Distributed Spatial Modulation: A Cooperative Diversity Protocol for Half-Duplex Relay-Aided Wireless Networks

Sandeep Narayanan, *Student Member, IEEE*, Marco Di Renzo, *Senior Member, IEEE*, Fabio Graziosi, *Member, IEEE*, and Harald Haas, *Member, IEEE*

***Abstract*—In this paper, distributed spatial modulation (DSM) is introduced. DSM is a cooperative diversity protocol for multirelay wireless networks, which is based on the concept of spatial modulation (SM). The distinguishable feature of DSM lies in improving the reliability of the source via distributed diversity and by increasing the aggregate throughput of the network since new data is transmitted during each transmission phase. This is achieved by encoding the data transmitted from the source into the spatial positions of the available relays and by exploiting the signal domain to transmit the data of the relays. At the destination, a diversity combiner that is robust to demodulation errors at the relays is proposed, and its end-to-end error probability and achievable diversity are studied. It is mathematically proved that DSM allows the source to achieve second-order diversity. With the aid of Monte Carlo simulations, DSM is compared against state-of-the-art cooperative protocols, and it is shown to provide a better error probability.**

***Index Terms*—Cooperation, diversity analysis, performance analysis, relaying, spatial modulation (SM).**

I. Introduction

In recent years, cooperative protocols have established themselves as a promising technology for future wireless networks [1], [2]. They enable single-antenna mobile terminals to harvest the benefits of multiple-input–multiple-output (MIMO) systems by being part of a distributed antenna array. Recent results have shown that cooperation is an effective means to combat multipath fading and shadowing, improve network coverage, and reduce transmit power. Moreover, several authors have investigated the potential benefits of combining MIMO-aided transmission and relay-aided cooperation, e.g., in [3]–[5].

In spite of these potential advantages, relay-aided cooperation faces some important design challenges [6], [7]. The first one is the half-duplex constraint, i.e., the relays cannot transmit and receive data on the same frequency at the same time, which results in a loss of system throughput. Although full-duplex relays can solve this issue and promising results have recently been reported [8], [9], half-duplex radios are widespread used and will remain so in the near future due to their maturity and low implementation cost. For this reason, in this paper, we focus our attention on half-duplex relaying. Second, the relays are forced to use their own resources for forwarding the data of the source, usually without receiving any rewards, except for the fact that the whole system may become more efficient. Finally, in classical cooperative protocols, the relays that perform a retransmission on behalf of the sources must delay the transmission of their own data frames, which has an impact on the network's latency.

Recently, many attempts for overcoming the limitations of relaying and distributed cooperation have been made. Notable examples include: 1) nonorthogonal relaying [10]–[12]; 2) successive relaying [13], [14]; 3) shifted successive relaying [15]; 4) two-way relaying (also known as physical-layer or analog network coding, NC) [16]–[18]; 5) cognitive cooperation [19]; and 6) complex-field NC [20]. A comprehensive survey and assessment of advantages/disadvantages of these solutions is available in [7, Fig. 6], to which we refer for further information. According to [6], a common assumption and limitation of these protocols is that the relays receive no direct reward from cooperation. They help the sources by performing retransmissions on their behalf, but they do not pursue any personal interests. In particular, *the relays must, in general, delay the transmission of their own data frames to first help the sources*. This operating principle is realistic when the relays are dedicated network elements with no data to be transmitted, but it might disincentive distributed cooperation when the relays have data to be transmitted.

Motivated by these considerations, two cooperative diversity protocols have recently been introduced, which allow the relays to help the sources while simultaneously working toward their own interests, i.e., to avoid delaying the transmission of their data frames while retransmitting those of the source. The first

Manuscript received October 17, 2014; revised February 28, 2015 and May 3, 2015; accepted May 19, 2015. Date of publication June 9, 2015; date of current version May 12, 2016. This work was supported in part by the European Commission through the FP7-PEOPLE ITN-GREENET Project under Grant 264759 and through the FP7-PEOPLE MITN-CROSSFIRE Project under Grant 317126. The review of this paper was coordinated by Dr. H. Lin. This paper was presented in part at the 78th IEEE Vehicular Technology Conference, Las Vegas, NV, USA, September 2013.

S. Narayanan was with WEST Aquila Srl, 67100 L'Aquila, Italy. He is now with the School of Electrical, Electronic, and Communications Engineering, University College Dublin, Dublin 4, Ireland (e-mail: sandeep.kadanveedu@ucd.ie).

M. Di Renzo is with the Laboratory of Signals and Systems (L2S, UMR-8506), CNRS-CentraleSupelec-University Paris-Sud XI, Paris-Saclay University, 91192 Gif-sur-Yvette, France (e-mail: marco.direnzo@lss.supelec.fr).

F. Graziosi is with the Department of Engineering, Computer, and Mathematical Sciences, University of L'Aquila, 67100 L'Aquila, Italy (e-mail: fabio.graziosi@univaq.it).

H. Haas is with the Institute for Digital Communications, University of Edinburgh, Edinburgh EH9 3JL, U.K. (e-mail: h.haas@ed.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TVT.2015.2442754

solution is referred to as MIMO-NC and was introduced in [21] and [22]. MIMO-NC is a transmission protocol that allows the relays to encode the data received from the source with their own data by leveraging the principle of digital NC. This approach avoids throughput reductions that are typical of half-duplex relaying. Recent results, however, have highlighted that the source receives no distributed diversity gain regardless of the Galois field being used for NC [23]–[25]. The second solution is referred to as super-position modulation (SPM) and was introduced in [26]. SPM can be thought as an NC scheme that is implemented in the modulation domain rather than in the code domain. Its performance and achievable diversity critically depend on the weight factors being used for superimposing the modulated symbols of source and relay, which should be appropriately optimized to reduce the impact of self-interference and for avoiding a nonnegligible performance degradation [27]. Compared with MIMO-NC, SPM is capable of increasing the diversity order of the source without throughput degradation. The choice of the weight factors is, however, a nontrivial optimization problem.

In this paper, we introduce a cooperative diversity protocol that, similar to MIMO-NC and SPM, allows the relays to transmit their own data frames while retransmitting the data frames of the source. It is based on the principle of spatial modulation (SM), which is an emerging low-complexity and energy-efficient transmission concept for multiple-antenna systems [28], [29]. A comprehensive state-of-the-art survey of SM research is available in [30] and [31], to which we refer for further information. In SM, the data to be transmitted in each channel use is encoded in both the conventional signal-constellation diagram and in the transmit antennas being activated. This encoding mechanism allows MIMO-aided systems to increase the rate of single-antenna transmission at low implementation complexity. In particular, the number of simultaneously activated transmit antennas per channel use can be optimized for achieving the desired tradeoff between spectral/energy efficiency and modulation/demodulation complexity. Several studies have confirmed that SM is capable of outperforming many MIMO transmission schemes with practical implementation constraints [32]–[47].

More recently, several researchers have leveraged the SM principle for application to relay-aided and cooperative communications. A summary of SM-based relay-aided protocols is available in [30, Section V.B]. Notable examples related to this paper include [48]–[66]. In particular, in [48] and [51], a protocol was proposed, where the SM concept is used for enhancing the rate of cooperative systems based on the concept of relayed and nonrelayed information. Moreover, iterative decoding techniques were proposed to take advantage of the proposed encoding method. In [49], the SM concept was applied to dual-hop relaying in an attempt of improving the performance of direct transmission. In [50], the work in [49] was generalized by considering cooperative protocols based on relay selection (RS) and by studying coherent and noncoherent demodulation methods. In [52], a relay-aided protocol was proposed, which provides a transmit-diversity gain, by adequately mapping information bits into the transmit-antenna indices and into the transmission time slots. In [53] and [54], the SM principle to distributed MIMO systems was applied, where the transmit antennas are not colocated, and the performance and diversity order of amplify-and-forward relaying were characterized. This analysis was generalized in [53] and [54] by considering decode-and-forward relaying and imperfect channel state information in [59] and [60], respectively. In [56], [61], [65], and [66], a comprehensive mathematical analysis of the achievable diversity order of decode-and-forward relaying was provided, by exploiting the relays as a distributed antenna array and by applying the SM principle to their spatial location. In [57] and [58], the achievable performance of space space–time shift keying modulation in the presence of relays was investigated, and several practical iterative decoding techniques were proposed. In [64], the performance of detect-and-forward relaying applied to SM was studied, and three low-complexity relay-aided protocols, in order to identify the most appropriate number of bits to be remodulated at the relays for improving the link reliability, were proposed. These papers have shown the potential benefits of using SM in the context of relay-aided transmission compared with conventional modulation and MIMO schemes. These relaying protocols, however, treat SM as a conventional modulation scheme since they aim either to increase the coverage, e.g., [49] or to enhance the link reliability of SM transmission via distributed diversity, e.g., [54], [66]. In this paper, we investigate another application of SM to relay-aided communications, which is aimed to mitigate the throughput reduction that originates from using half-duplex relays. Other studies more similar to ours, e.g., [51], do not account for demodulation errors at the relays and do not investigate the achievable diversity order of practical demodulators. Compared with [51], in particular, which relies on typical information-theoretic assumptions, we provide novel contributions that account for practical communication constraints. In this paper, in fact, we focus our attention on the design of diversity-achieving demodulators and provide a mathematical proof of the attainable diversity order. We provide these contributions by relying on typical communication-theoretic assumptions, where all the links are assumed error prone and discrete modulations are used. In [51], on the other hand, the links are assumed error-free since the analysis is based on the mutual information metric, which implicitly requires error-free transmission and Gaussian inputs. In addition, the encoding schemes are different since the protocol proposed in this paper is not based on relayed and nonrelayed information.

The proposed protocol takes advantage of the unique encoding mechanism of SM in a distributed fashion, and throughout this paper, it is referred to as distributed SM (DSM). In simple terms, each symbol transmitted from the source is univocally encoded into a unique identifier associated to each available relay. During the broadcasting phase, each relay decodes the received symbol independently of the others. During the relaying phase, only that particular relay whose identifier coincides with the demodulated symbol is allowed to transmit, whereas the other relays are kept silent. With the aid of this encoding mechanism, the activation of a given relay (spatial dimension) is exploited as an implicit means for relaying the symbol of the source instead of using conventional amplitude/phase modulations. Thus, this latter signal dimension can be used by the activated relay for transmitting its own data, instead of that of the source. With the aid of DSM, as a result, the relays are capable of helping the source without delaying their data transmission. Moreover, the average aggregate throughput is higher compared with half-duplex relaying, and in particular, it is the same as that of single-hop (SH) transmission if the modulation order of source and relay is the same.

Some practical issues, however, need to be addressed. Due to demodulation errors at the relays, either wrong or multiple relays may be activated. To ensure reliable data transmission, hence, a demodulator robust to these demodulation errors is needed. In addition, to be competitive against state-of-the-art cooperative protocols, DSM has to be capable of increasing the diversity order of the source. In this paper, we develop a demodulator that is robust to demodulation errors and study its error performance and achievable diversity. Our mathematical analysis confirms that DSM achieves second-order diversity, and Monte Carlo simulations show that DSM is capable of outperforming competing relaying protocols, such as MIMO-NC and SPM.

The remainder of this paper is organized as follows. In Section II, system model and DSM protocol are introduced. In Section III, a diversity combiner robust to demodulation errors at the relays is developed. In Section IV, its error performance and diversity order are studied. In Section V, the average power consumption and aggregate throughput of DSM are analyzed. In Section VI, numerical results to substantiate the analytical findings and to compare DSM against state-of-the-art cooperative protocols are shown. Finally, Section VII concludes this paper.

Notation: $\mathcal{P}\{\cdot\}$ denotes probability. $(\cdot)^*$ and $|\cdot|$ denote complex conjugate and absolute value operators, respectively. $\mathbb{E}_X\{\cdot\}$ denotes the expectation computed with respect to the random variable (RV) X. $\mathrm{Re}\{\cdot\}$ and $\mathrm{Im}\{\cdot\}$ denote real and imaginary part operators, respectively. $j=\sqrt{-1}$ denotes the imaginary unit. $Q(x)=(1/\sqrt{2\pi})\int_x^{+\infty}\exp(-t^2/2)dt$ denotes the Q-function. $\mathrm{card}\{\cdot\}$ denotes the cardinality of a set. Bold symbols denote strings of bits with fixed length. $\propto$ denotes the proportionality operator. $X\sim\mathcal{E}(\sigma_X^2)$ denotes an exponential RV with a probability density function (PDF) and a moment generating function (mgf) equal to $f_X(x)=(1/\sigma_X^2)\exp\{-x/\sigma_X^2\}$ and $\Phi_X(s)=\mathbb{E}_X\{\exp\{-s_X\}\}=(1+s\sigma_X^2)^{-1}$, respectively. The function $\delta(a,b)$ is defined as $\delta(a,b)=1$ if $a\neq b$ and $\delta(a,b)=0$ if $a=b$.

II. Distributed Spatial Modulation

A. System Model

A multirelay network topology with one source (S), N_R half-duplex relays (R_r for $r=1,2,\ldots,N_R$), and one destination (D) is considered. All nodes are equipped with a single antenna. Both source and relays have independent data to be delivered to the destination. The source transmits complex modulated symbols, by using either phase shift keying (PSK) or quadrature amplitude modulation (QAM) of constellation size M. The M complex modulated symbols are denoted by p_m for $m=1,2,\ldots,M$. Likewise, the relays use PSK/QAM modulation of constellation size N for transmitting their own data symbols. The N complex modulated symbols are denoted by q_n for $n=1,2,\ldots,N$. In general, the constellation size of source and relays is different, i.e., $N\neq M$. As it will become apparent in the sequel, DSM requires that the number of relays N_R is no less than the constellation size of the source, i.e., $N_R\geq M$. For ease of illustration, $N_R=M$ is assumed throughout this paper. The case study $N_R>M$, in fact, would require some criteria for choosing the relays, e.g., based on the minimization of the end-to-end error probability. This usually requires a feedback channel from the destination to the source and to the relays. The mathematical analysis of this case study is postponed to future research. A numerical example is, however, illustrated in Section VI. Thus, without ambiguity, N_R is replaced by M throughout this paper. Each relay is assigned a unique digital identifier $\mathbf{ID}_{R_r}$ for $r=1,2,\ldots,M$, which is a string of $\log_2(M)$ bits. Without loss of generality, a lexicographic labeling is used throughout this paper. If $M=4$, for example, the four relays are univocally identified by the strings of bits $\mathbf{ID}_{R_1}=00$, $\mathbf{ID}_{R_2}=01$, $\mathbf{ID}_{R_3}=10$, and $\mathbf{ID}_{R_4}=11$.

DSM consists of two transmission phases, i.e., broadcasting and relaying, that occur in two nonoverlapping time slots. In the first phase, the source is in transmission mode, and both relays and destination are in reception mode. In the second phase, the source is off, whereas the relays and the destination are in transmission mode and reception mode, respectively. Both phases are described in what follows and are shown in Fig. 1.

B. Broadcasting Phase

In this phase, the source broadcasts its data to the M relays and to the destination. The signals received at relays and destination can be formulated as follows ($r=1,2,\ldots,M$):

$$\begin{aligned} y_{SR_r} &= \sqrt{E_S}h_{SR_r}s_{\mathrm{tx}}+n_{SR_r}\\ y_{SD} &= \sqrt{E_S}h_{SD}s_{\mathrm{tx}}+n_{SD} \end{aligned} \tag{1}$$

where E_S is the source's average transmit energy per symbol, and h_{XY} is the fading gain of the link from node X to node Y, which is a circular symmetric complex Gaussian RV with zero mean and variance $\sigma_{XY}^2/2$ per real dimension. The fading gains over different links are independent but nonidentically distributed (i.n.i.d.) RVs, in order to account for different propagation distances and shadowing effects. n_{XY} is the noise at the input of node Y and related to the transmission from node X, which is a complex additive white Gaussian (AWG) RV with variance $N_0/2$ per real dimension. n_{XY} in different time slots or at the input of different nodes are independent and identically distributed (i.i.d.) RVs, and $s_{\mathrm{tx}}=\mathcal{M}_S(\mathbf{x}_S)\in\{p_1,p_2,\ldots,p_M\}$ is the complex modulated symbol transmitted by the source, where $\mathbf{x}_S$ are the $\log_2(M)$ bits emitted by the source and $\mathcal{M}_S(\cdot)$ is the bits-to-symbol mapping function.

