signals received at the destination over the 3 time slots for the proposed NC-DSM system.

A. Error-aware ML demodulator

If no demodulation errors occur at the relays, a conventional ML demodulator can be used for the proposed scheme. But in realistic operating conditions, this will not be the case, and therefore the conventional ML demodulator will give a

reasonable performance only if the source broadcasts with high average symbol energy, which is not a feasible solution for energy-constrained wireless networks. Motivated by these considerations, in this section we develop a robust demodulator, which is optimal in the presence of demodulation errors at the relays.

In this context, ML detection seeks to determine the most likely pair of source symbols, relay activations, *and* relay transmitted symbols in a joint manner. Therefore, the ML detector seeks to maximize

$$P_D = P\left(\tilde{p}_S(1), \tilde{p}_S(2), \tilde{\mathbf{p}}_R \mid y_D(1), y_D(2), y_D(3)\right) \quad (6)$$

where $\tilde{p}_S(t)$ represents a hypothesis for the symbol transmitted from the source in time slot $t \in \{1, 2\}$, and where $\tilde{\mathbf{p}}_R$ denotes a hypothesis for the *vector* of symbols transmitted from the relays in time slot $t = 3$, i.e., $\tilde{\mathbf{p}}_R = (\tilde{p}_{R_1}(3)\ \tilde{p}_{R_2}(3)\ \ldots\ \tilde{p}_{R_M}(3))^T$. Note that here the condition $\tilde{p}_F(3) = 0$ is allowed for each $F \in \Phi$, and is equivalent to the *non-activation* of relay $F \in \Phi$ in time slot 3.

Applying Bayes' rule, factorizing, and ignoring constants, (6) becomes

$$\begin{aligned} P_D = {} & p\left(y_D(1) \mid \tilde{p}_S(1)\right) p\left(y_D(2) \mid \tilde{p}_S(2)\right) p\left(y_D(3) \mid \tilde{\mathbf{p}}_R\right) \\ & \cdot P\big(\tilde{p}_S(1)\big) P\big(\tilde{p}_S(2)\big) P\big(\tilde{\mathbf{p}}_R \mid \tilde{p}_S(1), \tilde{p}_S(2)\big) \end{aligned} \quad (7)$$

Since the source broadcasts in time slots $t = 1, 2$, the first two terms of (7) will be

$$\begin{aligned} & p\big(y_D(t) | \tilde{p}_S(t)\big) = \\ & \frac{1}{\pi N_0} \exp\left(-\frac{\left| y_D(t) - \sqrt{E_s}\ h_{SD}(t)\ \tilde{p}_S(t) \right|^2}{N_0} \right), \end{aligned} \quad (8)$$

and the third term, corresponding to the relaying phase $t = 3$, will be

$$\begin{aligned} & p\big(y_D(3) | \tilde{\mathbf{p}}_R\big) = \\ & \frac{1}{\pi N_0} \exp\left(-\frac{\left| y_D(3) - \sqrt{E_r}\ \mathbf{h}_{RD}^T\ \tilde{\mathbf{p}}_R \right|^2}{N_0} \right) \end{aligned} \quad (9)$$

where $\mathbf{h}_{RD} = (h_{R_1 D}\ h_{R_2 D}\ \ldots\ h_{R_M D})^T$ denotes the vector of relay-destination channel coefficients. Also, the terms $P\big(\tilde{p}_S(1)\big)$ and $P\big(\tilde{p}_S(2)\big)$ in (7) can be ignored since the source symbols are equiprobable *a priori*. The only remaining term is $P\big(\tilde{\mathbf{p}}_R | \tilde{p}_S(1), \tilde{p}_S(2)\big)$ and plays the key role in designing a robust demodulator.

An optimal demodulator, which is robust against demodulation errors at the relays, can be developed by taking advantage of the knowledge of the instantaneous channel state information at the relays. The bit error probability at relay $F \in \Phi$ in time slot t is in general given by an expression of the form

$$P_{e,b}^{(F)}(t) = \beta Q\left(\sqrt{2\alpha\ |h_{SF}(t)|^2 (E_s/N_0)}\ \right) \quad (10)$$

where β and α are constants depending on the particular QAM or PSK modulation used at the source. Note that here we consider that the channel status can vary in each time slot. An error occurs in the XOR computation at the relay if and only if there is an erroneous demodulation in the first time slot and a correct detection in the second time slot, or visa versa. Hence, the probability of error in each bit of the bitwise-XOR computed at each relay $F \in \Phi$ is given by

$$P_{e,b}^{(F)} = P_{e,b}^{(F)}(1)\left(1 - P_{e,b}^{(F)}(2)\right) + \left(1 - P_{e,b}^{(F)}(1)\right) P_{e,b}^{(F)}(2), \quad (11)$$

and therefore the probability of an incorrect bitwise-XOR computation (and hence incorrect activation) for relay F is

$$P_e^{(F)} = 1 - (1 - P_{e,b}^{(F)})^m \quad (12)$$

where $m = \log_2 M$.

