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C-MRC-based cooperative spatial modulation with antenna selection

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Summary

A new high-performance low-complexity cooperative maximal ratio combining (C-MRC)-based cooperative relaying scheme, which is called antenna selection-aided cooperative spatial modulation scheme with C-MRC (AS-CSM), is proposed for decode and forward (DF)-based cooperative relaying networks operating over independent but non-identically distributed (i.n.d.) Rayleigh fading channels. The AS-CSM scheme is formed with the combination of cooperative SM with the high-performance low-complexity coherent demodulator C-MRC and antenna selection techniques. In the AS-CSM scheme, the information is transmitted from the source terminal (ST) to the relay terminal (RT) and the destination terminal (DT) in the form of not only modulated symbols but also antenna indices, which carry additional information bits in the spatial domain. Therefore, a high spectral efficiency is obtained by the proposed scheme for cooperative relaying networks. In this scheme, first, the index of the activated antenna of ST is estimated, and the best antenna selection at RT is investigated considering the received instantaneous equivalent to signal-to-noise values acquired at DT. The transmitted symbols are estimated with low-complexity coherent demodulator C-MRC at DT by using the noisy signals from ST and RT. An exact closed-form expression for the bit error probability (BEP) of the AS-CSM scheme is derived, and the theoretical results are validated with Monte-Carlo simulation results.

KEYWORDS

antenna selection, cooperative diversity, cooperative-maximal ratio combining, decode and forward, spatial modulation

1 | INTRODUCTION

By 2022, traffic volume in mobile 5G networks is expected to reach 77 exabytes per month. This will require the capacity provided by 5G networks to be at least 1000 times higher than existing cellular systems. However, this is not enough with existing systems; we need innovative next-generation communication systems because this situation can lead to severe economic and environmental problems. The current network architectures are designed to maximize capacity by increasing their power. However, the number of devices will grow tremendously in the coming years, especially with internet of thing (IoT) and the internet of everything (IoE), and consequently, network architectures will be inadequate. Using more energy each day to increase the communication capacity will result in severe operating costs and will be insufficient no matter how much effort they make. On the other hand, current information and

communication technology (ICT) is responsible for at least 5% of the world's CO₂ emissions. Besides, 75% of the ICT sector is expected to be wireless by the end of 2020; for this reason, next-generation communication techniques should be designed to be energy efficient in a way to reduce CO₂ emissions.¹⁻⁴

Multiple-input multiple-output (MIMO) systems offer reliable communications as well as higher capacity in the presence of multipath propagation.⁵ Consequently, MIMO transmission techniques have been comprehensively adapted into most of the recent communication standards.⁶ On the other hand, relaying transmission techniques in MIMO systems have been studied over the past decade by researchers and have recently emerged as powerful technologies for many wireless applications and standards.^{7,8} In the literature, several relaying protocols such as decode-and-forward (DF) and amplify and forward (AF) are proposed for cooperative networks. In DF relaying, the received signal at the relay terminal (RT) is decoded first and then remodulated and transmitted to the destination terminal (DT). On the other hand, in AF relaying protocol, RT simply amplifies the received signal and forwards the scaled version of the received signal to DT without decoding the message. Through terminal cooperation, relay transmission scheme can also obtain spatial diversity in a distributed manner. The use of multiple antennas at both MIMO and cooperative relaying systems has been considered as an effective way to improve the data rate and reliability.⁵ However, while MIMO and cooperative relaying systems have recently emerged as powerful potential technologies for many wireless applications and standards,^{6,7,9,10} using multiple antennas at the terminals of MIMO systems and the relay causes problems such as extra transceiver complexity due to interchannel interference (ICI) and high cost with multiple radio frequency (RF) chains.

Recently, some solutions have been put forward by the researchers to overcome the above-mentioned problems, and two general transmission strategies, spatial modulation (SM) and antenna selection techniques, have been proposed. The increasing demand for high data rates and, consequently, high spectral efficiencies has led to the development of antenna selection systems in which a combining technique, such as selection combining (SC), maximal ratio combining (MRC), and cooperative-MRC (C-MRC), is used to obtain the diversity gain.¹¹ C-MRC is a high-performance low-complexity coherent detector and provides maximum possible diversity while its error performance is very close to maximum likelihood (ML) performance. In Kumbhani and Kshetrimayum,¹² the error performance of two-hop cooperative communication systems with the help of transmit antenna selection at ST and RT is proposed over $\eta - \mu$ fading channels. A novel high data rate transmission concept, which is known as SM, has been introduced by Mesleh et al.¹³ to remove ICI completely between the transmit antennas of MIMO and cooperative relaying systems. SM appears as a promising form of index modulation (IM),¹⁴ in which the information is conveyed not only by amplitude/phase of the modulated signal but also by antenna indices. Its advantages make SM useful also in relay networks, and its application to the relay networks is investigated in recent studies.

A dual-hop SM scheme is proposed in Serafimovski et al.¹⁵ by exploiting SM in a DF relaying-aided three-node cooperative network. Similarly, a space-shift keying (SSK)-based dual-hop AF relaying scheme is investigated in Mesleh et al.¹⁶ Opportunistic relay selection is considered for SM-based dual-hop networks with multiple relays in Mesleh and Ikki.¹⁷ SM techniques have been also studied for classical relay networks, in which a direct transmission link exists between ST and DT. In Mesleh et al.,¹⁸ both DF and AF-based cooperative SSK schemes are proposed. Later, SM is adopted to classical relay networks in Mesleh and Ikki.^{19,20} Partial, hybrid, and hierarchical modulation-based DF relaying protocols are proposed for cooperative SM systems in Yang et al.²¹ On the other hand, previous studies²²⁻²⁴ investigated the application of SSK to cooperative networks, in which all nodes are equipped with multiple antennas. More recently, the outage probability of the cooperative SM scheme is analyzed for fixed DF/AF, selective DF, and incremental relaying.²⁵ In Li et al.,²⁶ the SM technique is adapted to the cooperative nonorthogonal multiple access (NOMA) structure. Furthermore, Altin et al.²⁷ examined the bit error probability (BEP) of cooperative SM. Recently, quadrature SM (QSM) is explored for cooperative DF networks in Afana et al.²⁸ Afana et al.²⁹ also considered QSM for cooperative dual-hop AF relaying systems.