The destination keeps the received signal for further processing. Each relay, on the other hand, demodulates the signal received from the source independently of the others. With the aid of the maximum-likelihood (ML) criterion, the demodulated symbol can be formulated as follows:

$$\begin{aligned} \hat{s}_{\mathrm{tx}}^{(R_r)} &= \operatorname*{arg\,min}_{p_m\in\{p_1,p_2,\ldots p_M\}}\left\{\left|y_{SR_r}-\sqrt{E_S}h_{SR_r}p_m\right|^2\right\}\\ \hat{\mathbf{x}}_S^{(R_r)} &= \mathcal{M}_S^{-1}\left(\hat{s}_{\mathrm{tx}}^{(R_r)}\right) \end{aligned} \tag{2}$$

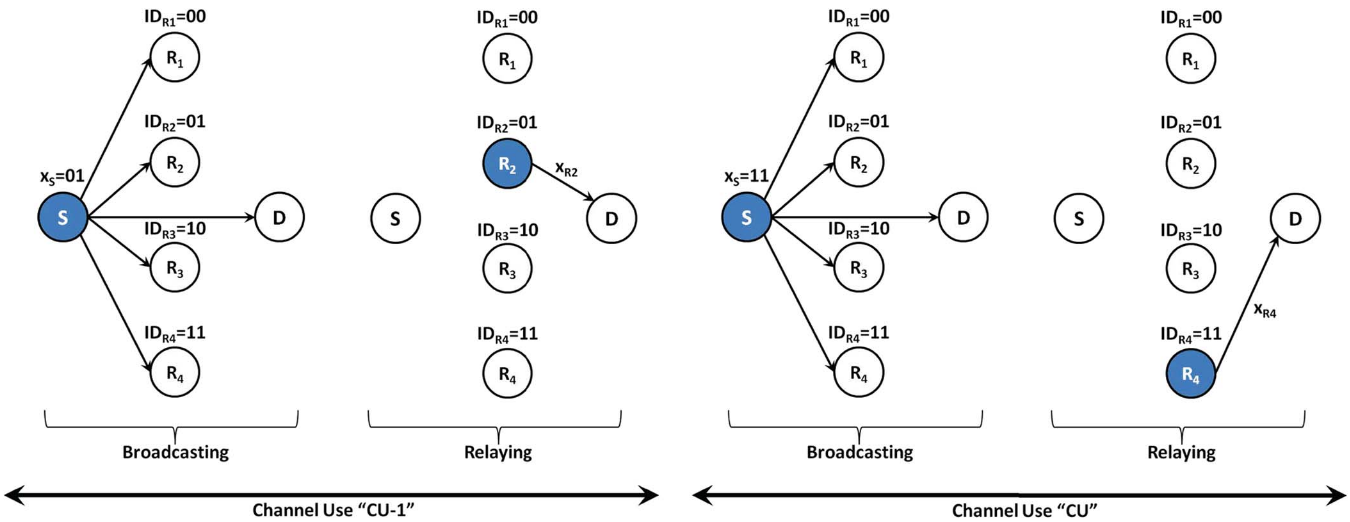

Fig. 1. DSM protocol for $N_R = M = 4$ and in the absence of demodulation errors at the relays. The shaded nodes are in transmission mode. The other nodes are in reception mode, and the source S is in idle mode during the relaying phase.

where $\hat{s}_{\mathrm{tx}}^{(R_r)}$ is the demodulated symbol at R_r for $r = 1, 2, \ldots, M$, $\mathcal{M}_S^{-1}(\cdot)$ is the inverse bits-to-symbol mapping function, and $\hat{\mathbf{x}}_S^{(R_r)}$ is the estimate of $\mathbf{x}_S$ at R_r for $r = 1, 2, \ldots, M$.

C. Relaying Phase

In this phase, the SM encoding principle applied to the set of M distributed relays is leveraged in order to *implicitly* forward the estimate of the source's data and to *explicitly* transmit the data of the activated relay. In particular, each relay, independently of the others, compares $\hat{\mathbf{x}}_S^{(R_r)}$ with its own unique digital identifier $\mathbf{ID}_{R_r}$. If they coincide, the relay is activated. If not, the relay is kept inactive. As such, the activation of a given relay is interpreted at the destination as the transmission of a specific symbol by the source. The activated relay exploits the unused signal dimension for modulating and for transmitting its own data symbol to the destination, instead of remodulating and transmitting the estimate of the source's data. As a result, relayed and new data are transmitted in this phase, and the aggregate throughput is increased.

If the source-to-relay links are error-free, no demodulation errors at the relays occur. Due to the uniqueness of the digital identifiers associated with each relay, a single relay is activated during the relaying phase. In practical operating conditions, however, demodulation errors at the relays may occur. Since each relay operates independently of the others, multiple or no relays may be activated during the relaying phase. In the presence of demodulation errors at the relays, the signal received at the destination can be formulated as follows:

$$y_{RD} = \sum_{r=1}^{M} \left(\sqrt{E_{R_r}} h_{R_r D} r_{\mathrm{tx}}^{(R_r)} \right) + n_{RD}$$
$$r_{\mathrm{tx}}^{(R_r)} = \begin{cases} \mathcal{M}_R(\mathbf{x}_{R_r}), & \text{if} \quad \mathbf{ID}_{R_r} = \hat{\mathbf{x}}_S^{(R_r)} \\ 0, & \text{if} \quad \mathbf{ID}_{R_r} \neq \hat{\mathbf{x}}_S^{(R_r)} \end{cases} \tag{3}$$

where E_{R_r} is the average transmit energy per symbol of R_r, and $\mathbf{x}_{R_r}$ are the $\log_2(N)$ bits emitted by the relay, if activated. These are relay's own bits that are independent of the source's bits $\mathbf{x}_S$. $\mathcal{M}_R(\cdot)$ is the bits-to-symbol mapping function. Since $M \neq N$, $\mathcal{M}_R(\cdot)$ and $\mathcal{M}_S(\cdot)$ are, in general, different. It is worth mentioning that, in (3), the source's data is implicitly encoded into the channel impulse responses $h_{R_r D}$ that correspond to the nonzero values of $r_{\mathrm{tx}}^{(R_r)}$. To better understand, let us assume that no demodulation errors occur at the relays and that $R_r = R_*$ is the only relay for which $\mathbf{ID}_{R*} = \mathbf{x}_S$. Thus, (3) reduces to $y_{RD} = \sqrt{E_{R_*}} h_{R_* D} \mathcal{M}_R(\mathbf{x}_{R_*}) + n_{RD}$, which shows that the source's data $\mathbf{x}_S$ is univocally encoded into $h_{R_* D}$.

The optimal demodulator in the absence of demodulation errors at the relays is formulated and studied in [63]. This demodulator, which is based on the error-free assumption at the relays, is provided in Table I. The notation used in Table I is introduced in Section VI. Throughout this paper, it is referred to as "DSM–Suboptimal demodulator." In Section III, a diversity combiner at the destination based on (3), i.e., in the presence of demodulation errors at the relays, is rigorously formulated. Furthermore, its error performance and achievable diversity are studied in Section IV.

D. Remarks

Some comments about practical implementation issues of the DSM protocol are as follows.

- In (1)–(3), a symbol-by-symbol signal model is considered. This is assumed for ease of description since DSM is compliant with packet-based transmission protocols in both broadcasting and relaying phases. In the relaying phase, in particular, "sparse" packets are transmitted by each relay, whose symbols are nonzero only if they are activated according to the DSM principle. The packets transmitted in broadcasting and relaying phases by source and relays, respectively, have the same length. Only the number of nonzero elements is different. This number may be added in the header of the packet. The zero symbols are discarded at the destination to reconstruct the bitstreams emitted by source and relays.
- The performance of DSM may be enhanced by reducing the impact of relay-induced error propagation with the aid of a

TABLE I

STATE-OF-THE-ART TRANSMISSION SCHEMES AND DEMODULATORS. THE DEMODULATORS ARE BASED ON THE MAP CRITERION. THE SAME NOTATION AS FOR DSM IS USED. AS FOR THE SIGNAL MODELS, (1) AND (2) APPLY TO ALL TRANSMISSION SCHEMES. $\oplus$ DENOTES BITWISE EXCLUSIVE OR OPERATION. γ IS A POSITIVE CONSTANT LESS THAN ONE

Auxiliary Functions
$\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right) = \exp\left(-\frac{\left\lvert y_{SD} - \sqrt{E_S} h_{SD} \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right)\right\rvert^2}{N_0}\right)$ $\mathrm{P}\left(y_{RD} \lvert \tilde{\mathbf{x}}_S^{(R_1)}\right) = \exp\left(-\frac{\left\lvert y_{RD} - \sqrt{E_{R_1}} h_{R_1 D} \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right)\right\rvert^2}{N_0}\right)$ $\mathrm{P}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) = \exp\left(-\frac{\left\lvert y_{RD} - \sqrt{E_{R_1}} h_{R_1 D}\left(\sqrt{1-\gamma^2}\mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_1}^{(D)}\right) + \gamma \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right)\right)\right\rvert^2}{N_0}\right)$ $\bar{\mathrm{P}}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) = \exp\left(-\frac{\left\lvert y_{RD} - \sqrt{E_{R_1}} h_{R_1 D} \mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_1}^{(D)} \oplus \tilde{\mathbf{x}}_S^{(R_1)}\right)\right\rvert^2}{N_0}\right)$ $\tilde{\mathrm{P}}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_*}^{(D)}\right) = \exp\left(-\frac{\left\lvert y_{RD} - \sqrt{E_{R_*}} h_{R_* D} \mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_*}^{(D)}\right)\right\rvert^2}{N_0}\right)$ $\mathrm{P}\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) \approx Q\left(\sqrt{\frac{E_S}{2N_0}\left\lvert \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right)\right\rvert^2 \left\lvert h_{SR_1}\right\rvert^2}\right) \quad \text{if} \quad \tilde{\mathbf{x}}_S^{(D)} \neq \tilde{\mathbf{x}}_S^{(R_1)}$ $\mathrm{P}\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) \approx 1 - \beta Q\left(\sqrt{2\alpha \frac{E_S}{N_0}\left\lvert h_{SR_1}\right\rvert^2}\right) \quad \text{if} \quad \tilde{\mathbf{x}}_S^{(D)} = \tilde{\mathbf{x}}_S^{(R_1)}$
Single-Hop (SH) Transmission
$\hat{s}_{tx}^{(D)} = \underset{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) \in \{p_1, p_2, \ldots, p_M\}}{\arg\max}\left\{\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right)\right\}$ $\mathcal{R}_{\mathrm{av}} = \log_2(M); \quad E_S = E_b \log_2(M); \quad E_{\mathrm{av}} = E_S$
Demodulate-and-Forward (DemF) Relaying [76]
$y_{RD} = \sqrt{E_{R_1}} h_{R_1 D} \mathcal{M}_S\left(\hat{\mathbf{x}}_S^{(R_1)}\right) + n_{RD}$ $\hat{s}_{tx}^{(D)} = \underset{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) \in \{p_1, p_2, \ldots, p_M\}}{\arg\max}\left\{\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right) \sum_{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right) \in \{p_1, p_2, \ldots, p_M\}} \mathrm{P}\left(y_{RD} \lvert \tilde{\mathbf{x}}_S^{(R_1)}\right) \mathrm{P}\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right)\right\}$ $\mathcal{R}_{\mathrm{av}} = (1/2)\log_2(M); \quad E_S = E_b \log_2(M); \quad E_R = E_b \log_2(M); \quad E_{\mathrm{av}} = E_S + E_R$
Super-Position Modulation (SPM) Relaying [26]
$y_{RD} = \sqrt{E_{R_1}} h_{R_1 D}\left(\sqrt{1-\gamma^2}\mathcal{M}_R\left(\mathbf{x}_{R_1}\right) + \gamma \mathcal{M}_S\left(\hat{\mathbf{x}}_S^{(R_1)}\right)\right) + n_{RD}$ $\left[\hat{s}_{tx}^{(D)}, \hat{r}_{tx}^{(R_1, D)}\right] = \underset{\substack{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) \in \{p_1, p_2, \ldots, p_M\} \\ \mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_1}^{(D)}\right) \in \{q_1, q_2, \ldots, q_N\}}}{\arg\max}\left\{\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right) \sum_{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right) \in \{p_1, p_2, \ldots, p_M\}} \mathrm{P}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) \mathrm{P}\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right)\right\}$ $\mathcal{R}_{\mathrm{av}} = (1/2)\left(\log_2(M) + \log_2(N)\right); \quad E_S = E_b \log_2(M); \quad E_R = E_b\left(\log_2(M) + \log_2(N)\right); \quad E_{\mathrm{av}} = E_S + E_R$
Network-Coded Cooperative (NCC) Relaying [25]
$y_{RD} = \sqrt{E_{R_1}} h_{R_1 D} \mathcal{M}_R\left(\mathbf{x}_{R_1} \oplus \hat{\mathbf{x}}_S^{(R_1)}\right) + n_{RD}$ $\left[\hat{s}_{tx}^{(D)}, \hat{r}_{tx}^{(R_1, D)}\right] = \underset{\substack{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) \in \{p_1, p_2, \ldots, p_M\} \\ \mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_1}^{(D)}\right) \in \{q_1, q_2, \ldots, q_N\}}}{\arg\max}\left\{\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right) \sum_{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(R_1)}\right) \in \{p_1, p_2, \ldots, p_M\}} \bar{\mathrm{P}}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right) \mathrm{P}\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_S^{(R_1)}\right)\right\}$ $\mathcal{R}_{\mathrm{av}} = (1/2)\left(\log_2(M) + \log_2(N)\right); \quad E_S = E_b \log_2(M); \quad E_R = E_b\left(\log_2(M) + \log_2(N)\right); \quad E_{\mathrm{av}} = E_S + E_R$
DSM - Sub-Optimal Demodulator
$\left[\hat{s}_{tx}^{(D)}, \hat{r}_{tx}^{(R_*, D)}\right] = \underset{\substack{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) \in \{p_1, p_2, \ldots, p_M\} \\ \mathcal{M}_R\left(\tilde{\mathbf{x}}_{R_*}^{(D)}\right) \in \{q_1, q_2, \ldots, q_N\}\ R_* \text{ such that } \mathbf{ID}_{R_*} = \tilde{\mathbf{x}}_S^{(D)}}}{\arg\max}\left\{\mathrm{P}\left(y_{SD} \lvert \tilde{\mathbf{x}}_S^{(D)}\right) \tilde{\mathrm{P}}\left(y_{RD} \lvert \tilde{\mathbf{x}}_{R_*}^{(D)}\right)\right\}$ $\mathcal{R}_{\mathrm{av}} = (1/2)\left(\log_2(M) + \log_2(N)\right); \quad E_S = E_b \log_2(M); \quad E_R = E_b\left(\log_2(M) + \log_2(N)\right); \quad E_{\mathrm{av}} = E_S + E_R$

cyclic redundancy check (CRC) mechanism. The adoption of a CRC usually increases the demodulation complexity at the relays and reduces the spectral efficiency since entire packets are discarded, although a few symbols are not demodulated correctly. CRC-based implementations are not investigated in this paper and are left to future research.

- In this paper, for ease of description, channel coding is not considered. It may, however, be applied to the DSM protocol by using the line of thought recently introduced in [67] and [68] for application to a broad class of relay-aided networks. It is worth noting, in particular, that the application of channel coding at the relays may relax the need to take the reliability of the source-to-relay links into account at the destination since relay-induced errors are less probable. The price to be paid for reducing the demodulation complexity at the destination is, however, the need to increase the demodulation complexity at the relays.