Next let $A(p_1, p_2) \in \Phi$ denote the (unique) relay which would be activated by *correct* demodulation at the relays given the source symbol hypotheses $\tilde{p}_S(1) = p_1$ and $\tilde{p}_S(2) = p_2$. Then,

$$\begin{aligned} P(\tilde{\mathbf{p}}_R \mid p_1, p_2) &= \prod_{F \in \Phi} P(\tilde{p}_F(3) \mid p_1, p_2) \\ &= \prod_{F \in \widetilde{\Phi}^{(\text{ON})}} P(\tilde{p}_F(3) \mid p_1, p_2) \ \cdot \prod_{F \in \widetilde{\Phi}^{(\text{OFF})}} P(\tilde{p}_F(3) \mid p_1, p_2) \end{aligned} \quad (13)$$

where $\widetilde{\Phi}^{(\text{ON})}$ denotes the set of relays which are *active* based on the relay symbol vector hypothesis $\tilde{\mathbf{p}}_R$; and $\widetilde{\Phi}^{(\text{OFF})}$ denotes the set of relays which are *inactive* based on $\tilde{\mathbf{p}}_R$. Next, for $F \in \widetilde{\Phi}^{(\text{OFF})}$ we have

$$P(\tilde{p}_F(3) \mid p_1, p_2) = \begin{cases} P_e^{(F)} & \text{if} \quad F = A(p_1, p_2) \\ 1 - P_e^{(F)} & \text{otherwise.} \end{cases} \quad (14)$$

while for $F \in \widetilde{\Phi}^{(\text{ON})}$,

$$P(\tilde{p}_F(3) \mid p_1, p_2) = \begin{cases} \frac{1}{N}\ (1 - P_e^{(F)}) & \text{if} \quad F = A(p_1, p_2) \\ \frac{1}{N}\ P_e^{(F)} & \text{otherwise,} \end{cases} \quad (15)$$

The first case in (14) is simply the error rate of the XOR computation at relay F, since in this case the ID matches but the relay is silent (i.e., *incorrect non-activation* of relay F). The second case in (14) then corresponds to the probability of *correct non-activation* of relay F. The first and second cases of (15) correspond to the probabilities of correct and incorrect *activation* of relay F, respectively. The term $\frac{1}{N}$ in (15) is due to the fact that when any relay is active, its transmitted symbols are equally likely.

The error-aware ML demodulator maximizes the metric P_D given by (7), or equivalently minimizes $-\log P_D$; after some algebraic simplification, this can be written as

$$\begin{aligned}\left\{\hat{p}_S(1), \hat{p}_S(2), \hat{\mathbf{p}}_R\right\} = \underset{\substack{\tilde{p}_S(1), \tilde{p}_S(2) \in \mathcal{A}_s \\ \tilde{\mathbf{p}}_R \in (\mathcal{A}_r \cup \{0\})^M}}{\arg\min} \Bigg\{ & \\ \left|y_D(1) - \sqrt{E_s}\, h_{SD}(1)\, \tilde{p}_S(1)\right|^2 & \\ + \left|y_D(2) - \sqrt{E_s}\, h_{SD}(2)\, \tilde{p}_S(2)\right|^2 & \\ + \left|y_D(3) - \sqrt{E_r}\, \mathbf{h}_{RD}^T\, \tilde{\mathbf{p}}_R\right|^2 & \\ - N_0 \log\left(P\left(\tilde{\mathbf{p}}_R \mid \tilde{p}_S(1), \tilde{p}_S(2)\right)\right) & \Bigg\}\end{aligned} \tag{16}$$

By considering the size of the search space in the $\arg\min$ operation, we conclude that the complexity of this demodulator is $O\left(M^2(N+1)^M\right)$, which is practical for small values of the source constellation size M.