Besides, antenna selection techniques have been studied for SM-based schemes in recent years.³⁰ Euclidean distance and capacity optimization-based antenna selection algorithms are proposed for point-to-point SM systems in Rajashekar et al.³¹ and Pillay and Xu.³² Ntontin et al.³³ investigated the error performance of SSK with antenna subset selection, while a low-complexity antenna selection method is proposed for SM systems in Ntontin et al.³⁴ Another antenna selection technique based on IM for SM is proposed in Aydin and Ilhan.³⁵ The outage probability of SM-MIMO scheme with transmit antenna selection for binary phase shift keying signals is derived over Rayleigh fading channels in Kumbhani and Kshetrimayum.³⁶ Finally, a cooperative SSK scheme, which employs transmit antenna selection at ST, is proposed in Yarkin et al.³⁷

Against this background, in this paper, we propose a new low-complexity SM-based cooperative relaying scheme with C-MRC, in which antenna selection is employed at RT. This scheme, which is called as antenna selection-aided cooperative SM (AS-CSM), exploits the benefits of both cooperative SM with C-MRC and antenna selection techniques. We use SM in ST for the transmission of source data through antenna indices as well as ordinary M -ary modulation symbols. Exploiting the feedback of DT, the best antenna based on instantaneous equivalent received SNR is selected at RT for relaying, while DT uses C-MRC to combine the signals received from ST and RT. The main contributions of this paper can be summarized as follows:

- This paper explores the application of SM in a C-MRC based cooperative network with RT antenna selection for the first time in the literature. As a result, a new high-rate DF-based cooperative relaying scheme called AS-CSM with the best RT antenna selection is proposed.
- A general system model is constructed for any number of antennas at ST, RT, and DT, while only a single RF chain is required at ST, which remarkably reduces its cost.
- Exact closed-form expressions for BEP of the considered DF-based AS-CSM scheme are derived in the presence of C-MRC technique with low-complexity over independent but nonidentically distributed (i.n.d.) Rayleigh fading channels. According to the computer simulations, the proposed AS-CSM scheme has significant performance advantages over point-to-point SM due to cooperative diversity advantages.

The remaining of the paper is organized as follows: In Section 2, we introduce the general AS-CSM scheme. In Section 3, the performance analyses for the BEP of AS-CSM scheme are provided. Simulation results and performance comparisons are given in Section 4. Finally, Section 5 concludes the paper.

Notation: The following notation is used throughout this paper. (i) Bold lower/upper case symbols represent vectors/matrices; (ii) $(\cdot)^H$, $(\cdot)^T$, $\|\cdot\|_F$, $|\cdot|$, and $E[\cdot]$ denote Hermitian, transpose, Frobenius norm, Euclidean norm, and expectation operators, respectively, $\Re(\cdot)$ and $\Im(\cdot)$ are the real and imaginary parts of a complex-valued quantity; (iii) $\binom{\cdot}{\cdot}$ denotes the binomial coefficient.

2 | SYSTEM MODEL

In this section, we generalize the SM scheme for a cooperative relaying network by using antenna selection technique at RT to cope with several problems that are explained in the previous section for classical MIMO and cooperative relaying networks.

2.1 | AS-CSM system design and relaying protocol

In this section, we introduce the AS-CSM scheme and represent the designed relaying protocol. We particularly benefit from a combination of two models: SM-based source model and antenna selection-based relay model. Figure 1 shows the block diagram of AS-CSM in which we consider a two-phase DF relaying cooperative communication system, which consists of one source with \mathcal{N}_S antennas, one relay with \mathcal{N}_R antennas and one destination with \mathcal{N}_D antennas. We assume that each terminal operates in a half-duplex mode, that is, a node cannot transmit and receive simultaneously, and time division multiple access protocol³⁸ is considered. Every fading coefficient between terminals is fixed within the coherence time interval and each coefficient experiences slow, flat, i.n.d. Rayleigh fading and CSI is known by DT. We also assume that M -QAM is used during signaling.

In the AS-CSM scheme, first, the pilot symbols are transmitted from ST to all available antennas of RT, DT as well as from RT to DT in order to determine CSI that will be used to determine the best antenna of RT and DT for relaying. Afterwards, the instantaneous equivalent SNRs for each antenna of RT are obtained at DT. After selecting the best antenna of RF based on the largest of the received instantaneous equivalent SNRs, DT feeds back index of the best antenna of RT to be used at each frame for relaying by a feedback channel illustrated by the dashed line given in Figure 1. After obtaining the best antenna information of RT, transmission protocol starts. The transmission protocol is divided into two main phases.

In the first phase, ST transmits spatially modulated symbol from its active antenna to RT and DT. In this phase, first, the active antenna index ℓ at ST is estimated by DT, and then, this information of $\hat{\ell}$ is transmitted to RT by a

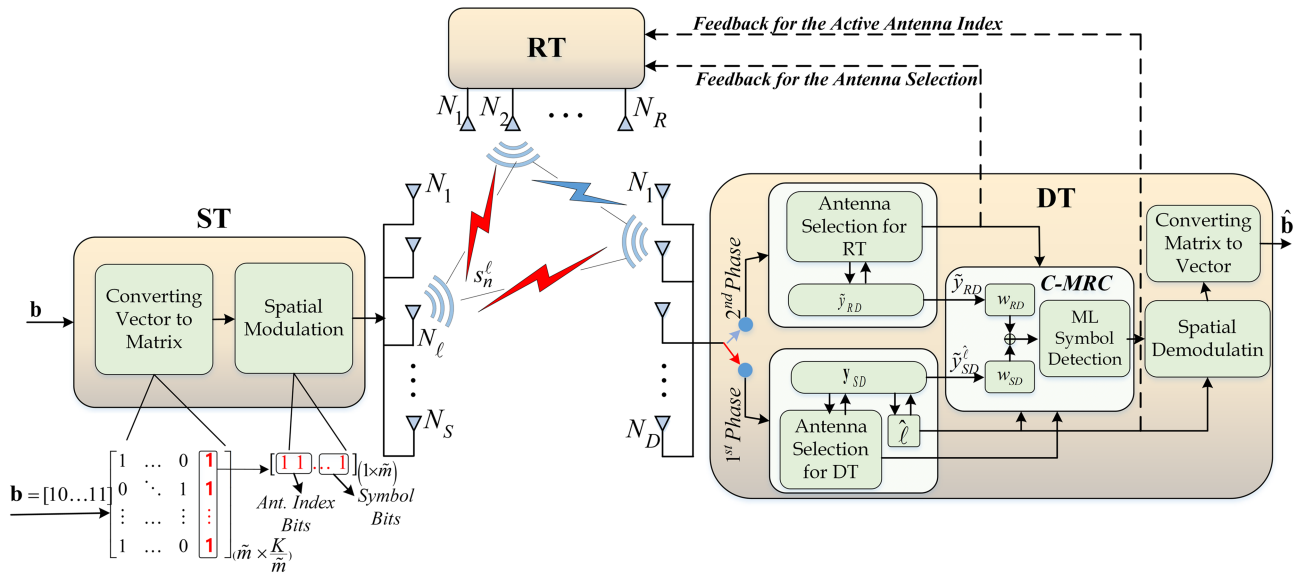


FIGURE 1 System model of the AS-CSM scheme

feedback channel illustrated by the dashed line shown in Figure 1. Here, the reason why we send the active antenna index from the feedback channel is that SM cannot be used at RT. According to AS-CSM scheme RT transmits only the source's data symbol to DT. Since the symbol transmitted by RT does not contain the index information about the ST's active antenna, the active antenna index of ST is transmitted to RT in order to decrease the complexity of detection at RT side.