- The signal formulation in (3) highlights that DSM requires, for appropriate demodulation at the destination, symbol-level synchronization among the relays. This requirement is needed for many cooperative transmission protocols, e.g., distributed space–time coding [69]. The analysis of the impact of synchronization errors on the performance of DSM is out of the scope of this paper and is left to future research.
- In DSM, the source transmits only in the broadcasting phase. Thus, it uses half of the available degrees of freedom for its transmission. Likewise, the relays *collectively* exploit half of the available degrees for their transmissions. The transmission of the relays, however, is discontinuous, since they transmit only if they are activated by the source. Under the assumption that the source emits equally likely symbols, the M relays equally share the remaining degrees of freedom, i.e., on average each of them uses $1/(2M)$ of the available degrees of freedom.
- Due to demodulation errors, multiple relays may be activated during the relaying phase. Nevertheless, the destination must be capable of associating, without ambiguity, each transmitted symbol to the activated relay that has transmitted it. This is guaranteed by the fact that the channel impulse responses of all relay-to-destination links are different. This concept is behind the correct operation of multiple-access channels, whose signal model is similar to (3). In DSM, the difference is that the activated relays have to be identified at the destination. To this end, an appropriate demodulator is needed. This demodulator is introduced in Section III.

III. Diversity Combiner at the Destination

Here, we propose a diversity combiner at the destination that is capable of retrieving the symbols transmitted from source and relays in the presence of demodulation errors at the relays. The demodulator is based on the maximum *a posteriori* (MAP) criterion [70]. By using y_{SD} and y_{RD} in (1) and (3), the diversity combiner can be formulated as in (4), shown at the bottom of the page, where $\hat{\mathbf{x}}_S^{(D)} = \mathcal{M}_S^{-1}(\hat{s}_{\text{tx}}^{(D)})$, $\hat{\mathbf{x}}_{R_r}^{(D)} = \widetilde{\mathcal{M}}_R^{-1}(\hat{r}_{\text{tx}}^{(R_r,D)})$ for $r = 1, 2, \ldots, M$. The following definitions also hold:

$$
\begin{aligned}
&P_1\left(y_{SD}, y_{RD}|\tilde{\mathbf{x}}^{(D)}\right)\\
&\quad= \mathcal{P}\left\{y_{SD}, y_{RD}|\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_{R_2}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)}\right\}\\
&\quad= \exp\left(-\frac{\left|y_{SD} - \sqrt{E_S}h_{SD}\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right)\right|^2}{N_0}\right)\\
&\quad\times \exp\left(-\frac{\left|y_{RD} - \sum_{r=1}^{M}\sqrt{E_{R_r}}h_{R_rD}\widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right)\right|^2}{N_0}\right)
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
&P_2(\tilde{\mathbf{x}}^{(D)})\\
&\quad= \mathcal{P}\left\{\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_{R_2}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)}\right\}\\
&\quad= \frac{1}{M}\prod_{r\in\widetilde{\Omega}_R^{(\text{ON})}}\frac{1}{N}\mathcal{P}\left\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\right\}\\
&\quad\times\prod_{r\in\widetilde{\Omega}_R^{(\text{OFF})}}\left(1 - \mathcal{P}\left\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\right\}\right).
\end{aligned}
\tag{6}
$$

$\hat{s}_{\text{tx}}^{(D)}$ and $\hat{\mathbf{x}}_S^{(D)}$ denote the estimates at the destination of information symbol s_{tx} and information bits, $\mathbf{x}_S$, respectively, transmitted by the source. $\hat{r}_{\text{tx}}^{(R_r,D)}$ and $\hat{\mathbf{x}}_{R_r}^{(D)}$ denote the estimates at the destination of information symbol $r_{\text{tx}}^{(R_r)}$ and information bits $\mathbf{x}_{R_r}$, respectively, transmitted by the relay R_r for $r = 1, 2, \ldots, M$. $\tilde{\mathbf{x}}_S^{(D)}$ and $\tilde{\mathbf{x}}_{R_r}^{(D)}$ for $r = 1, 2, \ldots, M$ are the trial bits used in the hypothesis detection problem, where $\tilde{\mathbf{x}}^{(D)} = (\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_{R_2}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)})$ is a shorthand introduced for notational simplicity. $\mathcal{M}_R^{-1}(\cdot)$ is the inverse function of $\mathcal{M}_R(\cdot)$, i.e., the symbol-to-bits mapping function. $\widetilde{\mathcal{M}}_R(\cdot)$ is the generalized mapping function used at the relays, which account for the *no transmission state* of the inactive relays. The no transmission state is identified by symbol "0." Likewise, $\widetilde{\mathcal{M}}_R^{-1}(\cdot)$ is the inverse of $\widetilde{\mathcal{M}}_R(\cdot)$, where $\widetilde{\mathcal{M}}_R^{-1}(0) = \mathcal{N}$ and $\mathcal{N}$ denotes the "null" (no transmission) state in the bits domain. $P_1(y_{SD}, y_{RD}|\tilde{\mathbf{x}}^{(D)})$ denotes the joint pdf of the received signals conditioned upon the hypothesis $\tilde{\mathbf{x}}^{(D)}$. $P_2(\tilde{\mathbf{x}}^{(D)})$ is the *a priori* probability that the M relays are active/inactive given the hypothesis of the data transmitted by the source $\tilde{\mathbf{x}}_S^{(D)}$. In (6), in particular, $\widetilde{\Omega}_R^{(\text{ON})}$ and $\widetilde{\Omega}_R^{(\text{OFF})}$ denote the sets of active and inactive relays, respectively. They are defined as $\widetilde{\Omega}_R^{(\text{ON})} = \{r = 1, 2, \ldots, M|\widetilde{\mathcal{M}}_R(\tilde{\mathbf{x}}_{R_r}^{(D)}) \neq 0\}$ and $\widetilde{\Omega}_R^{(\text{OFF})} = \{r = 1, 2, \ldots, M|\widetilde{\mathcal{M}}_R(\tilde{\mathbf{x}}_{R_r}^{(D)}) = 0\}$. Furthermore, $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$ denotes the probability that the relay R_r for $r = 1, 2, \ldots, M$ is activated, conditioned upon $\tilde{\mathbf{x}}_S^{(D)}$, i.e., the probability that the symbol demodulated at R_r is $\mathbf{ID}_{R_r}$ by assuming that the source has transmitted $\tilde{\mathbf{x}}_S^{(D)}$. The terms $1/M$ and $1/N$ take into account that the symbols transmitted by source and relays are equally likely.

The computation of (6) requires a closed-form expression of $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$. The exact computation of this probability is a nontrivial issue for general modulation schemes, as recently remarked in [24] and [25]. Fortunately, recent results

$$
\left[\hat{s}_{\text{tx}}^{(D)}, \hat{r}_{\text{tx}}^{(R_1,D)}, \ldots, \hat{r}_{\text{tx}}^{(R_M,D)}\right] = \underset{\substack{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right)\in\{p_1,p_2,\ldots,p_M\}\\ \widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right)\in\{0,q_1,q_2,\ldots,q_N\}\ \text{for}\ r=1,2,\ldots,M}}{\arg\max}\left\{P_1\left(y_{SD}, y_{RD}|\tilde{\mathbf{x}}^{(D)}\right)P_2(\tilde{\mathbf{x}}^{(D)})\right\}
\tag{4}
$$

related to the development of diversity-achieving demodulators in the context of relay-aided communications have highlighted that approximated expressions of these probabilities based on, e.g., the union-bound method, are sufficiently accurate from the diversity order standpoint. The interested reader is referred to [25] and [71] for further information. By using a similar line of thought and with the aid of the union-bound [70], $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$ can be approximated as in (7), shown at the bottom of the page, where (a) further simplifies the union-bound by avoiding the summation with respect to the modulated symbols. The approximation in (a) is widespread used in the literature, as discussed in [72]. The parameters α and β depend on the modulation scheme being used. For example, $\alpha = 3/(2(M-1))$ and $\beta = 4(1-1/\sqrt{M})$ for QAM. If $M = 2$, the union-bound and approximation in (a) coincide with each other and provide an exact expression of $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$ for $\alpha = \beta = 1$.

A. Remarks

Some comments about the demodulator in (4) are as follows.

- The demodulator in (4) is designed to jointly demodulate source's and relays' data, so that the relays are allowed to transmit their own data during the relaying phase. The active/inactive state of the relays is modeled as an additional symbol ("0") that is added to the constellation diagram. Thus, a symbol error occurs if a relay is estimated as active instead of inactive and *vice versa*, e.g., the symbol "0" is erroneously demodulated as any other symbol of the signal constellation diagram.
- Demodulation errors at the relays are taken into account via the *a priori* probabilities $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$, which depend on the channel state information of the source-to-relay links. This is a common requirement for diversity-achieving demodulators that do not rely upon CRC-based error mitigation methods [25]. This channel state information may be estimated at the relays and then forwarded to the destination, as discussed in [67].
- The demodulator in (4) is optimal; however, the approximations used in (7) for computing $\mathcal{P}\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\}$ make it suboptimal. This suboptimality refers to the resulting coding gain of the error probability [73]. The demodulator is optimal only if $M = 2$.
- In the absence of demodulation errors at the relays, e.g., if CRC-based methods are used, the demodulator in (4) can be simplified by letting $Q(\cdot) \to 0$ for $r = 1, 2, \ldots, M$ in (7) and by taking into account that only one relay is activated during the relaying phase. As mentioned in Section II-C, this demodulator is available in Table I (see DSM–suboptimal demodulator), and its performance is studied in Section VI.
- The demodulator in (4) can be thought as a generalized multiuser detector since the data of different users are jointly demodulated. It is "generalized" because the reliability of the source-to-relay links is taken into account by design.

B. High Signal-to-Noise-Ratio Approximation

Although the demodulator in (4) is near optimal, the associated signal processing complexity is nonnegligible, particularly because of the computation of several exponential and $Q(\cdot)$ functions. Furthermore, the presence of these functions does not facilitate its mathematical analysis in terms of error probability and diversity order. Motivated by these considerations, here, we propose a high-SNR approximation for (4).

In the high-SNR regime, $1 - Q(\sqrt{(E_S/N_0)x}) \approx 1$. Thus, $P_2(\tilde{\mathbf{x}}^{(D)})$ can be approximated as

$$P_2(\tilde{\mathbf{x}}^{(D)}) \approx \widetilde{\mathcal{K}} \left(\prod_{r \in \widetilde{\Omega}_{R,S}^{(\mathrm{ON})}} Q\left(\sqrt{\frac{E_S}{2N_0} \left| \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S(\mathbf{ID}_{R_r}) \right|^2 |h_{SR_r}|^2} \right) \right) \times \left(\prod_{r \in \widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}} Q\left(\sqrt{2\alpha \frac{E_S}{N_0} |h_{SR_r}|^2} \right) \right) \tag{8}$$

where $\widetilde{\mathcal{K}} = (1/M)(1/N)^{\mathrm{card}\{\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}\}} \beta^{\mathrm{card}\{\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}\}}$, and $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ and $\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}$ are defined as follows:

$$\widetilde{\Omega}_{R,S}^{(\mathrm{ON})} = \left\{ r = 1, 2, \ldots, M | \widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right) \neq 0 \text{ and } \tilde{\mathbf{x}}_S^{(D)} \neq \mathbf{ID}_{R_r} \right\}$$
$$\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})} = \left\{ r = 1, 2, \ldots, M | \widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right) = 0 \text{ and } \tilde{\mathbf{x}}_S^{(D)} = \mathbf{ID}_{R_r} \right\}. \tag{9}$$

$$\mathcal{P}\left\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\tilde{\mathbf{x}}_S^{(D)}\right\} \approx \begin{cases} Q\left(\sqrt{\frac{E_S}{2N_0} \left| \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S\left(\mathbf{ID}_{R_r}\right) \right|^2 |h_{SR_r}|^2} \right), & \text{if } \tilde{\mathbf{x}}_S^{(D)} \neq \mathbf{ID}_{R_r} \\ 1 - \sum_{z \neq r = 1}^{M} Q\left(\sqrt{\frac{E_S}{2N_0} \left| \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S\left(\mathbf{ID}_{R_z}\right) \right|^2 |h_{SR_z}|^2} \right), & \text{if } \tilde{\mathbf{x}}_S^{(D)} = \mathbf{ID}_{R_r} \end{cases}$$
$$\overset{(a)}{\approx} \begin{cases} Q\left(\sqrt{\frac{E_S}{2N_0} \left| \mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S\left(\mathbf{ID}_{R_r}\right) \right|^2 |h_{SR_r}|^2} \right), & \text{if } \tilde{\mathbf{x}}_S^{(D)} \neq \mathbf{ID}_{R_r} \\ 1 - \beta Q\left(\sqrt{2\alpha \frac{E_S}{N_0} |h_{SR_r}|^2} \right), & \text{if } \tilde{\mathbf{x}}_S^{(D)} = \mathbf{ID}_{R_r} \end{cases} \tag{7}$$

By applying the Chernoff bound, which is accurate for high SNR, i.e., $Q(\sqrt{(E_S/N_0)x}) \leq (1/2)\exp(-(1/2)(E_S/N_0)x)$, (4) can be formulated, using some algebra and neglecting some irrelevant constants, as

$$\left[\hat{s}_{\mathrm{tx}}^{(D)}, \hat{r}_{\mathrm{tx}}^{(R_1,D)}, \ldots, \hat{r}_{\mathrm{tx}}^{(R_M,D)}\right] = \underset{\substack{\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right)\in\{p_1,p_2,\ldots,p_M\} \\ \widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right)\in\{0,q_1,q_2,\ldots,q_M\},\ r=1,2,\ldots,M}}{\arg\min} \left\{\Lambda\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)}\right)\right\} \tag{10}$$

$$\begin{aligned}\Lambda&\left(\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)}\right) \\ &= \left(\frac{\left|y_{SD} - \sqrt{E_S}h_{SD}\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right)\right|^2}{N_0}\right) \\ &\quad + \left(\frac{\left|y_{RD} - \left(\sum_{r=1}^{M}\sqrt{E_{R_r}}h_{R_rD}\widetilde{\mathcal{M}}_R\left(\tilde{\mathbf{x}}_{R_r}^{(D)}\right)\right)\right|^2}{N_0}\right) \\ &\quad + \frac{E_S}{4N_0}\sum_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\left|\mathcal{M}_S\left(\tilde{\mathbf{x}}_S^{(D)}\right) - \mathcal{M}_S\left(\mathbf{ID}_{R_r}\right)\right|^2|h_{SR_r}|^2 \\ &\quad + \alpha\frac{E_S}{N_0}\sum_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}}|h_{SR_r}|^2 - \widetilde{\mathcal{H}}\end{aligned} \tag{11}$$

where $\widetilde{\mathcal{H}} = (\mathrm{card}\{\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}\} + \mathrm{card}\{\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}\})\ln(1/2) + \ln(\widetilde{\mathcal{K}})$. It is worth noting that $\widetilde{\mathcal{H}}$ is independent of the SNR and that it can usually be neglected for high SNR without a significant performance difference. As such, it is neglected in the remainder of this paper.

IV. Error Probability and Diversity Order

The proposed methodology to the computation of the error probability of DSM consists of two steps: First, the average pairwise error probability (APEP) is computed, and then the average symbol error probability (ASEP) is obtained from it with the aid of the union-bound [70]. In particular, the APEP is related to the codeword that is composed of the data of source and relays. Thus, it can interpreted as a codeword error probability. The ASEP of the source is subsequently obtained by considering only the codewords that correspond to an error for the source. This approach is usually used for the analysis of unequal error protection codes, which provide different diversity orders to different information bits of a codeword [74]. The proposed approach for performance evaluation relies upon some high-SNR approximations, in order to make the mathematical derivation tractable. This is sufficient since we are mainly interested in characterizing the diversity order of the protocol. Here, in particular, we focus our attention only on the computation of ASEP and diversity order of the source. In fact, the destination receives a single copy of the packets transmitted by each relay, and as a consequence, the diversity order of the relays is equal to one. The same mathematical development as for the analysis of the source may be applied, however, to the analysis of the relays. It is worth mentioning that the fact that the relays have diversity order equal to one is not a limitation of DSM. This is, in fact, the usual assumption of relay-aided transmission [1].