Finally, the estimated data is then obtained via $\hat{\mathbf{x}}_S(1) = \mathcal{M}_S^{-1}\big(\hat{p}_S(1)\big)$, $\hat{\mathbf{x}}_S(2) = \mathcal{M}_S^{-1}\big(\hat{p}_S(2)\big)$ and $\hat{x}_F(3) = \mathcal{M}_F^{-1}(\hat{p}_F(3))$ for each $F \in \Phi$ such that $\hat{p}_F(3) \neq 0$.

Finally, note that for larger values of M, the complexity of this ML demodulator can be dramatically reduced by restricting the set of hypothesized vectors $\tilde{\mathbf{p}}_R$ in (16) to those for which $\left|\widetilde{\Phi}^{(\mathrm{ON})}\right| \leq 2$. This reduction in the size of the search space results in a demodulator with complexity $O\left(M^2\left[1 + MN + \binom{M}{2}N^2\right]\right)$). Little optimality is sacrificed, as the probability of more than 2 simultaneous relay activations is negligible at reasonable values of the source-relay SNR.

B. Low-complexity demodulator

A low-complexity suboptimal demodulator may be derived by assuming that the relays always demodulate correctly. The resulting demodulator does *not* search over the entire set of relay transmission possibilities; instead exactly one relay is hypothesized to be active in time slot 3, i.e., that which is determined by the source symbol hypotheses in time slots $t = 1, 2$. Therefore, this low-complexity ML demodulator can be formulated as

$$\begin{aligned}\left\{\hat{p}_S(1),\ \hat{p}_S(2),\ \hat{p}_F(3)\right\} = \underset{\substack{\tilde{p}_S(1), \tilde{p}_S(2) \in \mathcal{A}_s \\ \tilde{p}_F(3) \in \mathcal{A}_r}}{\arg\min} \Bigg\{ & \\ \left|y_D(1) - \sqrt{E_s}\, h_{SD}(1)\, \tilde{p}_S(1)\right|^2 + & \\ \left|y_D(2) - \sqrt{E_s}\, h_{SD}(2)\, \tilde{p}_S(2)\right|^2 + & \\ \left|y_D(3) - \sqrt{E_r}\, h_{FD}(3)\, \tilde{p}_F(3)\right|^2 & \Bigg\}\end{aligned} \tag{17}$$

where $F = A(\tilde{p}_S(1), \tilde{p}_S(2))$. The estimated data is then obtained via $\hat{\mathbf{x}}_S(1) = \mathcal{M}_S^{-1}(\hat{p}_S(1))$, $\hat{\mathbf{x}}_S(2) = \mathcal{M}_S^{-1}(\hat{p}_S(2))$ and $\hat{\mathbf{x}}_F(3) = \mathcal{M}_F^{-1}(\hat{p}_F(3))$. It is easy to see that this demodulator has complexity $O\left(M^2 N\right)$; also, note that apart from the reduction in the search space size, this demodulator has the additional advantage that it does not need to know the noise power spectral density or the instantaneous bit error rates at the relays.

V. Simulation Results and Discussion

In this section, the proposed NC-DSM protocol is compared by simulation with DSM for two different channel geometries.

A. Simulation setup

For comparison of DSM and NC-DSM, we assume a system with 2 relays, with BPSK modulation employed at source and relays ($M = N = 2$). We assume that the average transmit symbol energy is the same for both source and relays, i.e., $E_s = E_r$. Two different node geometries are considered. In the first geometry (called G1), an equal distance between all pairs of communicating nodes is assumed i.e., $\sigma_{SD}^2 = \sigma_{SF}^2 = \sigma_{FD}^2 = 1$ for $F \in \{R_1, R_2\}$. In the second geometry (called G2), 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 here $\sigma_{SD}^2 = 1$ while $\sigma_{SF}^2 = \sigma_{FD}^2 = 4$ for $F \in \{R_1, R_2\}$. The average transmit energy at the relays is equal to that at the source, i.e., $E_r = E_s \triangleq E_b$, for both protocols (NC-DSM and DSM). The effect of inter-relay interference is also neglected for both protocols.

B. Simulation Results

In Fig. 2, a comparison of the destination's source data BER is shown for both geometries G1 and G2, for both the NC-DSM and DSM protocols. For both protocols, the optimal (ML) demodulator is considered as well as the suboptimal low-complexity demodulator which assumes error-free demodulation at the relay.