In order to obtain the spatially modulated symbol, the information bit stream \mathbf{b} , which is an $(1 \times K)$ binary information vector that will be transmitted through AS-CSM scheme, of ST is divided into two sets as follows: active antenna index-bits and M -ary signal constellation-bits. In the first stage, \mathbf{b} is converted into a matrix of size $\tilde{m} \times (K/\tilde{m})$ shown in Figure 1, where \tilde{m} is the total number of bits for each symbol. Since the channel is assumed to be flat throughout one frame with K bits, the channel will remain constant during (K/\tilde{m}) time slots. Next, each row vector with dimension $(1 \times \tilde{m})$ is further split into subvectors with $\log_2(N_S)$ and $\log_2(M)$ bits. The bits in the first subvector are used for activating a unique antenna for transmission. The remaining bits in the second subvector are mapped to an M -QAM symbol s . Note that the antenna activation process can be described by the N_S -dimensional standard basis vector $\mathbf{u}_\ell (1 \leq \ell \leq N_S)$ (e.g., $\mathbf{u}_2 = [0, 1, 0, \dots, 0]^T$). Finally, the transmitted symbol vector \mathbf{x}_{ℓ_n} comprised the symbol s_n^ℓ , where $n = 0, 1, 2, \dots, M-1$, emitted from the activated antenna ℓ . The modulated symbol can be formulated as $\mathbf{x}_{\ell_n} = s_n^\ell \mathbf{u}_\ell \in \mathbb{C}^{N_S \times 1}$,¹³ where \mathbb{C} denotes the field of complex numbers.

On the other hand, in the second phase, RT transmits the estimated symbol from its best antenna to the best antenna of DT.

2.2 | ML detector for AS-CSM system

In this section, the coherent ML detection for the AS-CSM scheme is formulated, and ML detector is used at both RT and DT.

2.2.1 | ML-based relaying model

The corresponding vector-based noisy signals received at DT and RT are given respectively by

$$\mathbf{y}_{SD} = \sqrt{E_S} \mathbf{H}_{SD} \mathbf{x}_{\ell_n} + \mathbf{n}_{SD}, \quad (1)$$

$$\mathbf{y}_{SR} = \sqrt{E_S} \mathbf{H}_{SR} \mathbf{x}_{\ell_n} + \mathbf{n}_{SR}, \quad (2)$$

where $\mathbf{y}_{SD} = [y_{SD_1}, y_{SD_2}, \dots, y_{SD_{N_D}}]^T$, $\mathbf{y}_{SR} = [y_{SR_1}, y_{SR_2}, \dots, y_{SR_{N_R}}]^T$ and E_S is the average transmitted energy per symbol. \mathbf{H}_{SD} and \mathbf{H}_{SR} are the channel matrices with dimensions $(N_D \times N_S)$ and $(N_R \times N_S)$, whose elements are complex Gaussian random variables with zero means and variances of $\sigma_{SD_i}^2$ and $\sigma_{SR_j}^2$, respectively. Furthermore, \mathbf{n}_{SD} and \mathbf{n}_{SR} are the AWGN components with zero mean and N_0 variance. The instantaneous SNRs in the links ST→DT and ST→RT from the activated antenna can be written as $\gamma_{SD_i}^\ell = E_S |h_{SD_i}^\ell|^2 / N_0$ and $\gamma_{SR_j}^\ell = E_S |h_{SR_j}^\ell|^2 / N_0$, respectively, where $i = 1, 2, \dots, N_D$ and $j = 1, 2, \dots, N_R$. $h_{SD_i}^\ell$ and $h_{SR_j}^\ell$ denote the i th and j th element of the ℓ th column of \mathbf{H}_{SD} and \mathbf{H}_{SR} , respectively. The average SNR values are given as $\bar{\gamma}_{SD_i} = (E_S \mu_{SD_i}) / N_0$ and $\bar{\gamma}_{SR_j} = (E_S \mu_{SR_j}) / N_0$, where $\mu_{SD_i} = E[|h_{SD_i}^\ell|^2]$ and $\mu_{SR_j} = E[|h_{SR_j}^\ell|^2]$. During the transmitting process, symbol blocks with (K/\tilde{m}) length are successively transmitted.

After determining the best antenna of RT by means of the feedback received from DT, RT detects and decodes only one symbol, which is transmitted by the $\hat{\ell}$ th active antenna of ST, by performing coherent ML detection. Thus, the complexities of RT and DT are reduced significantly. The ML decoded signal at RT can be written as

$$\hat{s}_{SR}^\ell = \arg \min_{s_n^\ell \in \{s_1^\ell, s_2^\ell, \dots, s_{M-1}^\ell\}} \left\{ \left| \tilde{y}_{SR}^\ell - \sqrt{E_S} \tilde{h}_{SR} s_n^\ell \right|^2 \right\}, \quad (3)$$

where \tilde{y}_{SR}^ℓ and \tilde{h}_{SR} denote the signal received at the best antenna of RT from the estimated $\hat{\ell}$ th active antenna of ST, and ST→RT channel coefficient of the best equivalent ST→RT→DT link, respectively. In (4), the estimated symbol \hat{s}_{SR}^ℓ is transmitted from the best antenna of RT to the best antenna of DT. The signal received at the best antenna of DT is given by

$$\tilde{y}_{RD} = \sqrt{E_R} \tilde{h}_{RD} \hat{s}_{SR}^\ell + \tilde{n}_{RD}, \quad (4)$$

where \tilde{y}_{RD} , \tilde{h}_{RD} and \tilde{n}_{RD} denote the signal received at DT from best antenna of RT, and RT→DT channel coefficient and the noise term of the best equivalent ST→RT→DT link, respectively.

2.2.2 | ML-based destination model

We describe the ML-based destination model that estimates information symbols of ST by using C-MRC technique. After estimating the active antenna index of ST, which will be discussed in Section 3, the noisy signals received from both the active antenna of ST and the best antenna of RT can be combined at the best antenna of DT by using C-MRC technique as shown in Figure 1, and then, ML detector of AS-CSM scheme can be formulated as

$$\hat{s}_D = \arg \min_{s \in \{s_1, s_2, \dots, s_{M-1}\}} \left\{ \left| \left(w_{SD} \tilde{y}_{SD}^\ell + w_{RD} \tilde{y}_{RD} \right) - \left(w_{SD} \sqrt{E_S} \tilde{h}_{SD}^\ell + w_{RD} \sqrt{E_R} \tilde{h}_{RD} \right) s \right|^2 \right\}, \quad (5)$$

where \tilde{y}_{SD}^ℓ denote the best received signal of the ST→DT link and the weighting factors for C-MRC are chosen as $w_{SD} = (\tilde{h}_{SD}^\ell)^*$ and $w_{RD} = (\tilde{h}_{RD})^* \tilde{\gamma}_{eq} / \tilde{\gamma}_{RD}$. Here $\tilde{\gamma}_{eq}$ denotes the best equivalent SNR in the ST→RT→DT link and will be described in detail in the next section. By using the estimated active antenna index information of ST, spatial demodulation is performed at DT, and the estimated information bit stream of ST $\hat{\mathbf{b}}$ is obtained by using the final matrix to vector conversion as depicted in Figure 1.