A. Error Probability

Let $\mathbf{x}^{(D)} = (\mathbf{x}_S^{(D)}, \mathbf{x}_{R_1}^{(D)}, \mathbf{x}_{R_2}^{(D)}, \ldots, \mathbf{x}_{R_M}^{(D)})$ and $\tilde{\mathbf{x}}^{(D)} = (\tilde{\mathbf{x}}_S^{(D)}, \tilde{\mathbf{x}}_{R_1}^{(D)}, \tilde{\mathbf{x}}_{R_2}^{(D)}, \ldots, \tilde{\mathbf{x}}_{R_M}^{(D)})$ be transmitted and be the hypothesis symbols' vectors. The pairwise error probability (PEP) is denoted by $\mathrm{PEP}(\mathbf{x}^{(D)} \to \tilde{\mathbf{x}}^{(D)}|\mathbf{n},\mathbf{h})$, and it is defined as the probability of demodulating $\tilde{\mathbf{x}}^{(D)}$ in lieu of $\mathbf{x}^{(D)}$, by assuming that they are the only two available codewords and that AWG noise (AWGN) $\mathbf{n}$ and fading channels $\mathbf{h}$ are fixed. In particular, $\mathbf{n}$ and $\mathbf{h}$ are shorthands used to denote all noise and fading channels available in the decision variable, respectively. The APEP is obtained from the PEP by removing the conditioning with respect to AWGN and fading gains. In mathematical terms, they can be formulated as follows:

$$\begin{aligned}&\mathrm{PEP}(\mathbf{x}^{(D)} \to \tilde{\mathbf{x}}^{(D)}|\mathbf{n},\mathbf{h}) \\ &\quad = \mathcal{P}\left\{\Lambda(\tilde{\mathbf{x}}^{(D)}) < \Lambda(\mathbf{x}^{(D)})|\mathbf{n},\mathbf{h}\right\}\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\} \\ &\quad = \mathcal{P}\left\{\Delta(\mathbf{x}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0|\mathbf{n},\mathbf{h}\right\}\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\} \\ &\mathrm{APEP}(\mathbf{x}^{(D)} \to \tilde{\mathbf{x}}^{(D)}) \\ &\quad = \mathbb{E}_{\mathbf{h}}\left\{\mathbb{E}_{\mathbf{n}}\left\{\mathrm{PEP}(\mathbf{x}^{(D)} \to \tilde{\mathbf{x}}^{(D)}|\mathbf{n},\mathbf{h})\right\}\right\} \\ &\quad = \mathbb{E}_{\mathbf{h}}\left\{\mathcal{P}\left\{\Delta(\mathbf{x}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0|\mathbf{h}\right\}\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\}\right\}\end{aligned} \tag{12}$$

where $\mathcal{P}\{\Delta(\mathbf{x}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0|\mathbf{h}\} = \mathbb{E}_{\mathbf{n}}\{\mathcal{P}\{\Delta(\mathbf{x}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0|\mathbf{n},\mathbf{h}\}\}$, $\Delta(\mathbf{x}^{(D)}, \tilde{\mathbf{x}}^{(D)}) = \Lambda(\tilde{\mathbf{x}}^{(D)}) - \Lambda(\mathbf{x}^{(D)})$, and $\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\} = P_2(\mathbf{x}^{(D)})$ is defined in (6). For high SNR, $\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\}$ can be formulated similar to (8) and by applying the Chernoff bound.

Based on (12), the ASEP can be formulated as follows:

$$\mathrm{ASEP} \approx \sum_{\mathbf{x}^{(D)}}\sum_{\tilde{\mathbf{x}}^{(D)}}\delta\left(\mathbf{x}_S^{(D)}, \tilde{\mathbf{x}}_S^{(D)}\right)\mathrm{APEP}(\mathbf{x}^{(D)} \to \tilde{\mathbf{x}}^{(D)}) \tag{13}$$

where the function $\delta(\cdot,\cdot)$ takes into account that, for the source, an error occurs only if $\mathbf{x}_S^{(D)} \neq \tilde{\mathbf{x}}_S^{(D)}$.

The computation of the APEP in (12) is not an easy task. To proceed further, we introduce an approximation that is accurate for high SNR. For ease of description, the approximated expression of the ASEP is first provided and then discussed.

1) Proposed Approximation: Let Ω_{exact} be the set of codewords $\bar{\mathbf{x}}^{(D)}$ corresponding to the ideal scenario in the absence of demodulation errors at the relays. Accordingly, Ω_{exact} is a subset of all possible codewords $\mathbf{x}^{(D)}$, which can be formulated as follows:

$$\begin{aligned}\Omega_{\mathrm{exact}} = \Big\{\bar{\mathbf{x}}^{(D)}|\bar{\mathbf{x}}^{(D)} &= \left(\mathbf{x}_S^{(D)}, \mathbf{x}_{R_1}^{(D)}, \mathcal{N}, \ldots, \mathcal{N}\right) \\ \bar{\mathbf{x}}^{(D)} &= \left(\mathbf{x}_S^{(D)}, \mathcal{N}, \mathbf{x}_{R_2}^{(D)}, \mathcal{N}, \ldots, \mathcal{N}\right) \\ &\ldots \\ \bar{\mathbf{x}}^{(D)} &= \left(\mathbf{x}_S^{(D)}, \mathcal{N}, \ldots, \mathcal{N}, \mathbf{x}_{R_M}^{(D)}\right)\Big\}\end{aligned} \tag{14}$$

where the position of the single active relay in each codeword satisfies the condition $\mathbf{x}_S^{(D)} = \mathbf{ID}_{R_r}$ for $r = 1, 2, \ldots, M$.

The proposed high-SNR approximation for the ASEP is

$$\begin{aligned}\text{ASEP} &\approx \sum_{\bar{\mathbf{x}}^{(D)}} \sum_{\tilde{\mathbf{x}}^{(D)}} \delta\left(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}_S^{(D)}\right) \text{APEP}(\bar{\mathbf{x}}^{(D)} \to \tilde{\mathbf{x}}^{(D)}) \\ &\overset{(a)}{\approx} \frac{1}{MN} \sum_{\bar{\mathbf{x}}^{(D)}} \sum_{\tilde{\mathbf{x}}^{(D)}} \delta\left(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}_S^{(D)}\right) \\ &\quad \times \mathbb{E}_{\mathbf{h}}\left\{\mathcal{P}\left\{\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0 | \mathbf{h}\right\}\right\} \end{aligned} \tag{15}$$

where $\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}) = \Lambda(\tilde{\mathbf{x}}^{(D)}) - \Lambda(\bar{\mathbf{x}}^{(D)})$, and (a) follows by taking into account that, for high-SNR, $\mathcal{P}\{\bar{\mathbf{x}}^{(D)}|\mathbf{h}\} \approx 1/MN$. $\Lambda(\bar{\mathbf{x}}^{(D)})$ can be formulated as in (11), by replacing $\tilde{\mathbf{x}}^{(D)}$ with $\bar{\mathbf{x}}^{(D)}$, as follows:

$$\begin{aligned}\Lambda(\bar{\mathbf{x}}^{(D)}) &= \frac{\left|y_{SD} - \sqrt{E_S} h_{SD} \mathcal{M}_S\left(\mathbf{x}_S^{(D)}\right)\right|^2}{N_0} \\ &\quad + \frac{\left|y_{RD} - \sum_{r=1}^{M} \sqrt{E_{R_r}} h_{R_r D} \widetilde{\mathcal{M}}_R\left(\mathbf{x}_{R_r}^{(D)}\right)\right|^2}{N_0} \\ &\quad + \frac{E_S}{4N_0} \sum_{r \in \Omega_{R,S}^{(\text{ON})}} \left|\mathcal{M}_S\left(\mathbf{x}_S^{(D)}\right) - \mathcal{M}_S(\mathbf{ID}_{R_r})\right|^2 |h_{SR_r}|^2 \\ &\quad + \alpha \frac{E_S}{N_0} \sum_{r \in \Omega_{R,S}^{(\text{OFF})}} |h_{SR_r}|^2 - \mathcal{H} \\ &\overset{(a)}{\approx} \frac{\left|y_{SD} - \sqrt{E_S} h_{SD} \mathcal{M}_S\left(\mathbf{x}_S^{(D)}\right)\right|^2}{N_0} - \mathcal{H}_{\text{exact}} \\ &\quad + \frac{\left|y_{RD} - \sum_{r=1}^{M} \sqrt{E_{R_r}} h_{R_r D} \widetilde{\mathcal{M}}_R\left(\mathbf{x}_{R_r}^{(D)}\right)\right|^2}{N_0} \end{aligned} \tag{16}$$

where $\mathcal{K} = (1/M)(1/N)^{\text{card}\{\Omega_{R,S}^{(\text{ON})}\}} \beta^{\text{card}\{\Omega_{R,S}^{(\text{OFF})}\}}$, $\mathcal{H} = (\text{card}\{\Omega_{R,S}^{(\text{ON})}\} + \text{card}\{\Omega_{R,S}^{(\text{OFF})}\}) \ln(1/2) + \ln(\mathcal{K})$, and $\Omega_{R,S}^{(\text{ON})}$ and $\Omega_{R,S}^{(\text{OFF})}$ are defined, similar to (9), as follows:

$$\begin{aligned}\Omega_{R,S}^{(\text{ON})} &= \left\{r = 1, 2, \ldots, M | \widetilde{\mathcal{M}}_R\left(\mathbf{x}_{R_r}^{(D)}\right) \neq 0 \text{ and } \mathbf{x}_S^{(D)} \neq \mathbf{ID}_{R_r}\right\} \\ \Omega_{R,S}^{(\text{OFF})} &= \left\{r = 1, 2, \ldots, M | \widetilde{\mathcal{M}}_R\left(\mathbf{x}_{R_r}^{(D)}\right) = 0 \text{ and } \mathbf{x}_S^{(D)} = \mathbf{ID}_{R_r}\right\} \end{aligned} \tag{17}$$

The approximation in (a) follows because $\Omega_{R,S}^{(\text{ON})}$ and $\Omega_{R,S}^{(\text{OFF})}$ are empty sets if $\mathbf{x}^{(D)} = \bar{\mathbf{x}}^{(D)}$. Thus, $\mathcal{H} = \mathcal{H}_{\text{exact}} = \ln(1/M)$. Since $\mathcal{H}_{\text{exact}}$ is independent of $\bar{\mathbf{x}}^{(D)}$, it can be neglected in the hypothesis-testing problem. It is worth noting that a single addend of $\sum_{r=1}^{M} \sqrt{E_{R_r}} h_{R_r D} \widetilde{\mathcal{M}}_R(\mathbf{x}_{R_r}^{(D)})$ in (16) is nonzero if $\mathbf{x}^{(D)} = \bar{\mathbf{x}}^{(D)}$.

2) Remarks About the Approximation: The rationale behind (15) lies in realizing that, for high SNR, the *a priori* probabilities $\mathcal{P}\{\mathbf{x}^{(D)}|\mathbf{h}\}$ that mainly contribute to the ASEP in (13) are those corresponding to $\mathbf{x}^{(D)} = \bar{\mathbf{x}}^{(D)}$. In (15), in particular, it is assumed that $\mathcal{P}\{\mathbf{x}^{(D)} = \bar{\mathbf{x}}^{(D)}|\mathbf{h}\} \approx 1/MN$ and that $\mathcal{P}\{\mathbf{x}^{(D)} \neq \bar{\mathbf{x}}^{(D)}|\mathbf{h}\} \approx 0$. The proposed approximation is substantiated with the aid of Monte Carlo simulations in Section VI. The obtained tightness justifies its use for evaluating the diversity order of DSM. It is worth noting that the approximations in (15) and (16) do not boil down to a system with error-free relays. The proposed approximation just takes into account the events that, for high-SNR, contribute the most to the ASEP. The reliability of the source-to-relay links, in fact, affects the APEP since $\Lambda(\tilde{\mathbf{x}}^{(D)})$ still depends on these links. In other words, some codewords (those for which $\mathbf{x}^{(D)} \neq \bar{\mathbf{x}}^{(D)}$ hold) are excluded from the computation of the ASEP, but they are taken into account in the decision metric $\Lambda(\tilde{\mathbf{x}}^{(D)})$ and, thus, in the implementation of the demodulator.

3) Computation of the APEP: From (11) and (16), neglecting $\widetilde{\mathcal{H}}$, $\mathcal{H}_{\text{exact}}$, and other irrelevant terms to the computation of the APEP, $\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)})$ can be formulated as follows:

$$\begin{aligned}\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}) &= \Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}; \mathbf{n}, \mathbf{h}) \\ &\propto \frac{|\sqrt{E_S} h_{SD} d_S|^2}{N_0} + \frac{\left|\sum_{r=1}^{M} \sqrt{E_{R_r}} h_{R_r D} d_{R_r}\right|^2}{N_0} \\ &\quad + \frac{2\text{Re}\left\{\sqrt{E_S} h_{SD} d_S n_{SD}^*\right\}}{N_0} \\ &\quad + \frac{2\text{Re}\left\{\left(\sum_{r=1}^{M} \sqrt{E_{R_r}} h_{R_r D} d_{R_r}\right) n_{RD}^*\right\}}{N_0} \\ &\quad + \frac{E_S}{4N_0} \sum_{r \in \tilde{\Omega}_{R,S}^{(\text{ON})}} |d_S(\mathbf{ID}_{R_r})|^2 |h_{SR_r}|^2 \\ &\quad + \alpha \frac{E_S}{N_0} \sum_{r \in \tilde{\Omega}_{R,S}^{(\text{OFF})}} |h_{SR_r}|^2 \end{aligned} \tag{18}$$

where $d_S = \mathcal{M}_S(\mathbf{x}_S^{(D)}) - \mathcal{M}_S(\tilde{\mathbf{x}}_S^{(D)})$, $d_{R_r} = \widetilde{\mathcal{M}}_R(\mathbf{x}_{R_r}^{(D)}) - \widetilde{\mathcal{M}}_R(\tilde{\mathbf{x}}_{R_r}^{(D)})$, and $d_S(\mathbf{ID}_{R_r}) = \mathcal{M}_S(\tilde{\mathbf{x}}_S^{(D)}) - \mathcal{M}_S(\mathbf{ID}_{R_r})$ for $r = 1, 2, \ldots, M$.

From (18), the generic addend in (15) can be computed as

$$\begin{aligned}&\mathbb{E}_{\mathbf{h}}\left\{\mathcal{P}\left\{\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0 | \mathbf{h}\right\}\right\} \\ &\quad = \mathbb{E}_{\mathbf{h}}\left\{\mathbb{E}_{\mathbf{n}}\left\{\mathcal{P}\left\{\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}) < 0 | \mathbf{n}, \mathbf{h}\right\}\right\}\right\} \\ &\quad \overset{(a)}{=} \frac{1}{2\pi j} \int_{\mathcal{C}-j\infty}^{\mathcal{C}+j\infty} \mathbb{E}_{\mathbf{h}}\left\{\mathbb{E}_{\mathbf{n}}\left\{\exp\left\{-s\Delta(\bar{\mathbf{x}}^{(D)}, \tilde{\mathbf{x}}^{(D)}; \mathbf{n}, \mathbf{h})\right\}\right\}\right\} \frac{ds}{s} \\ &\quad \overset{(b)}{=} \frac{1}{2\pi j} \int_{\mathcal{C}-j\infty}^{\mathcal{C}+j\infty} \mathbb{E}_{\mathbf{h}}\left\{\Phi_{\Delta}(s; \mathbf{h})\right\} \frac{ds}{s} \end{aligned} \tag{19}$$

where (a) follows from [75, Eq. (5)] with $\mathcal{C}$ being an integration pole that, according to [75], can be chosen equal to half of the smallest real part of the nonnegative poles of the integrand function after removing the conditioning with respect to $\mathbf{n}$ and $\mathbf{h}$. Further comments about $\mathcal{C}$ are provided in the sequel, and (b) follows from the equality $\mathbb{E}_{\eta}\{\exp\{-\text{Re}\{\mu\eta^*\}\}\} = \exp\{|\mu|^2/4\}$, which holds if μ is a complex number and η is a complex Gaussian RV with zero mean and unit variance, as well as by introducing $\Phi_\Delta(s) = \mathbb{E}_{\mathbf{h}}\{\Phi_\Delta(s;\mathbf{h})\}$ defined as follows:

$$\begin{aligned}\Phi_\Delta(s;\mathbf{h}) &= \exp\left\{-s\gamma_0\kappa_S|d_S|^2|h_{SD}|^2\right\}\\ &\times \exp\left\{-s\gamma_0\left|\sum_{r=1}^{M}\sqrt{\kappa_{R_r}}h_{R_rD}d_{R_r}\right|^2\right\}\\ &\times \exp\left\{s^2\gamma_0\kappa_S|d_S|^2|h_{SD}|^2\right\}\\ &\times \exp\left\{s^2\gamma_0\left|\sum_{r=1}^{M}\sqrt{\kappa_{R_r}}h_{R_rD}d_{R_r}\right|^2\right\}\\ &\times \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\exp\left\{-s\left(\frac{\gamma_0}{4}\right)\kappa_S|d_S(\mathbf{ID}_{R_r})|^2|h_{SR_r}|^2\right\}\\ &\times \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}}\exp\left\{-s\gamma_0\kappa_S\alpha|h_{SR_r}|^2\right\}\end{aligned} \quad (20)$$

where $\gamma_0 = E_0/N_0$, $E_S = \kappa_S E_0$, and $E_{R_r} = \kappa_{R_r}E_0$ for $r = 1,2,\ldots,M$.