Regarding the low-complexity demodulator in geometry G1, it can be seen that the proposed technique has very slightly worse performance compared to DSM. The reason is that the relay activation condition for NC-DSM is based on a match between the output of the bitwise-XOR operation and each relay's ID. Correct evaluation of the bitwise-XOR requires two consecutive error-free demodulations at the relay, instead of only one as for DSM; this slightly degrades the overall error rate. As expected, this effect is more pronounced for geometry G1, as in that case the source-to-relay links have a poorer quality.

Note that for both protocols, the use of the error-aware ML detector is required to achieve a diversity order of 2 for the source data (this was observed for DSM in [11], [12]). On the other hand, as can be seen from Fig. 3, the relays' data experiences no diversity enhancement through cooperation (this is true for both NC-DSM and conventional DSM, since only one copy of the relays' data is available to the destination in each case). The key point to note is that while the *overall* throughput (source plus relay data rates) is the same for both protocols,

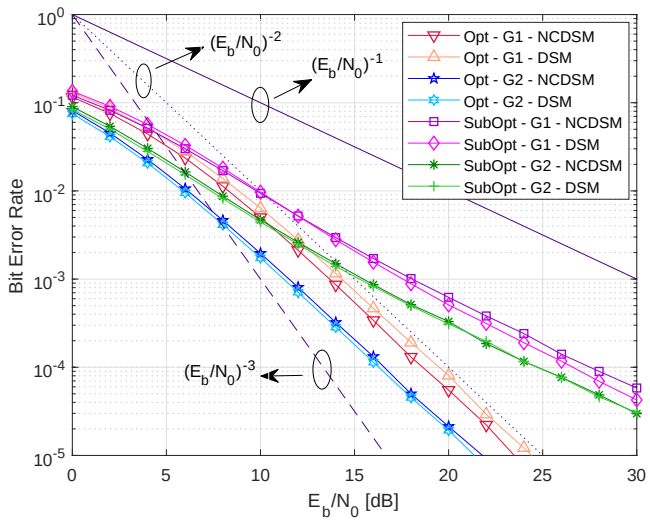

Fig. 2. BER of the source data at the destination, for the proposed NC-DSM and DSM, considering both the error-aware ML demodulator and the low-complexity demodulator in channel geometries G1 and G2.

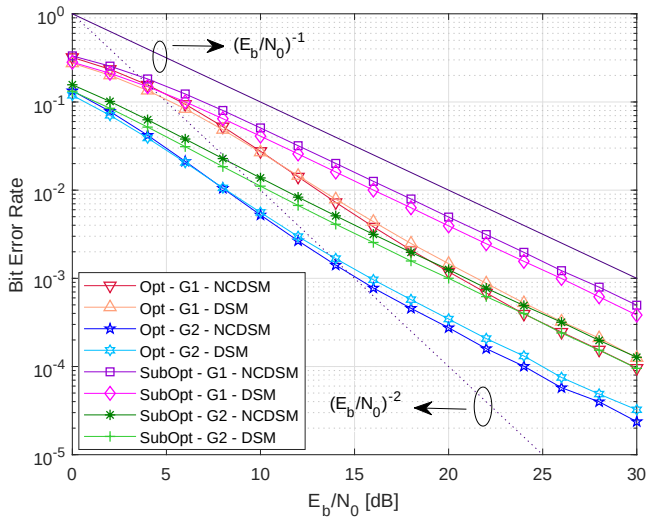

Fig. 3. BER of the relay data at the destination, for the proposed NC-DSM and DSM, considering both the error-aware ML demodulator and the low-complexity demodulator in channel geometries G1 and G2.

the NC-DSM protocol has approximately 33.3% advantage in the source-to-destination data rate compared to DSM; this data has a diversity order of improvement in reliability compared to the relays' data, which is particularly significant at high SNR.

VI. Conclusion

In this paper, a new protocol for cooperative communication was introduced based on the association of network coding with distributed spatial modulation. An error-aware ML demodulator and a low-complexity suboptimal demodulator were proposed for implementation of joint symbol detection at the destination over three time slots. The error rate of the proposed protocol was compared to that of distributed spatial modulation in two different channel geometries. Simulation results confirm that while the proposed technique has a gain of 33% in the source data rate compared to distributed spatial modulation, both NC-DSM and DSM systems have similar BER performance for the source data as well as relay data for both demodulators in both channel geometries.

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