3 | BEP ANALYSIS OF THE PROPOSED AS-CSM SCHEME

In this section, first, we obtain the total error probability of the AS-CSM scheme at DT, then, the analytical error calculation of the transmit antenna index estimation process and ML symbol detection of the transmitted symbols are performed. Finally, we derive a closed form expression for the BEP performance of the proposed AS-CSM scheme.

3.1 | Total error probability of the proposed AS-CSM scheme

Computation of the analytical BEP performance of the AS-CSM scheme requires four estimation processes. These steps are given as follows:

- Step 1. The active antenna index of ST should be estimated by DT.
- Step 2. The best antenna of RT in terms of the link SNRs is determined by DT.
- Step 3. Information obtained at steps 1 and 2 are both transmitted from DT to RT via a reliable feedback channel illustrated by the dashed line as shown in Figure 1.
- Step 4. DT combines the received signals of ST and RT by using C-MRC technique and estimates the symbol transmitted. Afterwards, by using both estimated active antenna index number and symbol information, the transmitted bit streams are constructed at DT by using the SM demapping table.

In the AS-CSM scheme, the transmitted bits are correctly recovered only if it estimates both the active antenna index of ST and the transmitted symbol correctly. In this case, the probability of correct estimation of information bits \mathcal{P}_c can be written as

$$\mathcal{P}_c = (1 - \mathcal{P}_{ind})(1 - \mathcal{P}_\epsilon), \quad (6)$$

where \mathcal{P}_{ind} denotes the probability that estimation of the active antenna index of ST is incorrect, and \mathcal{P}_ϵ expresses the probability that estimation of the transmitted bits is incorrect. Then, the total error probability $(1 - \mathcal{P}_c)$ of the proposed AS-CSM scheme at the destination can be written as

$$\mathcal{P}_e = \mathcal{P}_{ind} + \mathcal{P}_\epsilon - \mathcal{P}_{ind}\mathcal{P}_\epsilon. \quad (7)$$

Note that, when \mathcal{P}_{ind} is zero, i.e., there is only a single transmit antenna of ST, the overall error probability of the system is reduced to \mathcal{P}_ϵ . Thus, \mathcal{P}_ϵ (without SM) is an upper bound of BER for the performance of the proposed AS-CSM scheme.

3.2 | BEP analysis of the active antenna index estimation

In this section, error probability of the active antenna index estimation process (\mathcal{P}_{ind}) will be calculated. The modified decision rule of estimation of the active antenna index at DT can be written as follows³⁹:

$$\theta_\ell = \frac{\mathbf{h}_{SD_\ell}^H \mathbf{y}_{SD}}{\|\mathbf{h}_{SD_\ell}\|_F}, \quad \ell = 1, 2, \dots, \mathcal{N}_S, \quad (8)$$

where \mathbf{h}_{SD_ℓ} is the ℓ th column of \mathbf{H}_{SD} . The active antenna index of ST is estimated by the vector $\boldsymbol{\theta} = [\theta_1, \theta_2, \dots, \theta_{\mathcal{N}_S}]^T$ whose index or position of the maximum absolute value corresponds to the active antenna. Then, the active antenna index is estimated by

$$\hat{\ell} = \underset{\ell}{\operatorname{argmin}}\{|\theta_\ell|\}, \quad \ell \in \{1, 2, \dots, \mathcal{N}_S\} \quad (9)$$

where $\hat{\ell}$ represents the estimated active antenna index.

The BEP of the active antenna index detection can be derived by using the same approach as in Jeganathan et al.⁴⁰ The union-bound formula of the average BEP of the active antenna index number is given by⁴¹

$$\begin{aligned} \mathcal{P}_{ind} &\leq \mathbb{E}_\ell \left[\sum_{\hat{\ell}} \mathcal{N}(\ell, \hat{\ell}) \mathcal{P}(\mathbf{x}_{\ell n} \rightarrow \mathbf{x}_{\hat{\ell} n}) \right] \\ &= \sum_{\ell=1}^{\mathcal{N}_S} \sum_{n=1}^M \sum_{\hat{\ell}=1}^{\mathcal{N}_S} \frac{\mathcal{N}(\ell, \hat{\ell}) \Pr(\mathbf{x}_{\ell n} \rightarrow \mathbf{x}_{\hat{\ell} n})}{\mathcal{N}_S M}, \end{aligned} \quad (10)$$

where $N(\ell, \hat{\ell})$ denotes the number of bits in error between the active antenna index ℓ and the estimated active antenna index $\hat{\ell}$ and $\mathcal{P}(\mathbf{x}_{\ell n} \rightarrow \mathbf{x}_{\hat{\ell} n})$ is the pairwise error probability (PEP) of selecting signal vector $\mathbf{x}_{\hat{\ell} n}$ given that $\mathbf{x}_{\ell n}$ is transmitted.

The PEP conditioned on channel matrix \mathbf{H} can be expressed as³⁹

$$\begin{aligned} \mathcal{P}(\mathbf{x}_{\ell n} \rightarrow \mathbf{x}_{\hat{\ell} n} | \mathbf{H}) &= \mathcal{P}\left(\|\mathbf{y}_{SD} - \sqrt{E_S} \mathbf{h}_{\hat{\ell}} x_n\|_F < \|\mathbf{y}_{SD} - \sqrt{E_S} \mathbf{h}_{\ell} x_n\|_F | \mathbf{H}\right) \\ &= Q\left(\sqrt{\frac{E_S}{2}} \|\mathbf{h}_{\ell} x_n - \mathbf{h}_{\hat{\ell}} x_n\|_F^2\right) \\ &= \sum_{k=1}^{2N_S} \alpha_k^2, \end{aligned} \quad (11)$$

where $\alpha_k \sim \mathcal{N}(0, \sigma_\alpha^2)$ with $\sigma_\alpha^2 = \frac{E_S}{2} |x_n|^2$.

After some mathematical operations, unconditional BEP is obtained by the following final expression³⁹:

$$\mathcal{P}(\mathbf{x}_{\ell n} \rightarrow \mathbf{x}_{\hat{\ell} n}) = \mathcal{A}_\alpha^{N_S} \sum_{v=0}^{N_S-1} \binom{N_S-1+v}{v} [1 - \mathcal{A}_\alpha]^v, \quad (12)$$

where $\mathcal{A}_\alpha = \frac{1}{2} \left(1 - \sqrt{\frac{\sigma_\alpha^2}{1 + \sigma_\alpha^2}}\right)$.