The expectation with respect to $\mathbf{h}$, i.e., $\Phi_\Delta(s) = \mathbb{E}_{\mathbf{h}}\{\Phi_\Delta(s;\mathbf{h})\}$, can be formulated as (21), shown at the bottom of the page, where $h_{RD} = \sum_{r=1}^{M}\sqrt{\kappa_{R_r}}h_{R_rD}d_{R_r}$, and (a) follows by taking into account that the sets $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ and $\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}$ are disjoint, i.e., a relay can be either in $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ or in $\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}$, and hence the associated channels h_{SR_r} are independent for $r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ and $r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}$.

The expectations in (21) can be computed in closed form as in (22), shown at the bottom of the page, where (a$_1$), (b$_1$), and (c$_1$) follow from the definition of mgf of an exponential RV and by taking into account that $|h_{SD}|^2 \sim \mathcal{E}(\sigma_{SD}^2)$, $|h_{RD}|^2 \sim \mathcal{E}(\sigma_{RD}^2)$ with $\sigma_{RD}^2 = \sum_{r=1}^{M}\kappa_{R_r}\sigma_{R_rD}^2|d_{R_r}|^2$, and $|h_{SR_r}|^2 \sim \mathcal{E}(\sigma_{SR_r}^2)$, respectively, and (a$_2$), (b$_2$), and (c$_2$) are approximations that hold for high SNR, i.e., for $\gamma_0 \gg 1$. Moreover, the following definitions hold:

$$\begin{aligned}\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= \delta\left(|d_S|^2,0\right)\\ \omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= \delta\left(\sum_{r=1}^{M}|d_{R_r}|^2,0\right)\\ \omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) &= \sum_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\delta\left(|d_S(\mathbf{ID}_{R_r})|^2,0\right) \stackrel{(d)}{=} \mathrm{card}\left\{\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}\right\}\\ \omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) &= \mathrm{card}\left\{\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}\right\}\end{aligned} \quad (23)$$

where (d) follows from the definition of $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ in (9), i.e., if the generic relay r belongs to $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$, then $|d_S(\mathbf{ID}_{R_r})|^2 \neq 0$ and $\delta(|d_S(\mathbf{ID}_{R_r})|^2,0) = 1$.

From (15) and (23), in conclusion, the ASEP can be rewritten, for high SNR, as follows:

$$\begin{aligned}\mathrm{ASEP} \approx \frac{1}{MN}\sum_{\bar{\mathbf{x}}^{(D)}}\sum_{\tilde{\mathbf{x}}^{(D)}}\delta\left(\mathbf{x}_S^{(D)},\tilde{\mathbf{x}}_S^{(D)}\right)\gamma_0^{-\mathcal{G}_d(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})}\\ \times\mathcal{G}_c(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})\mathcal{I}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})\end{aligned} \quad (24)$$

where the functions in (25), shown at the bottom of the next page, are introduced, and the approximation in (a) follows from [75, pp. 17]. The complex integral $\mathcal{I}(\cdot,\cdot)$ may be solved in closed form by using the residue theorem [75], but the result would depend on the pair $(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})$; thus, for brevity, it is not provided here. From the expression of $\mathcal{I}(\cdot,\cdot)$, the integration pole $\mathcal{C}$ can be chosen equal to $\mathcal{C} = 1/2$, based on the guidelines reported in [75]. As highlighted in Section IV-B, in fact, $\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 1$ for every pair $\tilde{\mathbf{x}}^{(D)} \neq \bar{\mathbf{x}}^{(D)}$. As a consequence, the pole $s = 1$ always exists in $\mathcal{I}(\cdot;\cdot,\cdot)$.

$$\begin{aligned}\Phi_\Delta(s) &= \mathbb{E}_{\mathbf{h}}\left\{\Phi_\Delta(s;\mathbf{h})\right\} = \Phi_\Delta^{(SD)}(s)\Phi_\Delta^{(RD)}(s)\Phi_\Delta^{(SR)}(s)\\ \Phi_\Delta^{(SD)}(s) &= \mathbb{E}_{|h_{SD}|^2}\left\{\exp\left\{-s\gamma_0\kappa_S|d_S|^2|h_{SD}|^2\right\}\exp\left\{s^2\gamma_0\kappa_S|d_S|^2|h_{SD}|^2\right\}\right\}\\ \Phi_\Delta^{(RD)}(s) &= \mathbb{E}_{|h_{RD}|^2}\left\{\exp\left\{-s\gamma_0|h_{RD}|^2\right\}\exp\left\{s^2\gamma_0|h_{RD}|^2\right\}\right\}\\ \Phi_\Delta^{(SR)}(s) &\stackrel{(a)}{=} \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\mathbb{E}_{|h_{SR_r}|^2}\left\{\exp\left\{-s\left(\frac{\gamma_0}{4}\right)\kappa_S|d_S(\mathbf{ID}_{R_r})|^2|h_{SR_r}|^2\right\}\right\}\prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}}\mathbb{E}_{|h_{SR_r}|^2}\left\{\exp\left\{-s\gamma_0\kappa_S\alpha|h_{SR_r}|^2\right\}\right\}\end{aligned} \quad (21)$$

$$\begin{aligned}\Phi_\Delta^{(SD)}(s) &\stackrel{(a_1)}{=} \left(1+\gamma_0\kappa_S\sigma_{SD}^2|d_S|^2 s(1-s)\right)^{-1} \stackrel{(a_2)}{\approx} \left(\gamma_0\kappa_S\sigma_{SD}^2|d_S|^2 s(1-s)\right)^{-\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})}\\ \Phi_\Delta^{(RD)}(s) &\stackrel{(b_1)}{=} \left(1+\gamma_0\left(\sum_{r=1}^{M}\kappa_{R_r}\sigma_{R_rD}^2|d_{R_r}|^2\right)s(1-s)\right)^{-1} \stackrel{(b_2)}{\approx} \left(\gamma_0\left(\sum_{r=1}^{M}\kappa_{R_r}\sigma_{R_rD}^2|d_{R_r}|^2\right)s(1-s)\right)^{-\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})}\\ \Phi_\Delta^{(SR)}(s) &\stackrel{(c_1)}{=} \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\left(1+\frac{\gamma_0}{4}\kappa_S\sigma_{SR_r}^2|d_S(\mathbf{ID}_{R_r})|^2 s\right)^{-1}\prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}}\left(1+\gamma_0\kappa_S\alpha\sigma_{SR_r}^2 s\right)^{-1}\\ &\stackrel{(c_2)}{\approx} \gamma_0^{-\omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)})-\omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)})}\prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}}\left(\frac{1}{4}\kappa_S\sigma_{SR_r}^2|d_S(\mathbf{ID}_{R_r})|^2 s\right)^{-\delta\left(|d_S(\mathbf{ID}_{R_r})|^2,0\right)}\prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}}\left(\kappa_S\alpha\sigma_{SR_r}^2 s\right)^{-1}\end{aligned} \quad (22)$$

Finally, we close this section with a comment about the novelty of the methodological approach used, in this paper, for performance analysis. From [30], it is apparent that the error probability performance of SM has been studied extensively. The most general frameworks for computing its error probability, in particular, are available in [39] and [42]. These mathematical frameworks, however, are applicable to classical combining methods at the destination, which do not account for the reliability of the source-to-relay links. For this reason, in this paper, we have used a methodology that is different from all other papers available in the literature. The proposed approach, in particular, is based on complex analysis and on residues theory [75], which, to the best of the authors' knowledge, has never been applied in the context of SM. The error performance of the demodulator in (11), in addition, has never been studied, since it has been introduced in this paper for the first time.

B. Diversity Order

Here, we focus our attention on the diversity order of the source. Based on the operating principle of DSM, the diversity order of the source may only be 0, 1, or 2. In fact, the destination receives two copies of the data of the source: one explicitly from the source itself and one implicitly from the relay activation process. Here, we prove that the diversity order is equal to 2 for every pair $\tilde{\mathbf{x}}^{(D)} \neq \bar{\mathbf{x}}^{(D)}$.

According to [73], the diversity order of the source can be formulated as follows:

$$\begin{aligned}\mathcal{G}_d &= \min_{\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}\neq\bar{\mathbf{x}}^{(D)}} \left\{\mathcal{G}_d(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})\right\} \\ &\overset{(a)}{=} 1 + \min_{\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}\neq\bar{\mathbf{x}}^{(D)}} \Big\{\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) \\ &\qquad + \omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) + \omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)})\Big\} \end{aligned} \tag{26}$$

where (a) follows from (24) by definition of ASEP of the source, i.e., $\mathbf{x}_S^{(D)} \neq \tilde{\mathbf{x}}_S^{(D)}$, which implies $|d_S|^2 \neq 0$, and then, $\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 1$.

From (26), we conclude that $\mathcal{G}_d \geq 1$. To prove second-order diversity, it is necessary to prove that $\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) + \omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) + \omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) \geq 1$ for every pair $\tilde{\mathbf{x}}^{(D)} \neq \bar{\mathbf{x}}^{(D)}$. To this end, it is sufficient to prove that $\omega_{RD}(\cdot,\cdot)$, $\omega_{SR}^{(\mathrm{ON})}(\cdot)$, and $\omega_{SR}^{(\mathrm{OFF})}(\cdot)$ are not equal to zero simultaneously. This can be proved as follows.

- If $\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 0$, then $\omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) = 1$. Based on (14), in fact, the condition $\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 0$ implies that a single relay is active in the hypothesis $\tilde{\mathbf{x}}^{(D)}$, and it is the correct one. If so, the set $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ cannot be empty since $\mathbf{x}_S^{(D)} \neq \tilde{\mathbf{x}}_S^{(D)}$ by assumption. It is worth mentioning that correct relay is, here, always referred to $\bar{\mathbf{x}}^{(D)}$, i.e., to the relay R_* for which $\mathbf{x}_S^{(D)} = \mathbf{ID}_{R_*} \neq \tilde{\mathbf{x}}_S^{(D)}$.
- If $\omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) = 0$ or $\omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) = 0$, then $\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 1$. If $\omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) = 0$, then $\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}$ is empty. Thus, (9) implies that the single relay of the hypothesis $\tilde{\mathbf{x}}^{(D)}$ for which $\tilde{\mathbf{x}}_S^{(D)} = \mathbf{ID}_{R_r}$ is active. Since $\mathbf{x}_S^{(D)} \neq \tilde{\mathbf{x}}_S^{(D)}$ by assumption, this active relay cannot be the correct one. If $\omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) = 0$, then $\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}$ is empty. Thus, (9) implies that the correct relay is inactive in the hypothesis $\tilde{\mathbf{x}}^{(D)}$. In conclusion, if $\omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) = 0$ or $\omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) = 0$, based on (14), this implies that $\sum_{r=1}^{M} |d_{R_r}|^2 \neq 0$, and then, $\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) = 1$.

In the light of these considerations, we conclude that the diversity order to the source is equal to two, i.e., $\mathcal{G}_d = 2$.

V. Average Energy Consumption and Average Rate of Distributed Spatial Modulation

In DSM, the number of activated relays during the relaying phase depends on the demodulation outcome at the relays,

$$\begin{aligned}\mathcal{G}_d(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= \omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) + \omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) + \omega_{SR}^{(\mathrm{ON})}(\tilde{\mathbf{x}}^{(D)}) + \omega_{SR}^{(\mathrm{OFF})}(\tilde{\mathbf{x}}^{(D)}) \\ \mathcal{G}_c(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= \left(\kappa_S\sigma_{SD}^2|d_S|^2\right)^{-\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})} \left(\sum_{r=1}^{M}\kappa_{R_r}\sigma_{R_rD}^2\,|d_{R_r}|^2\right)^{-\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})} \\ &\quad\times \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{ON})}} \left(\frac{1}{4}\kappa_S\sigma_{SR_r}^2\,|d_S(\mathbf{ID}_{R_r})|^2\right)^{-\delta\left(|d_S(\mathbf{ID}_{R_r})|^2,0\right)} \prod_{r\in\widetilde{\Omega}_{R,S}^{(\mathrm{OFF})}} \left(\alpha\kappa_S\sigma_{SR_r}^2\right)^{-1} \\ \mathcal{I} = \mathcal{I}(s;\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= s^{-\mathcal{G}_d(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})}(1-s)^{-\omega_{SD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})-\omega_{RD}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)})} \\ \mathcal{I}(\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}) &= \frac{1}{2\pi j}\int_{\mathcal{C}-j\infty}^{\mathcal{C}+j\infty} \mathcal{I}\left(s;\bar{\mathbf{x}}^{(D)},\tilde{\mathbf{x}}^{(D)}\right)\frac{ds}{s} \\ &\overset{(a)}{\approx} \frac{1}{2\pi}\int_{-1}^{+1}\mathrm{Re}\left\{\mathcal{I}\left(\mathcal{C}+j\mathcal{C}\frac{\sqrt{1-x^2}}{x}\right)\right\}\frac{dx}{\sqrt{1-x^2}} + \frac{1}{2\pi}\int_{-1}^{+1}\mathrm{Im}\left\{\mathcal{I}\left(\mathcal{C}+j\mathcal{C}\frac{\sqrt{1-x^2}}{x}\right)\right\}\frac{dx}{x}\end{aligned} \tag{25}$$

as mathematically formulated in (2) and (3), which, in turn, depends on the quality of the source-to-relay links. During the relaying phase, in particular, the transmitted energy is equal to $\sum_{r\in\Omega_R^{(\mathrm{ON})}} E_{R_r} = E_R \mathrm{card}\{\Omega_R^{(\mathrm{ON})}\}$, where for ease of description, it is assumed that $E_R = E_{R_r}$ for $r = 1, 2, \ldots, M$. In other words, the larger the number of activated relay is, the higher the energy consumption is. This is in stark contrast compared with conventional relaying protocols, where the set of activated relays is fixed and the net effect of an incorrect demodulation at the relays results only in forwarding erroneous data to the destination. In DSM, on the other hand, the activation of multiple relays may lead to an increase in the energy consumption. The objective of this section is to show that the average (i.e., with respect to all possible activation patterns of the relays) energy consumption of DSM in the presence of demodulation errors at the relays is the same as the energy consumption of DSM in the absence of demodulation errors at the relays, i.e., $E_S + E_R$. This result is important for guaranteeing a fair comparison with conventional relaying protocols and for ensuring that the power consumption does not increase in the presence of unreliable source-to-relay links.

Similar comments apply to the average (i.e., with respect to all possible activation patterns of the relays) rate of DSM. In particular, the rate of DSM during the relaying phase is equal to $\log_2(N)\mathrm{card}\{\Omega_R^{(\mathrm{ON})}\}$. In fact, $\log_2(M) + \log_2(N)$ bits are transmitted during the relaying phase. Only $\log_2(N)$ bits of them are, however, "new" bits. For computing the rate, in fact, only new data needs to be considered. Similar to the energy consumption, it is possible to show that the average rate of DSM in the presence of demodulation errors at the relays is the same as the average rate of DSM in the absence of demodulation errors at the relays, i.e., $\log_2(M) + \log_2(N)$ bits. Since the mathematical development is the same, i.e., it is sufficient to replace E_R with $\log_2(N)$ and E_S with $\log_2(M)$, the details are omitted. This result implies that the average rate of DSM is $\mathcal{R}_{\mathrm{av}} = (1/2)(\log_2(M) + \log_2(N))$ bits per channel use (bpcu) since $\log_2(M) + \log_2(N)$ bits are transmitted, on average, in two time-slots.

Let $\mathbf{x}_S$ be the equiprobable $\log_2(M)$-long bitstream emitted by the source. The average energy consumption of DSM can be formulated as follows:

$$
\begin{aligned}
E_{\mathrm{av}} &= \left(\frac{1}{M}\right)\sum_{\tilde{\mathbf{x}}_S^{(D)}} E_{\mathrm{av}}(\mathbf{x}_S)\\
E_{\mathrm{av}}(\mathbf{x}_S) &= E_S + E_R\sum_{\mathbf{m}}\mathrm{card}\left\{\Omega_R^{(\mathrm{ON})}(\mathbf{m})\right\}\prod_{r\in\Omega_R^{(\mathrm{ON})}(\mathbf{m})}\mathcal{Q}_r(\mathbf{x}_S)\\
&\quad\times\prod_{r\in\Omega_R^{(\mathrm{OFF})}(\mathbf{m})}\left(1-\mathcal{Q}_r(\mathbf{x}_S)\right)
\end{aligned}
\tag{27}
$$

where $\mathbf{m}$ is a M-long binary vector whose rth entry is $\mathbf{m}[r] \in \{0, 1\}$ for $r = 1, 2, \ldots, M$. Thus, the number of binary vectors $\mathbf{m}$ is 2^M, and each of them identifies one possible active/inactive state of the M available relays. If $M = 2$, for example, $\mathbf{m} = (0, 0)$ denotes that both relays are inactive, $\mathbf{m} = (0, 1)$ denotes that R_1 is inactive and R_2 is active, $\mathbf{m} = (1, 0)$ denotes that R_1 is active and R_2 is inactive, and $\mathbf{m} = (1, 1)$ denotes that both relays are active. The sets $\Omega_R^{(\mathrm{ON})}(\cdot)$ and $\Omega_R^{(\mathrm{OFF})}(\cdot)$ denote the active and inactive relays, respectively, and are defined as follows:

$$
\begin{aligned}
\Omega_R^{(\mathrm{ON})}(\mathbf{m}) &= \{r = 1, 2, \ldots, M | \mathbf{m}[r] = 1\}\\
\Omega_R^{(\mathrm{OFF})}(\mathbf{m}) &= \{r = 1, 2, \ldots, M | \mathbf{m}[r] = 0\}
\end{aligned}
\tag{28}
$$

and similar to (7), $\mathcal{Q}_r(\cdot)$ accounts for the demodulation reliability at the relays according to (2), and it can be formulated as in (29), shown at the bottom of the page, where (a) follows from the identity $\mathbb{E}_X\{Q(\sqrt{kX})\} = 1/2 - 1/2\sqrt{k\sigma_X^2(2 + k\sigma_X^2)^{-1}}$, which holds for $X \sim \mathcal{E}(\sigma_X^2)$. It is worth mentioning that the mathematical formulation of $E_{\mathrm{av}}(\mathbf{x}_S)$ in (27) is an approximation because the union-bound is used in (29). Moreover, we note that the modulation scheme of the relays does not affect (27) since modulation schemes with average unit energy are assumed throughout the this paper.

For any number of relays M, the average energy consumption of DSM can be computed by using (27). In what follows, we provide explicit results for two case studies: $M = 2$ and $M = 4$. The mathematical development for arbitrary M is in

$$
\begin{aligned}
\mathcal{Q}_r(\mathbf{x}_S) &= \mathbb{E}\left\{\mathcal{P}\left\{\hat{\mathbf{x}}_S^{(R_r)} = \mathbf{ID}_{R_r}|\mathbf{x}_S\right\}\right\}\\
&\approx \begin{cases}
\mathbb{E}_{|h_{SR_r}|^2}\left\{Q\left(\sqrt{\frac{E_S}{2N_0}\left|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S\left(\mathbf{ID}_{R_r}\right)\right|^2|h_{SR_r}|^2}\right)\right\}, & \text{if} \quad \mathbf{x}_S \neq \mathbf{ID}_{R_r}\\
1-\sum\limits_{z\neq r=1}^{M}\mathbb{E}_{|h_{SR_z}|^2}\left\{Q\left(\sqrt{\frac{E_S}{2N_0}\left|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S\left(\mathbf{ID}_{R_z}\right)\right|^2|h_{SR_z}|^2}\right)\right\}, & \text{if} \quad \mathbf{x}_S = \mathbf{ID}_{R_r}
\end{cases}\\
&\overset{(a)}{=} \begin{cases}
1/2-1/2\sqrt{\frac{\left(\frac{E_S}{N_0}\right)\sigma_{SR_r}^2|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S(\mathbf{ID}_{R_r})|^2}{2+\left(\frac{E_S}{N_0}\right)\sigma_{SR_r}^2|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S(\mathbf{ID}_{R_r})|^2}}, & \text{if} \quad \mathbf{x}_S \neq \mathbf{ID}_{R_r}\\
1-\sum\limits_{z\neq r=1}^{M}\left(1/2-1/2\sqrt{\frac{\left(\frac{E_S}{N_0}\right)\sigma_{SR_z}^2|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S(\mathbf{ID}_{R_z})|^2}{2+\left(\frac{E_S}{N_0}\right)\sigma_{SR_z}^2|\mathcal{M}_S(\mathbf{x}_S)-\mathcal{M}_S(\mathbf{ID}_{R_z})|^2}}\right), & \text{if} \quad \mathbf{x}_S = \mathbf{ID}_{R_r}
\end{cases}
\end{aligned}
\tag{29}
$$

fact quite tedious, and numerical examples are reported for ease of illustration instead.

a) $M = 2$: If $M = 2$, $E_{\rm av}(\mathbf{x}_S)$ in (27) can be explicitly formulated as follows:

$$\begin{aligned} E_{\rm av}(\mathbf{x}_S = 0) &= E_S + E_R + \left(\frac{E_R}{2}\right)(\chi_{SR_1}(1) - \chi_{SR_2}(1)) \\ E_{\rm av}(\mathbf{x}_S = 1) &= E_S + E_R + \left(\frac{E_R}{2}\right)(-\chi_{SR_1}(1) + \chi_{SR_2}(1)) \end{aligned} \tag{30}$$

where the following definition holds: $\chi_{SR_r}(\upsilon) = \sqrt{(1/\upsilon)(E_S/N_0)\sigma^2_{SR_r}(1+(1/\upsilon)(E_S/N_0)\sigma^2_{SR_r})^{-1}}$. From (27) and (30), it follows, by direct inspection, that $E_{\rm av} = E_S + E_R$.

b) $M = 4$: If $M = 4$, $E_{\rm av}(\mathbf{x}_S)$ in (27) can be explicitly formulated as follows:

$$\begin{aligned} E_{\rm av}(\mathbf{x}_S = 00) &= E_S + E_R + \left(\frac{E_R}{2}\right) \\ &\times (2\chi_{SR_1}(2) + \chi_{SR_1}(1) - \chi_{SR_2}(2) - \chi_{SR_3}(2) - \chi_{SR_4}(1)) \\ E_{\rm av}(\mathbf{x}_S = 01) &= E_S + E_R + \left(\frac{E_R}{2}\right) \\ &\times (-\chi_{SR_1}(2) + 2\chi_{SR_2}(2) + \chi_{SR_2}(1) - \chi_{SR_3}(1) - \chi_{SR_4}(2)) \\ E_{\rm av}(\mathbf{x}_S = 10) &= E_S + E_R + \left(\frac{E_R}{2}\right) \\ &\times (-\chi_{SR_1}(2) - \chi_{SR_2}(1) + 2\chi_{SR_3}(2) + \chi_{SR_3}(1) - \chi_{SR_4}(2)) \\ E_{\rm av}(\mathbf{x}_S = 11) &= E_S + E_R + \left(\frac{E_R}{2}\right) \\ &\times (-\chi_{SR_1}(1) - \chi_{SR_2}(2) - \chi_{SR_3}(2) + 2\chi_{SR_4}(2) + \chi_{SR_4}(1)). \end{aligned} \tag{31}$$

Again, from (27) and (30), it follows, by direct inspection, that $E_{\rm av} = E_S + E_R$.

c) Generic M: Since the computation of (27) is quite tedious for arbitrary M, we show some numerical results in Fig. 2. These results are obtained by simulating the DSM protocol based on (1)–(3) and by computing the energy consumption as $1/\mathrm{MC}\sum_{i=1}^{\mathrm{MC}}(E_S + E_R \mathrm{card}\{\Omega_R^{(\mathrm{ON})}\})_i$, where MC is the number of Monte Carlo trials. The figure confirms that, regardless of the number of relays and the i.i.d./i.n.i.d. channel conditions, the average energy consumption of DSM is equal to $E_{\rm av} = E_S + E_R$, similar to conventional relaying protocols. This result is important for a fair performance comparison of DSM against other relaying protocols (see Section VI).

Due to space limitations, a detailed analysis of the energy consumption of state-of-the-art relaying protocols cannot be reported here. The outcome of this analysis, however, is summarized in Table I.

VI. Numerical and Simulation Results

Here, we present numerical results for assessing the performance of DSM, for substantiating the mathematical findings on the achievable diversity, and for comparing the ASEP of DSM against state-of-the-art relaying. For ease of reproducibility, i.i.d. fading channels are assumed, i.e., $\sigma^2 = \sigma^2_{SD} = \sigma^2_{SR_r} = \sigma^2_{R_rD} = 1$ for $r = 1, 2, \ldots, M$. Moreover, the relays are assumed to transmit the same average energy during the relaying phase, i.e., $E_{R_r} = E_R$ for $r = 1, 2, \ldots, M$. PSK modulation is used. Other simulation parameters are provided in the caption of the figures.

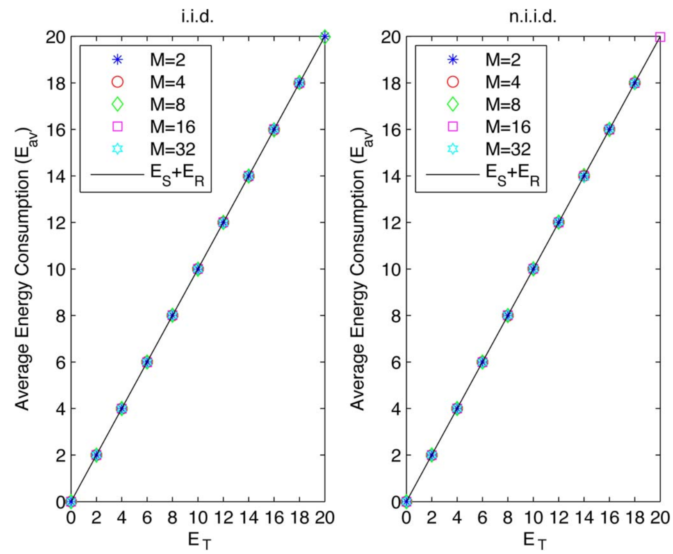

Fig. 2. Energy consumption of DSM for $N_R = M$ and in the presence of demodulation errors at the relays. Setup: 1) PSK modulation; 2) $E_T = E_S + E_R$ with $E_S = E_T/2$ and $E_R = E_T/2$; 3) $N_0 = 1$; 4) MC = 100 000; 5) $\sigma^2_{SR_r} = 1$ for the i.i.d. setup; 6) $\sigma^2_{SR_r}$ are generated uniformly at random in [0,10] for the i.n.i.d. setup.

For ensuring a fair comparison among different relaying protocols, which may provide a different rate (in bpcu) and may rely upon a different number of active relays, the following two conditions are enforced to all considered relaying protocols: 1) The average energy consumption $E_{\rm av}$ is the same; and 2) the average rate in bpcu ($\mathcal{R}_{\rm av}$) is the same. As an example, let us consider DSM. Similar calculations for state-of-the-art relaying protocols analyzed here are summarized in Table I. Let $\mathcal{R}_{\rm av}$ and the possible pairs (M, N) be such that the equality $\mathcal{R}_{\rm av} = (1/2)(\log_2(M) + \log_2(N))$ is satisfied (see Section V). Let $E_{\rm av} = E_S + E_R$ (see Section V), the pair (M, N), and the average energy per bit (E_b) be computed such that the transmit energy for broadcasting and relaying phases are set equal to $E_S = E_b \log_2(M)$ and $E_R = E_b(\log_2(M) + \log_2(N))$.

a) Diversity-achieving diversity combining: In Fig. 3, the ASEP of three diversity combiners for DSM is compared. The results confirm that second-order diversity cannot be achieved if relay-induced demodulation errors are not taken into account at the destination, i.e., the suboptimal demodulator (referred to as "DSM–suboptimal demodulator") in Table I is used. Furthermore, it is shown that the performance difference between the demodulators in (4) and (10) is negligible. In the following, as a consequence, only the demodulator in (10) is considered.

b) Validation of mathematical framework and diversity analysis: In Fig. 4, Monte Carlo simulations are compared against the mathematical framework of Section IV. The results confirm the tightness of the proposed approach for performance

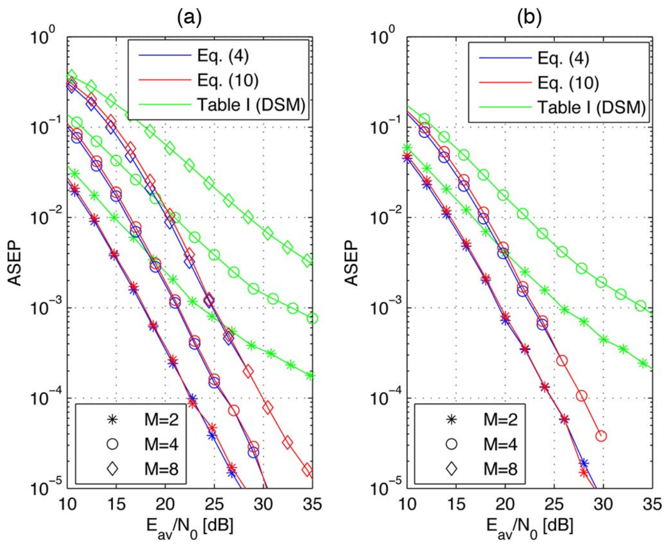

Fig. 3. Comparison of different demodulators for DSM. (a) $N = 2$ and (b) $N = 4$. As for the demodulator in (10), $\widetilde{\mathcal{H}}$ is neglected.

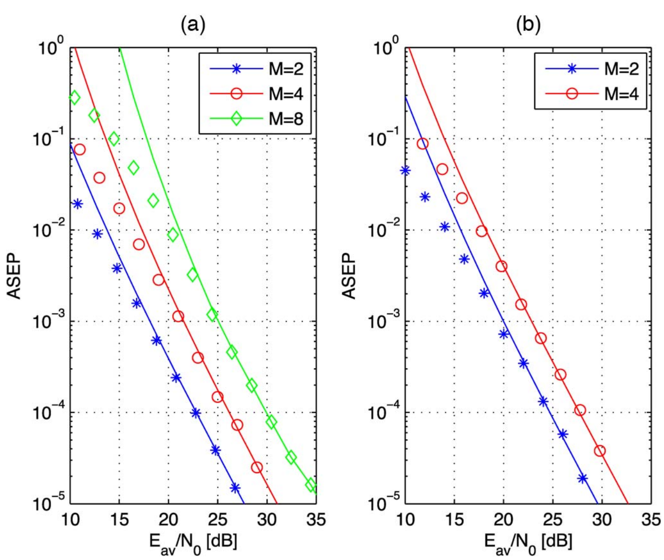

Fig. 4. Comparison of Monte Carlo simulations (markers) and the mathematical framework in (24) and (25) (solid lines). (a) $N = 2$ and (b) $N = 4$.

evaluation. This provides a sound justification of the approximation used in (15) for computing the ASEP and for using the resulting framework for studying the achievable diversity order of DSM. Indeed, Fig. 4 confirms that the demodulators introduced in Section III are capable of achieving second-order diversity.

c) Performance comparison with state-of-the-art relaying protocols: In Figs. 5 and 6, DSM is compared against the state-of-the-art relaying protocols summarized in Table I. In particular, Fig. 5 confirms that DSM is, for the analyzed range of SNRs, always better than demodulate and forward (DemF). On the other hand, both DemF and DSM may be worse than SH transmission for a low SNR. This originates from the i.i.d. assumption for the fading channels and from the need of using two time slots for DemF and DSM. As expected, however, DemF and DSM are superior for high SNR since they provide second-order diversity. Furthermore, Fig. 6 confirms that DSM

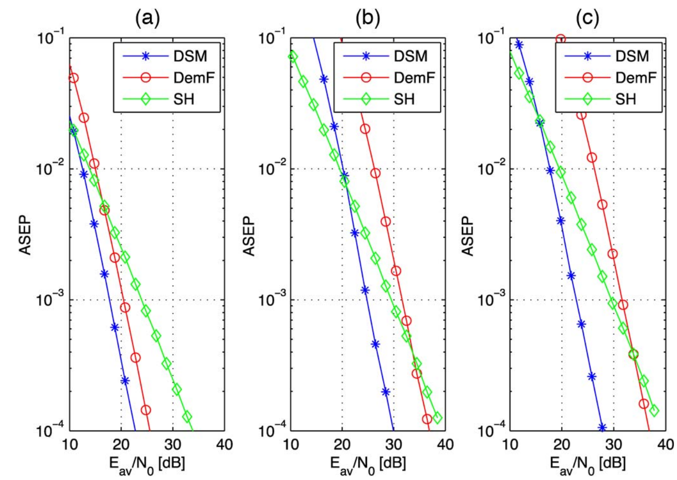

Fig. 5. Comparison of DSM (demodulator in (10) where $\widetilde{\mathcal{H}}$ is neglected) against DemF relaying and SH transmission (as summarized in Table I). (a) $\mathcal{R}_{\rm av} = 1$ bpcu: $M = 2$ and $N = 2$ for DSM, $M = 4$ for DemF, and $M = 2$ for SH. (b) $\mathcal{R}_{\rm av} = 2$ bpcu: $M = 8$ and $N = 2$ for DSM, $M = 16$ for DemF, and $M = 4$ for SH. (c) $\mathcal{R}_{\rm av} = 2$ bpcu: $M = 4$ and $N = 4$ for DSM, $M = 16$ for DemF, and $M = 4$ for SH.