Finally, substituting (12) into (10), BEP of the active antenna index detection is bounded by

$$\mathcal{P}_{ind} \leq \sum_{\ell=1}^{N_S} \sum_{n=1}^M \sum_{\hat{\ell}=1}^{N_S} \frac{N(\ell, \hat{\ell}) \mathcal{A}_\alpha^{N_S} \sum_{v=0}^{N_S-1} \binom{N_S-1+v}{v} [1 - \mathcal{A}_\alpha]^v}{N_S M}. \quad (13)$$

3.3 | Analytical BEP of AS-CSM scheme for M-QAM signal

In this section, analytical BEP calculation of the proposed AS-CSM scheme for M-QAM signaling is presented. Considering the theorem on total probability, the average BEP at DT can be formulated as a weighted sum of BEP for C-MRC corresponding to each set of decoding antennas χ_{set} . The number of antennas at RT in the decoding set χ_{set} is a random variable n with $n \in \{1, 2, \dots, N_{\mathcal{R}}\}$, since χ_{set} is a random set. Therefore, for each n , there are $\binom{N_{\mathcal{R}}}{n}$ possible subsets with size of n . Thus, the exact average BEP expression at DT can be written over all antennas of RT and DT as follows:

$$\begin{aligned} \mathcal{P}_\varepsilon &= \mathcal{P}(\chi_{set} = \{\emptyset\}) \bar{\mathcal{B}}_\chi(\chi_{set} = \{\emptyset\}) \\ &+ \sum_{i_1=1}^{N_{\mathcal{R}}} \mathcal{P}(\chi_{set} = \{\mathcal{T}_{i_1}\}) \bar{\mathcal{B}}_\chi(\chi_{set} = \{\mathcal{T}_{i_1}\}) \\ &+ \sum_{\substack{i_1, i_2=1 \\ i_1 < i_2}}^{N_{\mathcal{R}}} \mathcal{P}(\chi_{set} = \{\mathcal{T}_{i_1}, \mathcal{T}_{i_2}\}) \bar{\mathcal{B}}_\chi(\chi_{set} = \{\mathcal{T}_{i_1}, \mathcal{T}_{i_2}\}) + \dots \\ &+ \sum_{\substack{i_1, \dots, i_n=1 \\ i_1 < \dots < i_n}}^{N_{\mathcal{R}}} \mathcal{P}(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_n}\}) \bar{\mathcal{B}}_\chi(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_n}\}) \\ &+ \dots \\ &+ \sum_{\substack{i_1, i_2, \dots, i_{N_{\mathcal{R}}}=1 \\ i_1 < i_2 < \dots < i_{N_{\mathcal{R}}}}}^{N_{\mathcal{R}}} \mathcal{P}(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_{N_{\mathcal{R}}}}\}) \bar{\mathcal{B}}_\chi(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_{N_{\mathcal{R}}}}\}), \end{aligned} \quad (14)$$

where $\mathcal{P}(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_n}\})$ represents the probability of decoding set χ_{set} whose cardinality equals to n , $\mathcal{P}(\chi_{set} = \{\emptyset\})$ and $\bar{\mathcal{B}}_\chi(\chi_{set} = \{\emptyset\})$ describes the probability and average BEP expression in ST→DT link, respectively.

$\bar{B}_\chi(\chi_{set} = \{\mathcal{T}_{i_1}, \dots, \mathcal{T}_{i_n}\})$ expresses the average BEP conditioned on the decoding set χ_{set} for the combined signal obtained by using C-MRC. The probability of decoding set can be represented by

$$\mathcal{P}(\chi_{set}) = \left(\prod_{T_j \in \chi_{set}} (1 - \bar{e}_{T_j}) \right) \left(\prod_{T_j \notin \chi_{set}} \bar{e}_{T_j} \right), j = 1, 2, \dots, \mathcal{N}_R, \quad (15)$$

where \bar{e}_{T_j} denotes the average symbol error probability (SEP) of M -ary square QAM modulated symbols at the j th antenna of RT and will be explained in detail in subsection-part 3. For example, if RT has two antennas, (14) can be rewritten as follows:

$$\begin{aligned} \bar{\mathcal{P}}_e &= \bar{e}_{T_1} \bar{e}_{T_2} \bar{B}_\chi(\chi_{set} = \{\emptyset\}) + (1 - \bar{e}_{T_1}) \bar{e}_{T_2} \times \bar{B}_\chi(\chi_{set} = \{\mathcal{T}_1\}) \bar{e}_{T_1} (1 - \bar{e}_{T_2}) \bar{B}_\chi(\chi_{set} = \{\mathcal{T}_2\}) \\ &\quad + (1 - \bar{e}_{T_1})(1 - \bar{e}_{T_2}) \bar{B}_\chi(\chi_{set} = \{\mathcal{T}_1, \mathcal{T}_2\}). \end{aligned}$$

The average BEP ($\bar{B}_\chi(e)$) of M -QAM in slow Rayleigh fading channels is formulated by averaging the error rate in the presence of AWGN channel over the pdf of SNR in Rayleigh fading as follows:

$$\bar{B}_\chi(e) = \int_0^\infty \bar{B}_\chi(e|\gamma) f_\gamma(\gamma) d\gamma, \quad (16)$$

where $\bar{B}_\chi(e|\gamma)$ and $f_\gamma(\gamma)$ represent the BEP conditioned on γ and the end-to-end pdf at DT after the C-MRC combiner, respectively. In the following, derivations for pdf of γ , that is, $f_\gamma(\gamma)$ and then conditional BEP $\bar{B}_\chi(e|\gamma)$ and the average BEP $\bar{B}_\chi(e)$ of the proposed AS-CSM scheme are presented, respectively.

3.3.1 | End-to-end PDF after C-MRC combiner

Under the policy of AS-CSM scheme, C-MRC type receiver combines the best equivalent $ST_{\hat{\ell}} \rightarrow RT \rightarrow DT$ link SNR (γ_1^*) with the best $ST_{\hat{\ell}} \rightarrow DT$ link SNR (γ_2^*). Therefore, the combined SNR at DT can be written as $\gamma = \gamma_1^* + \gamma_2^*$. The pdf of γ can be obtained after convolution of $f_{\gamma_1^*}(\gamma)$ with $f_{\gamma_2^*}(\gamma)$, that is, by assuming the independence of γ_1^* with γ_2^* :

$$f_\gamma(\gamma) = \int_0^\gamma f_{\gamma_1^*}(\tau) f_{\gamma_2^*}(\gamma - \tau) d\tau, \quad (17)$$