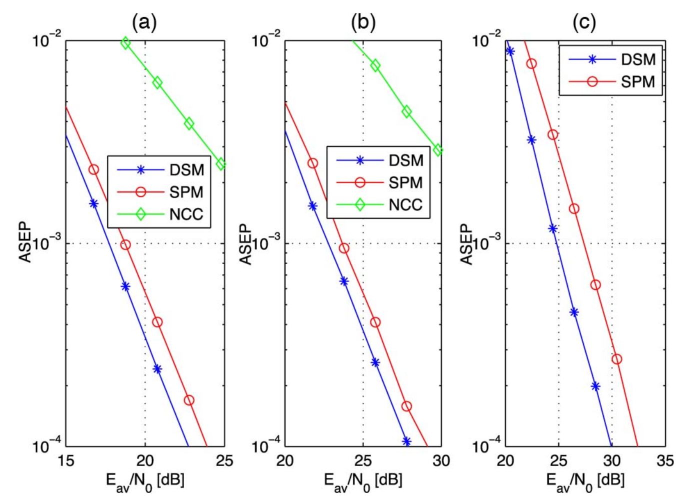

Fig. 6. Comparison of DSM (demodulator in (10) where $\widetilde{\mathcal{H}}$ is neglected) against SPM and NCC relaying (as summarized in Table I). (a) $\mathcal{R}_{\rm av} = 1$ bpcu: $M = 2$ and $N = 2$ for DSM, SPM ($\gamma^2 = 0.2$), and NCC. (b) $\mathcal{R}_{\rm av} = 2$ bpcu: $M = 4$ and $N = 4$ for DSM, SPM ($\gamma^2 = 0.25$), and NCC. (c) $\mathcal{R}_{\rm av} = 2$ bpcu: $M = 8$ and $N = 2$ for DSM and SPM ($\gamma^2 = 0.4$). A "zoom in" view is provided to enhance the readability of the figure.

provides a better ASEP than SPM and network-coded cooperation (NCC). Compared with NCC, the gain is significant since NCC is not capable of achieving any diversity gains for the considered setup [25]. Compared with SPM, the gain is at least equal to 1 dB for the considered setup, and it depends on the parameter γ used for SPM. The values of γ considered in Fig. 6 provide near-optimal performance for the analyzed setup. This gain comes, however, at the cost of a higher demodulation complexity for DSM. Possible solutions for reducing the demodulation complexity of DSM are currently under investigation by the authors. Potential options encompass, e.g., the application of sphere decoding [43]. More specifically, the demodulator in (4) can be interpreted as a multiuser detector, and thus, several algorithms for reducing its signal processing complexity exist. The difference compared with conventional

TABLE II
COMPUTATIONAL COMPLEXITY OF THE RELAY-AIDED PROTOCOLS/DEMODULATORS IN TABLE I AND SECTION III IN TERMS OF REAL ADDITIONS AND MULTIPLICATIONS

Protocol	Complexity (based on the demodulators in Table I)		Complexity (Case Study)		
	Real Additions	Real Multiplications	Case Study	Real Additions	Real Multiplications
SH	$5M$	$12M$	$M=2$	10	24
			$M=4$	20	48
DemF	$11M^2+2M$	$35M^2+12M$	$M=4$	184	608
			$M=16$	2848	9152
SPM	$14M^2N+2MN$	$41M^2N+12MN$	$M=2, N=2$	120	376
			$M=8, N=2$	1824	5440
			$M=4, N=4$	928	2816
NCC	$12M^2N+2MN$	$35M^2N+12MN$	$M=2, N=2$	104	328
			$M=8, N=2$	1568	4672
			$M=4, N=4$	800	2432
DSM (Table I)	$10MN$	$25MN$	$M=2, N=2$	40	100
			$M=8, N=2$	160	400
			$M=4, N=4$	160	400
DSM (Sec. III)	$7M^2(N+1)^M$ $+8M(N+1)^M$	$22M^2(N+1)^M$ $+24M(N+1)^M$	$M=2, N=2$	396	1224
			$M=8, N=2$	3359232	10497600
			$M=4, N=4$	90000	280000
DSM (Sec. III-B)	$2M^2(N+1)^M$ $+12M(N+1)^M$	$3M^2(N+1)^M$ $+25M(N+1)^M$	$M=2, N=2$	288	558
			$M=8, N=2$	1469664	2571912
			$M=4, N=4$	50000	92500

sphere decoders and multiuser demodulators lies in the need to generalize them for taking into account the reliability of the source-to-relay links. In the presence of channel coding at the relays and at the destination, the computational complexity may be made affordable by jointly using sphere decoding and the Bahl, Cocke, Jelinek, and Raviv (BCJR) algorithm [77]. Other possible options, which include joint and iterative symbol demodulation and channel decoding at the destination, may be similar to those recently introduced in [67] and [68] for application to a broad class of relay-aided wireless networks. Since all state-of-the-art protocols considered in this paper do not consider channel coding, the analysis, design, and comparison of relay-induced error-aware diversity combiners in the presence of channel coding are left to future research.

d) Analysis of the computational complexity: As stated previously, the performance gain provided by DSM is expected to come at the cost of higher demodulation complexity, which originates from the need to implement a multiuser-like demodulator for achieving full diversity. To quantify the computational complexity cost associated with the better ASEP provided by DSM, the computational complexity of all demodulators studied in this paper is analyzed in Table II. The computational complexity is formulated in terms of real additions and multiplications. More specifically, the computational complexity of each operation and function is computed by following the guidelines provided in [78]. In Table II, in particular, arbitrary values of the modulation order of source and relays, and the case studies shown in Figs. 3–6 are considered. As expected, the optimal DSM demodulator introduced in Section III has the highest computational complexity. It is interesting to note, however, the large computational complexity reduction that is obtained by using the proposed high-SNR approximation in Section III-B, without largely degrading, as shown in Fig. 3, the ASEP. The suboptimal DSM demodulator in Table I constitutes

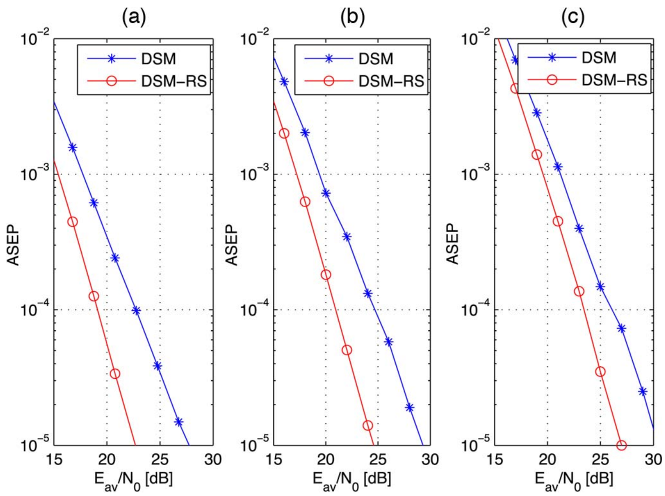

Fig. 7. Comparison of DSM with RS and without (demodulator in (10), where $\widetilde{\mathcal{H}}$ is neglected). (a) $\mathcal{R}_{\mathrm{av}} = 1$ bpcu: $N_R = M = 2$ and $N = 2$ for DSM and $N_R = 3$, $M = 2$, and $N = 2$ for DSM-RS. (b) $\mathcal{R}_{\mathrm{av}} = 1.5$ bpcu: $N_R = M = 2$ and $N = 4$ for DSM and $N_R = 3$, $M = 2$, and $N = 4$ for DSM-RS. (c) $\mathcal{R}_{\mathrm{av}} = 1.5$ bpcu: $N_R = M = 4$ and $N = 2$ for DSM, and $N_R = 5$, $M = 4$, and $N = 2$ for DSM-RS.

a low-complexity alternative but, based on Fig. 3, at the cost of, probably, an unacceptable ASEP degradation. In light of the promising ASEP offered by DSM that uses the demodulator in Section III-B and of the low-complexity implementation of DSM that uses the demodulator in Table I, we believe that the development of new low-complexity but diversity-achieving demodulators for DSM is an interesting research field and that this paper has only unveiled the tip of the iceberg.

e) Performance enhancement with relay selection: Finally, Fig. 7 investigates the potential gain of combining DSM with RS for those scenarios where $N_R > M$. The criterion used for RS is based on choosing the relays that provide the lowest (instantaneous) SEP at the destination. For simplicity, the relays are selected by neglecting demodulation errors at the relays. Accordingly, the system reduces to an MIMO scheme with colocated antennas, and a (simplified) closed-form expression of the instantaneous SEP is obtained from [39]. The demodulation errors, however, are accounted for after RS and for computing the ASEP shown in Fig. 7, which highlights the potential gain of combining DSM with RS, both in terms of coding gain and diversity order. The mathematical analysis of the achievable diversity order of DSM with RS is currently under investigation by the authors.

VII. Conclusion

In this paper, a new cooperative diversity protocol based on the concept of SM has been introduced. The distinguishable feature of DSM lies in allowing the network nodes acting as relays to forward the data of the source while transmitting their own data. This increases the aggregate throughput. A demodulator robust to demodulation errors at the relay has been introduced, and its performance has been studied. In particular, it has been mathematically proved that, with the aid of the proposed demodulator, DSM is capable of providing second-order diversity to the data transmitted by the source. This is not possible, on the other hand, by using the conventional ML-optimum demodulator for SM, i.e., the DSM–suboptimal demodulator in Table I. With the aid of Monte Carlo simulations, the performance of DSM has been compared against that of several closely related state-of-the-art relaying protocols, and it has been shown that DSM is capable of providing better error performance. The price to be paid for this performance improvement is an increase in the demodulation complexity at the destination. Hence, the development of low-complexity but diversity-achieving demodulators is an interesting future research direction, in order to leverage the potential of DSM.

References

[1] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative communications in wireless networks," *IEEE Commun. Mag.*, vol. 42, no. 10, pp. 74–80, Oct. 2004.
[2] J. N. Laneman, D. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.
[3] Y. Rong, X. Tang, and Y. Hua, "A unified framework for optimizing linear non-regenerative multicarrier MIMO relay communication systems," *IEEE Trans. Signal Process.*, vol. 57, no. 12, pp. 4837–4851, Dec. 2009.
[4] W. Xu, X. Dong, and H. Yongming, "Asymptotic achievable rate analysis for selection strategies in amplify-and-forward MIMO two-hop networks with feedback," *IEEE Trans. Veh. Technol.*, vol. 59, no. 7, pp. 3662–3668, Sep. 2010.
[5] W. Xu, X. Dong, and W.-S. Lu, "Joint precoding optimization for multiuser multiantenna relaying downlinks using quadratic programming," *IEEE Trans. Commun.*, vol. 59, no. 5, pp. 1228–1235, May 2011.
[6] A. Munari, F. Rossetto, and M. Zorzi, "Phoenix: Making cooperation more efficient through network coding in wireless networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 10, pp. 5248–5258, Oct. 2009.
[7] Z. Ding *et al.*, "On combating the half-duplex constraint in modern cooperative networks: Protocols and techniques," *IEEE Wireless Commun. Mag.*, vol. 19, no. 6, pp. 20–27, Jun. 2012.
[8] I. Krikidis, H. Suraweera, S. Yang, and K. Berberidis, "Full-duplex relaying over block fading channel: A diversity perspective," *IEEE Trans. Wireless Commun.*, vol. 11, no. 12, pp. 4524–4535, Dec. 2012.
[9] D. Bharadia and S. Katti, "Full duplex MIMO radios," in *Proc. ACM UNISEX*, Apr. 2014, pp. 1–13.
[10] R. U. Nabar, H. Bolcskei, and F. W. Kneubuhler, "Fading relay channels: Performance limits and space-time signal designs," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1099–1109, Aug. 2004.
[11] K. Azarian, H. El Gamal, and P. Schniter, "On the achievable diversity-multiplexing tradeoff in half-duplex cooperative channels," *IEEE Trans. Inf. Theory*, vol. 51, no. 12, pp. 4152–4172, Dec. 2005.
[12] S. Yang and J.-C. Belfiore, "Optimal space-time codes for the MIMO amplify-and-forward cooperative channel," *IEEE Trans. Inf. Theory*, vol. 53, no. 2, pp. 647–663, Feb. 2007.
[13] S. Yang and J.-C. Belfiore, "Towards the optimal amplify-and-forward cooperative diversity scheme," *IEEE Trans. Inf. Theory*, vol. 53, no. 9, pp. 3114–3126, Sep. 2007.
[14] Y. Fan, C. Wang, J. S. Thompson, and H. V. Poor, "Recovering multiplexing loss through successive relaying using repetition coding," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4484–4493, Dec. 2007.
[15] C. Wang, Y. Fan, J. S. Thompson, M. Skoglund, and H. V. Poor, "Approaching the optimal diversity-multiplexing tradeoff in a four-node cooperative network," *IEEE Trans. Wireless Commun.*, vol. 9, no. 12, pp. 3690–3700, Dec. 2010.
[16] S. Zhang, S. Liew, and P. Lam, "Physical layer network coding," in *Proc. ACM MobiCom*, Sep. 2006, pp. 358–365.
[17] S. Katti, S. Gollakota, and D. Katabi, "Embracing wireless interference: Analog network coding," in *Proc. ACM SIGCOMM*, Oct. 2007, pp. 397–408.
[18] A. Yang *et al.*, "Design of binary network codes for multiuser multiway relay networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3786–3799, Oct. 2013.
[19] A. K. Sadek, K. J. R. Liu, and A. Ephremides, "Cognitive multiple access via cooperation: Protocol design and performance analysis," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3677–3696, Oct. 2007.

[20] T. Wang and G. B. Giannakis, "Complex field network coding for multiuser cooperative communications," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 3, pp. 561–571, Apr. 2008.

[21] E. Fasolo, F. Rossetto, and M. Zorzi, "Network coding meets MIMO," in *Proc. Workshop Network Coding Theory Appl.*, Jan. 2008, pp. 1–6.

[22] F. Rossetto and M. Zorzi, "Mixing network coding and cooperation for reliable wireless communications," *IEEE Wireless Commun. Mag.*, vol. 18, no. 2, pp. 15–21, Feb. 2011.