In the following, first, the equivalent pdf of γ_1^* is obtained and, then, the pdf of γ_2^* is defined. Finally, the convolution expression in (17) is calculated. The best instantaneous equivalent SNR (γ_1^*) can be defined as

$$\gamma_1^* = \max \left\{ \gamma_{eq,1}, \gamma_{eq,2}, \dots, \gamma_{eq,\mathcal{N}_R \times \mathcal{N}_D} \right\}, \quad (18)$$

where $\gamma_{eq,j}$ is the equivalent SNR per bit for j th channel of the relaying links,⁴² and it is calculated as $\gamma_{eq,j} = \frac{1}{\psi} \left\{ Q^{-1} \left[\mathcal{P}_{eq,j}^b(\gamma_{SR_j}, \gamma_{R_jD}) \right] \right\}^2$, where ψ is a constant depending on underlying constellation; for example, $\psi = 4$ for 4-QAM, and $Q(t) = \int_t^\infty \frac{1}{\sqrt{2\pi}} e^{(-z^2/2)} dz$, and $\mathcal{P}_{eq,j}^b(\gamma_{SR_j}, \gamma_{R_jD})$ is the end-to-end BEP of $ST \rightarrow RT_j \rightarrow DT$ link for any type of modulation and it is defined as

$$\mathcal{P}_{eq,j}^b(\gamma_{SR_j}, \gamma_{R_jD}) = \left[1 - \mathcal{P}_{SR_j}^b(\gamma_{SR_j}) \right] \mathcal{P}_{R_jD}^b(\gamma_{R_jD}) + \left[1 - \mathcal{P}_{R_jD}^b(\gamma_{R_jD}) \right] \mathcal{P}_{SR_j}^b(\gamma_{SR_j}), \quad (19)$$

where $\mathcal{P}_{SR_j}^b(\gamma_{SR_j}) = 2pQ(\sqrt{q\gamma_{SR_j}}) - 2p^2Q^2(\sqrt{q\gamma_{SR_j}})$ and $\mathcal{P}_{R_jD}^b(\gamma_{R_jD}) = 2pQ(\sqrt{q\gamma_{R_jD}}) - 2p^2Q^2(\sqrt{q\gamma_{R_jD}})$ with $p = 2\left(1 - \frac{1}{\sqrt{M}}\right)$ and $q = \frac{3\log_2 M 4^1}{(M-1)}$ are the of instantaneous BEPs of the ST→RT link and the RT→DT link, respectively. If these links are independently faded; then, CDF of instantaneous equivalent SNR can be written as

$$\begin{aligned} F_{\gamma_1^*}(\gamma) &= \mathcal{P}\left[\gamma_{\text{eq},1} \leq \gamma, \dots, \gamma_{\text{eq},\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \leq \gamma\right] \\ &= \prod_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} F_{\text{eq},j}(\gamma), \end{aligned} \quad (20)$$

where $F_{\text{eq},j}(\gamma)$ represents the CDF of $\gamma_{\text{eq},j}$. When the strongest diversity branch is selected from a total $\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}$ available i.n.d. diversity branches to decide the best antenna by DT, the joint pdf of γ_1^* can be derived by differentiating (20) as follows:

$$\begin{aligned} f_{\gamma_1^*}(\gamma) &= \frac{\partial}{\partial \gamma} \left(\prod_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} F_{\text{eq},j}(\gamma) \right) \\ &= \sum_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} f_{\text{eq},j}(\gamma) \prod_{m=1, m \neq j}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \mathcal{P}(\gamma_m \leq \gamma), \end{aligned} \quad (21)$$

where for Rayleigh fading channel case, with the help of Wang et al.,⁴² we can write the pdf of equivalent SNR $f_{\text{eq},j}(\gamma)$ and $\mathcal{P}(\gamma_m \leq \gamma)$, respectively, as follows:

$$f_{\text{eq},j}(\gamma) \approx f_{\gamma_{\min,j}}(\gamma_{\min,j}) = \frac{1}{\bar{\gamma}_{\min,j}} e^{\left(\frac{\gamma_{\min,j}}{\bar{\gamma}_{\min,j}}\right)}, \quad (22a)$$

$$\mathcal{P}(\gamma_m \leq \gamma) = 1 - e^{\left(-\frac{\gamma}{\bar{\gamma}_j}\right)}. \quad (22b)$$

Finally, substituting (22a) and (22b) into (21), the selected pdf of γ_1^* is calculated as

$$\begin{aligned} f_{\gamma_1^*}(\gamma) &= \sum_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \frac{1}{\bar{\gamma}_{\min,j}} e^{\left(-\frac{\gamma}{\bar{\gamma}_{\min,j}}\right)} \prod_{\substack{m=1 \\ m \neq j}}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \left(1 - e^{\left(-\frac{\gamma}{\bar{\gamma}_{\min,m}}\right)}\right) \\ &= \sum_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \left[(-1)^{j-1} \sum_{\substack{i_1, i_2, \dots, i_j=1 \\ i_1 < i_2 < \dots < i_j}}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \left\{ \sum_{m=1}^j \left(\bar{\gamma}_{i_{\min,im}} \right)^{-1} e^{-\left(\sum_{m=1}^j \left(\bar{\gamma}_{i_{\min,im}} \right)^{-1} \gamma \right)} \right\} \right] \\ &= \sum_{j=1}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \left[(-1)^{(j-1)} \sum_{\substack{i_1, i_2, \dots, i_j=1 \\ i_1 < i_2 < \dots < i_j}}^{\mathcal{N}_{\mathcal{R}} \times \mathcal{N}_{\mathcal{D}}} \mathcal{W}_j e^{-\gamma \mathcal{W}_j} \right], \end{aligned} \quad (23)$$

where to simplify the representation of (23) \mathcal{W}_j is defined as $\mathcal{W}_j \triangleq \sum_{m=1}^j \left(\frac{1}{\bar{\gamma}_{\min,im}} \right)$.

The best instantaneous SNR (γ_2^*) of the ST _{\hat{e}} → DT link can be written in a similar manner of γ_1^* as $\gamma_2^* = \max\{\gamma_1, \gamma_2, \dots, \gamma_{\mathcal{N}_{\mathcal{D}}}\}$. As in (21), the joint pdf of γ_2^* is given by $f_{\gamma_2^*}(\gamma) = \sum_{i=1}^{\mathcal{N}_{\mathcal{D}}} f_i(\gamma) \prod_{m=1, m \neq i}^{\mathcal{N}_{\mathcal{D}}} \mathcal{P}(\gamma_m \leq \gamma)$, where the pdf of γ_i follows the Rayleigh distribution and defined as $f_i(\gamma) = \frac{1}{\bar{\gamma}_i} e^{(\gamma/\bar{\gamma}_i)}$. By performing similar operations used in $f_{\gamma_1^*}(\gamma)$, the selected pdf of γ_2^* can be written as follows:

$$f_{\gamma_2^*}(\gamma) = \sum_{i=1}^{\mathcal{N}_{\mathcal{D}}} \left[(-1)^{(i-1)} \sum_{\substack{i_1, i_2, \dots, i_i=1 \\ i_1 < i_2 < \dots < i_i}}^{\mathcal{N}_{\mathcal{D}}} \mathcal{U}_i e^{(-\gamma \mathcal{U}_i)} \right], \quad (24)$$

where $\mathcal{U}_i \triangleq \sum_{m=1}^i \left(\frac{1}{\bar{\gamma}_{i_m}} \right)$. Substituting (23) and (24) into (17), the combined pdf of SNR after C-MRC combiner can be finally calculated as follows:

$$f_\gamma(\gamma) = \sum_{j=1}^{\mathcal{N}_R \times \mathcal{N}_D} (-1)^{(j-1)} \sum_{\substack{i_1, i_2, \dots, i_j=1 \\ i_1 < i_2 < \dots < i_j}}^{\mathcal{N}_R \times \mathcal{N}_D} \left[\sum_{i=1}^{\mathcal{N}_D} (-1)^{(i-1)} \sum_{\substack{i_1, i_2, \dots, i_i=1 \\ i_1 < i_2 < \dots < i_i}}^{\mathcal{N}_D} \mathcal{W}_j \mathcal{U}_i \int_0^\gamma e^{-\tau \mathcal{W}_j} e^{-(\gamma-\tau) \mathcal{U}_i} d\tau \right]. \quad (25)$$

The integral in (25) is calculated after some tedious manipulations as follows:

$$\begin{aligned} \Delta(\mathcal{W}_j, \mathcal{U}_i) &\triangleq \mathcal{W}_j \mathcal{U}_i \int_0^\gamma e^{-\tau \mathcal{W}_j} e^{-(\gamma-\tau) \mathcal{U}_i} d\tau \\ &= \begin{cases} \frac{\mathcal{W}_j \mathcal{U}_i}{\mathcal{W}_j - \mathcal{U}_i} [e^{-\gamma \mathcal{W}_j} - e^{-\gamma \mathcal{U}_i}], & \text{if } \mathcal{W}_j \neq \mathcal{U}_i \\ \mathcal{W}_j \mathcal{U}_i \gamma e^{-\gamma \mathcal{W}_j}, & \text{if } \mathcal{W}_j = \mathcal{U}_i. \end{cases} \end{aligned} \quad (26)$$

The pdf obtained in (25) represents the pdf of end-to-end SNR of AS-CSM scheme, and it can be employed for deriving the expression for M -ary BEP calculation.

3.3.2 | Average BEP analysis of the proposed AS-CSM scheme for M -QAM signal

Using (16), the average BEP of M -QAM signaling is formulated by averaging the error rate in presence of AWGN channel over the pdf of SNR in Rayleigh fading as $\bar{\mathcal{B}}_\chi(e) = \int_0^\infty \bar{\mathcal{B}}_\chi(e|\gamma) f_\gamma(\gamma) d\gamma$, where the BEP conditioned on γ for square M -QAM, where $M = 4^m$ with $m = 1, 2, \dots$, in the AWGN channel is given in Cho and Yoon⁴³ as

$$\bar{\mathcal{B}}_\chi(e|\gamma) = \mathcal{Z} \sum_{d=1}^{\log_2 \sqrt{M}} \sum_{t=0}^{(1-2^{-d})\sqrt{M}-1} \mathcal{G}_t^d \operatorname{erfc}(\sqrt{\mathcal{K}_t \gamma}), \quad (27)$$

where $\mathcal{Z} = \frac{1}{\sqrt{M \log_2 \sqrt{M}}}$, $\mathcal{G}_t^d = (-1)^{\lfloor \frac{t \times 2^{d-1}}{\sqrt{M}} \rfloor} \times \left(2^{d-1} - \lfloor \frac{t \times 2^{d-1}}{\sqrt{M}} \rfloor + \frac{1}{2} \right)$ and $\mathcal{K}_t = \frac{s(2t+1)^2 3 \log_2 M}{2(M-1)}$, where $\lfloor \nu \rfloor$ represents the largest integer to ν , and $\operatorname{erfc}(\cdot)$ is the complimentary error function and denoted as $\operatorname{erfc}(x) = \frac{2}{\pi} \int_0^{\pi/2} e^{\left(\frac{-x^2}{2 \sin^2 \theta} \right)} d\theta$. For AS-CSM scheme with i.n.d. Rayleigh channel, using (25) and (27), the final form of average BEP expression can be derived by interchanging the order of integration and some tedious manipulations as follows in case of $\mathcal{W}_j = \mathcal{U}_i$ and $\mathcal{W}_j \neq \mathcal{U}_i$:

$$\begin{aligned} \bar{\mathcal{B}}_\chi(e) &= \mathcal{Z} \sum_{d=1}^{\log_2 \sqrt{M} (1-2^{-d}) \sqrt{M}-1} \sum_{t=0}^{\log_2 \sqrt{M} (1-2^{-d}) \sqrt{M}-1} \left\{ \mathcal{G}_t^d \sum_{j=1}^{\mathcal{N}_R \times \mathcal{N}_D} (-1)^{(j-1)} \sum_{\substack{i_1, i_2, \dots, i_j=1 \\ i_1 < i_2 < \dots < i_j}}^{\mathcal{N}_R \times \mathcal{N}_D} \left[\sum_{i=1}^{\mathcal{N}_D} (-1)^{(i-1)} \sum_{\substack{i_1, i_2, \dots, i_i=1 \\ i_1 < i_2 < \dots < i_i}}^{\mathcal{N}_D} \int_0^\infty \operatorname{erfc}(\sqrt{\mathcal{K}_t \gamma}) \Delta(\mathcal{W}_j, \mathcal{U}_i) d\gamma \right] \right\} \\ &= \mathcal{Z} \sum_{d=1}^{\log_2 \sqrt{M} (1-2^{-d}) \sqrt{M}-1} \sum_{t=0}^{\log_2 \sqrt{M} (1-2^{-d}) \sqrt{M}-1} \left\{ \mathcal{G}_t^d \sum_{j=1}^{\mathcal{N}_R \times \mathcal{N}_D} (-1)^{(j-1)} \sum_{\substack{i_1, i_2, \dots, i_j=1 \\ i_1 < i_2 < \dots < i_j}}^{\mathcal{N}_R \times \mathcal{N}_D} \left[\sum_{i=1}^{\mathcal{N}_D} (-1)^{(i-1)} \sum_{\substack{i_1, i_2, \dots, i_i=1 \\ i_1 < i_2 < \dots < i_i}}^{\mathcal{N}_D} \right. \right. \\ &\quad \times \left. \begin{cases} \frac{1}{\mathcal{W}_j - \mathcal{U}_i} \left[\mathcal{W}_j \left(1 - \sqrt{\frac{\mathcal{K}_t \mathcal{W}_j^{-1}}{1 + \mathcal{K}_t \mathcal{W}_j^{-1}}} \right) - \mathcal{U}_i \left(1 - \sqrt{\frac{\mathcal{K}_t \mathcal{W}_j^{-1}}{1 + \mathcal{K}_t \mathcal{W}_j^{-1}}} \right) \right], & \text{if } \mathcal{W}_j \neq \mathcal{U}_i \\ \frac{\mathcal{U}_i \mathcal{W}_j \left(2 - 3 \sqrt{\frac{\mathcal{K}_t}{\mathcal{K}_t + \mathcal{U}_i}} \right) - 2 \mathcal{K}_t \mathcal{W}_j \left(\sqrt{\frac{\mathcal{K}_t}{\mathcal{K}_t + \mathcal{U}_i}} - 1 \right)}{2 \mathcal{U}_i (\mathcal{K}_t + \mathcal{U}_i)}, & \text{if } \mathcal{W}_j = \mathcal{U}_i. \end{cases} \right. \end{aligned} \quad (28)$$