[23] M. Di Renzo, M. Iezzi, and F. Graziosi, "On diversity order and coding gain of multisource multirelay cooperative wireless networks with binary network coding," *IEEE Trans. Veh. Techol.*, vol. 62, no. 3, pp. 1138–1157, Mar. 2013.

[24] M. Di Renzo, M. Iezzi, and F. Graziosi, "Error performance and diversity analysis of multi-source multi-relay wireless networks with binary network coding and cooperative MRC," *IEEE Trans. Wireless Commun.*, vol. 12, no. 6, pp. 2883–2903, Jun. 2013.

[25] M. Di Renzo, "On the achievable diversity of repetition-based and relay selection network-coded cooperation," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2296–2313, Jul. 2014.

[26] E. G. Larsson and B. R. Vojcic, "Cooperative transmit diversity based on superposition modulation," *IEEE Commun. Lett.*, vol. 9, no. 9, pp. 778–780, Sep. 2005.

[27] I. Krikidis, "Analysis and optimization issues for superposition modulation in cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 4837–4847, Nov. 2009.

[28] R. Y. Mesleh, H. Haas, S. Sinanovic, C. W. Ahn, and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 57, no. 4, pp. 2228–2241, Jul. 2008.

[29] M. Di Renzo, H. Haas, and P. Grant, "Spatial modulation for multiple-antenna wireless systems—A survey," *IEEE Commun. Mag.*, vol. 49, no. 12, pp. 182–191, Dec. 2011.

[30] M. Di Renzo, H. Haas, A. Ghrayeb, S. Sugiura, and L. Hanzo, "Spatial modulation for generalized MIMO: Challenges, opportunities and implementation," *Proc. IEEE*, vol. 102, no. 1, pp. 56–103, Jan. 2014.

[31] P. Yang, M. Di Renzo, Y. Xiao, S. Li, and L. Hanzo, "Design guidelines for spatial modulation," *IEEE Commun. Surveys Tuts.*, vol 17, no. 1, pp. 6–26, 1st Quart. 2015.

[32] M. Di Renzo and H. Haas, "Improving the performance of space shift keying (SSK) modulation via opportunistic power allocation," *IEEE Commun. Lett.*, vol. 14, no. 6, pp. 500–502, Jun. 2010.

[33] R. Y. Mesleh, M. Di Renzo, H. Haas, and P. M. Grant, "Trellis coded spatial modulation," *IEEE Trans. Wireless Commun.*, vol. 9, no. 7, pp. 2349–2361, Jul. 2010.

[34] M. Di Renzo and H. Haas, "A general framework for performance analysis of space shift keying (SSK) modulation for MISO correlated Nakagami-m fading channels," *IEEE Trans. Commun.*, vol. 58, no. 9, pp. 2590–2603, Sep. 2010.

[35] M. Di Renzo and H. Haas, "Space shift keying (SSK) modulation with partial channel state information: Optimal detector and performance analysis over fading channels," *IEEE Trans. Commun.*, vol. 58, no. 11, pp. 3196–3210, Nov. 2010.

[36] M. Di Renzo and H. Haas, "Space shift keying (SSK-) MIMO over correlated Rician fading channels: Performance analysis and a new method for transmit-diversity," *IEEE Trans. Commun.*, vol. 59, no. 1, pp. 116–129, Jan. 2011.

[37] M. Di Renzo and H. Haas, "Bit error probability of space modulation over Nakagami-m fading: Asymptotic analysis," *IEEE Commun. Lett.*, vol. 15, no. 10, pp. 1026–1028, Oct. 2011.

[38] M. Di Renzo and H. Haas, "Bit error probability of space shift keying MIMO over multiple-access independent fading channels," *IEEE Trans. Veh. Technol.*, vol. 60, no. 8, pp. 3694–3711, Oct. 2011.

[39] M. Di Renzo and H. Haas, "Bit error probability of SM-MIMO over generalized fading channels," *IEEE Trans. Veh. Technol.*, vol. 61, no. 3, pp. 1124–1144, Mar. 2012.

[40] M. Di Renzo, D. De Leonardis, F. Graziosi, and H. Haas, "Space shift keying (SSK-) MIMO with practical channel estimates," *IEEE Trans. Commun.*, vol. 60, no. 4, pp. 998–1012, Apr. 2012.

[41] A. Stavridis, S. Sinanovic, M. Di Renzo, H. Haas, and P. M. Grant, "An energy saving base station employing spatial modulation," in *Proc. IEEE Int. Workshop Comput.-Aided Model. Anal. Des. Commun. Links Netw.*, Sep. 2012, pp. 1–6.

[42] M. Di Renzo and H. Haas, "On transmit-diversity for spatial modulation MIMO: Impact of spatial-constellation diagram and shaping filters at the transmitter," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2507–2531, Jul. 2013.

[43] A. Younis, S. Sinanovic, M. Di Renzo, R. Y. Mesleh, and H. Haas, "Generalised sphere decoding for spatial modulation," *IEEE Trans. Commun.*, vol. 61, no. 7, pp. 2805–2815, Jul. 2013.

[44] A. Younis *et al.*, "Performance of spatial modulation using measured real-world channels," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Sep. 2013, pp. 1–5.

[45] A. Stavridis, S. Sinanovic, M. Di Renzo, and H. Haas, "Energy evaluation of spatial modulation at a multi-antenna base station," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Sep. 2013, pp. 1–5.

[46] N. Serafimovski *et al.*, "Practical implementation of spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4511–4523, Nov. 2013.

[47] M.-T. Le, V.-D. Ngo, H.-A. Mai, X.-N. Tran, and M. Di Renzo, "Spatially modulated orthogonal space-time block codes with non-vanishing determinants," *IEEE Trans. Commun.*, vol. 62, no. 1, pp. 85–99, Jan. 2014.

[48] Y. Yang, "Information-guided relay selection for high throughput in half-duplex relay channels," in *Proc. IEEE Global Commun. Conf.*, Nov./Dec. 2009, pp. 1–5.

[49] N. Serafimovski, S. Sinanovic, M. Di Renzo, and H. Haas, "Dual-hop spatial modulation (Dh-SM)," in *Proc. IEEE Veh. Technol. Conf.—Spring*, May 2011, pp. 1–5.

[50] S. Sugiura, S. Chen, H. Haas, P. M. Grant, and L. Hanzo, "Coherent versus non-coherent decode-and-forward relaying aided cooperative space-time shift keying," *IEEE Trans. Commun.*, vol. 59, no. 6, pp. 1707–1719, Jun. 2011.

[51] Y. Yang and S. Aïssa, "Information-guided transmission in decode-and-forward relaying systems: Spatial exploitation and throughput enhancement," *IEEE Trans. Wireless Commun.*, vol. 10, no. 7, pp. 2341–2351, Jul. 2011.

[52] D. Yang, C. Xu, L.-L. Yang, and L. Hanzo, "Transmit-diversity-assisted space-shift keying for colocated and distributed/cooperative MIMO elements," *IEEE Trans. Veh. Technol.*, vol. 60, no. 6, pp. 2864–2869, Jul. 2011.

[53] R. Y. Mesleh, S. Ikki, and M. Alwakeel, "Performance analysis of space shift keying with amplify and forward relaying," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1350–1352, Dec. 2011.

[54] R. Y. Mesleh, S. Ikki, H. Aggoune, and A. Mansour, "Performance analysis of space shift keying (SSK) modulation with multiple cooperative relays," *EURASIP J. Adv. Signal Process.*, vol. 2012, no. 1, p. 201, Sep. 2012.

[55] S. Narayanan, M. Di Renzo, F. Graziosi, and H. Haas, "Distributed space shift keying for the uplink of relay-aided cellular networks," in *Proc. IEEE Int. Workshop Comput.-Aided Model. Anal. Des. Commun. Links Netw.*, Sep. 2012, pp. 130–134.

[56] P. Som and A. Chockalingam, "End-to-end BER analysis of space shift keying in decode-and-forward cooperative relaying," in *Proc. IEEE Wireless Commun. Netw. Conf.*, Apr. 2013, pp. 3465–3470.

[57] P. Zhang, S. Chen, and L. Hanzo, "Differential space-time shift keying-aided successive-relaying-assisted decode-and-forward cooperative multiuser CDMA," *IEEE Trans. Veh. Technol.*, vol. 62, no. 5, pp. 2156–2169, Jun. 2013.

[58] M. I. Kadir, L. Li, S. Chen, and L. Hanzo, "Successive-relaying-aided decode-and-forward coherent versus noncoherent cooperative multicarrier space-time shift keying," *IEEE Trans. Veh. Technol.*, vol. 62, no. 6, pp. 2544–2557, Jul. 2013.

[59] R. Mesleh and S. Ikki, "Performance analysis of spatial modulation with multiple decode and forward relays," *IEEE Wireless Commun. Lett.*, vol. 2, no. 4, pp. 423–426, Aug. 2013.

[60] R. Y. Mesleh and S. Ikki, "Analysis of cooperative communication spatial modulation with imperfect channel estimation," in *Proc. IEEE Int. Symp. Pers., Indoor, Mobile Radio Commun.*, Sep. 2013, pp. 2027–2023.

[61] P. Som and A. Chockalingam, "BER analysis of space shift keying in cooperative multi-hop multi-branch DF relaying," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Sep. 2013, pp. 1–5.

[62] S. Narayanan, A. Stavridis, M. Di Renzo, F. Graziosi, and H. Haas, "Distributed spatially-modulated space-time-block-codes," in *Proc. IEEE Int. Workshop Comput.-Aided Model. Anal. Des. Commun. Links Netw.*, Sep. 2013, pp. 159–163.

[63] S. Narayanan, M. Di Renzo, F. Graziosi, and H. Haas, "Distributed spatial modulation for relay networks," in *Proc. IEEE Veh. Technol. Conf.—Fall*, Sep. 2013, pp. 1–6.

[64] P. Yang *et al.*, "Detect-and-forward relaying aided cooperative spatial modulation for wireless networks," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4500–4511, Nov. 2013.

[65] P. Som and A. Chockalingam, "Bit error probability analysis of SSK in DF relaying with threshold-based best relay selection and selection combining," *IEEE Commun. Lett.*, vol. 18, no. 1, pp. 18–21, Jan. 2014.

[66] P. Som and A. Chockalingam, "Performance analysis of space shift keying in decode-and-forward multi-hop MIMO networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 132–146, Jan. 2015.

[67] X.-T. Vu, M. Di Renzo, and P. Duhamel, “Multiple-access relaying with network coding: Iterative network/channel decoding with imperfect CSI,” *EURASIP J. Adv. Signal Process.*, vol. 2013, no. 1, p. 170, Nov. 2013.

[68] X.-T. Vu, P. Duhamel, and M. Di Renzo, “Performance analysis of network coded cooperation with channel coding and adaptive DF-based relaying in Rayleigh fading channels,” *IEEE Signal Process. Lett.*, vol. 22, no. 9, pp. 1354–1358, Sep. 2015.

[69] J. N. Laneman and G. W. Wornell, “Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks,” *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.

[70] M. K. Simon and M.-S. Alouini, *Digital Communication Over Fading Channels*, 2nd ed. Hoboken, NJ, USA: Wiley, 2005.

[71] A. Nasri, R. Schober, and M. Uysal, “Performance and optimization of network-coded cooperative diversity systems,” *IEEE Trans. Commun.*, vol. 61, no. 3, pp. 1111–1122, Mar. 2013.

[72] H. Kim and C. Tepedelenlioglu, “Performance bounds on average error rates using the AM-GM inequality and their applications in relay networks,” *IEEE Trans. Wireless Commun.*, vol. 11, no. 8, pp. 2986–2995, Aug. 2012.

[73] Z. Wang and G. B. Giannakis, “A simple and general parameterization quantifying performance in fading channels,” *IEEE Trans. Commun.*, vol. 51, no. 8, pp. 1389–1398, Aug. 2003.

[74] B. Masnick and J. Wolf, “On linear unequal error protection codes,” *IEEE Trans. Inf. Theory*, vol. IT-3, no. 4, pp. 600–607, Oct. 1967.

[75] E. Biglieri, C. Caire, G. Taricco, and J. Ventura-Traveset, “Computing error probabilities over fading channels: A unified approach,” *Eur. Trans. Telecommun.*, vol. 9, no. 1, pp. 15–25, Feb. 1998.

[76] T. Wang, A. Cano, G. B. Giannakis, and J. N. Laneman, “High-performance cooperative demodulation with decode-and-forward relays,” *IEEE Trans. Commun.*, vol. 55, no. 7, pp. 1427–1438, Jul. 2007.

[77] L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, “Optimal decoding of linear codes for minimizing symbol error rate,” *IEEE Trans. Inf. Theory*, vol. IT-20, no. 2, pp. 284–87, Feb. 1974.

[78] J. M. Muller, *Elementary Functions—Algorithms and Implementation*, 2nd ed. Cambridge, MA, USA: Birkhaüser, Oct. 2005.

Sandeep Narayanan (S’08) received the B.Tech. degree from Amrita University, Coimbatore, India, in 2010; the M.Sc. degree from The University of Edinburgh, Edinburgh, U.K., in 2011; and the Ph.D. degree in electrical and information engineering from the University of L’Aquila, L’Aquila, Italy, in 2015.

From 2011 to 2014, he was a Marie Curie Early Stage Researcher with the Center of Excellence for Research DEWS, University of L’Aquila, and with Wireless Embedded Systems Technologies Aquila srl, L’Aquila. Since 2015, he has been a Postdoctoral Research Fellow with the School of Electrical, Electronic and Communications Engineering, University College Dublin, Dublin, Ireland. His main research interests include wireless communication theory and signal processing.

Marco Di Renzo (SM’14) received the Laurea (*cum laude*) and Ph.D. degrees in electrical engineering from the University of L’Aquila, L’Aquila, Italy, in 2003 and 2007, respectively, and the Habilitation à Diriger des Recherches from the University Paris-Sud XI, Gif-sur-Yvette, France, in 2013.

He has held various research and academic positions in Italy, in the U.S. with the Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; in Spain with CTTC; and in the U.K. with The University of Edinburgh, Edinburgh, U.K. Since 2010, he has been a “Chargé de Recherche Titulaire CNRS” with the Laboratory of Signals and Systems (UMR-8506), Paris-Saclay University—CNRS, Centrale Supelec, University Paris-Sud XI. He is a Cofounder of the university spin-off company WEST Aquila srl, L’Aquila.

Dr. Di Renzo currently serves as an Editor for IEEE COMMUNICATIONS LETTERS and IEEE TRANSACTIONS ON COMMUNICATIONS, where he is the Editor for Heterogeneous Networks Modeling and Analysis of the IEEE Communications Society. He received Best Paper Awards at the IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks in 2012 and 2014, at the IEEE Vehicular Technology Conference in Fall 2013, and at the IEEE International Conference on Advanced Technologies for Communication in 2014; the Network of Excellence NEWCOM# Best Paper Award in 2013; and the IEEE Communication Society Best Young Researcher Award for Europe, the Middle East, and Africa (EMEA Region) in 2013. He is a Distinguished Visiting Fellow of the Royal Academy of Engineering, U.K., and a member of the European Association for Communications and Networking.

Fabio Graziosi (M’97) received the Laurea (*cum laude*) and the Ph.D. degrees in electronic engineering from the University of L’Aquila, L’Aquila, Italy, in 1993 and 1997, respectively.

Since 1997, he has been with the University of L’Aquila, where he currently is an Associate Professor and the Associate Chair of the Department of Engineering, Computer, and Mathematical Sciences. He is a Cofounder, the President, and the Chief Executive Officer of the university spin-off company WEST Aquila srl, L’Aquila. His main research interests include wireless communications and communication theory.

Harald Haas (M’03) received the Ph.D. degree from The University of Edinburgh, Edinburgh, U.K., in 2001.

He is currently the Chair of Mobile Communications with the School of Engineering, University of Edinburgh. Since 2013, he has been the Director of the Li-Fi Research and Development Centre, University of Edinburgh. He is a Cofounder and the Chief Scientific Officer of the university spin-off company pureLiFi Ltd., Edinburgh.

Dr. Haas serves as an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS. He received the Established Career Fellowship from the Engineering and Physical Sciences Research Council, U.K., in 2012 and the Tam Dalyell Prize from the University of Edinburgh in 2013. His main research interests include wireless communications and optical wireless communications.