3.3.3 | Average SEP (\bar{e}) analysis of ST→RT link for M-QAM signal

The average SEP \bar{e} of ST→RT link can be calculated as in (16) as follows:

$$\bar{e}_{T_j}(e) = \int_0^\infty \bar{e}(e|\gamma) f_\gamma(\gamma) d\gamma, \quad (29)$$

where $\bar{e}(e|\gamma) = 2pQ(\sqrt{q\gamma}) - 2p^2Q^2(\sqrt{q\gamma})$ and $f_\gamma(\gamma) = \frac{1}{\gamma_j} e^{-\gamma/\gamma_j}$ for i.n.d. Rayleigh fading case. Therefore, the average SEP \bar{e} can be derived as follows:

$$\begin{aligned} \bar{e}_{T_j}(e) &= \int_0^\infty (2pQ(\sqrt{q\gamma}) - 2p^2Q^2(\sqrt{q\gamma})) \frac{1}{\gamma_j} e^{-\gamma/\gamma_j} d\gamma \\ &= \frac{2p}{\gamma_j} \frac{1}{\pi} \int_0^{\pi/2} \frac{2\sin^2\theta}{q\gamma_j + 2\sin^2\theta} d\theta - \frac{p^2}{\gamma_j} \frac{1}{\pi} \int_0^{\pi/4} \frac{2\sin^2\theta}{q\gamma_j + 2\sin^2\theta} d\theta \\ &= \frac{p}{\gamma_j} \left(1 - \sqrt{\frac{q\gamma_j}{2 + q\gamma_j}} \right) - \frac{p^2}{\gamma_j} \frac{1}{4} \left[1 - \sqrt{\frac{q\gamma_j}{2 + q\gamma_j}} \left(\frac{4}{\pi} \tan^{-1} \sqrt{\frac{2 + q\gamma_j}{q\gamma_j}} \right) \right]. \end{aligned} \quad (30)$$

Finally, substituting (30), (28), (16), (14), and (13) into (7), we obtain average BEP expression of AS-CSM with C-MRC.

3.4 | Complexity and optimality analysis of AS-CSM system

We can express the total complexity of the AS-CSM system ($\mathcal{O}_{\text{AS-CSM}}$) as follows:

$$\mathcal{O}_{\text{AS-CSM}} = \mathcal{O}_{\text{RT}} + \mathcal{O}_{\text{DT}}, \quad (31)$$

where \mathcal{O}_{RT} refers to the complexity of RT; on the other hand, \mathcal{O}_{DT} refers to the complexity at DT. Considering (3), it seems that only the best antenna is active in RT since DT gives the best antenna information with feedback. Hence, the complexity of the ML detector in RT can be expressed in real-valued multiplications (RVMs) type as follows:

$$\mathcal{O}_{\text{RT}} = 6M. \quad (32)$$

In (3), the product of $\tilde{h}_{SR} s_n^{\hat{\ell}}$ takes 4 RVMs, while $\left| \tilde{y}_{SR}^{\hat{\ell}} - \sqrt{E_S} \tilde{h}_{SR} s_n^{\hat{\ell}} \right|^2 = \left[\Re(\tilde{y}_{SR}^{\hat{\ell}} - \sqrt{E_S} \tilde{h}_{SR} s_n^{\hat{\ell}}) \right]^2 + \left[\Im(\tilde{y}_{SR}^{\hat{\ell}} - \sqrt{E_S} \tilde{h}_{SR} s_n^{\hat{\ell}}) \right]^2$ expression takes place with two RVMs. Therefore, a total of 6 RVMs are required for a single symbol. For the possible M symbol, the complexity of RT will be $6M$ RVMs. If the best antenna of RT is not selected for relaying, the RVMs expression would be $\mathcal{O}_{\text{RT}} = 6N_R$ for the single symbol; on the other hand, the total complexity would be $6MN_R$. As seen here, the complexity of RT is significantly reduced.

On the other hand, we can express the complexity of DT as follows:

$$\mathcal{O}_{\text{DT}} = \mathcal{O}_{\text{ind}} + \mathcal{O}_{\text{C-MRC}}, \quad (33)$$

where \mathcal{O}_{ind} refers to the complexity resulting from Equations (8) and (9) to obtain the active antenna index of ST. $\mathcal{O}_{\text{C-MRC}}$ refers to the detection complexity of the symbol transmitted using the C-MRC technique on the DT presented in the (5). Considering the (8) and (9), the computational complexity of the $\hat{\ell}$ ($\hat{\ell} = \arg\min_{\ell} \{|\Theta_{\ell}|\}$, here $\Theta_{\ell} = \frac{\mathbf{h}_{SD}^H \mathbf{y}_{SD}}{\|\mathbf{h}_{SD_{\ell}}\|_F}$, $\ell \in \{1, 2, \dots, N_S\}$) expressed as \mathcal{O}_{ind} can be obtained step by step as follows:

1. $\mathbf{h}_{SD_\ell}^H \mathbf{y}_{SD}$ takes $4\mathcal{N}_D$ RVMS,
2. $|\mathbf{h}_{SD_\ell}^H \mathbf{y}_{SD}|$ takes 2 RVMS,
3. $\|\mathbf{h}_{SD_\ell}\|_F$ takes $2\mathcal{N}_D$ RVMS,
4. The division $\frac{\mathbf{h}_{SD_\ell}^H \mathbf{y}_{SD}}{\|\mathbf{h}_{SD_\ell}\|_F}$ takes 1 RVMS.

As a result, \mathcal{O}_{ind} can be written as follows:

$$\mathcal{O}_{\text{ind}} = (6\mathcal{N}_D + 3)\mathcal{N}_S. \quad (34)$$

Finally, for (5), $\mathcal{O}_{\text{C-MRC}}$ is obtained step by step as follows:

1. $w_{SD}\tilde{y}_{SD}^{\hat{\ell}}$ takes 4 RVMS,
2. $w_{RD}\tilde{y}_{RD}$ takes 4 RVMS,
3. $(w_{SD}\sqrt{E_S}\tilde{h}_{SD}^{\hat{\ell}} + w_{RD}\sqrt{E_R}\tilde{h}_{RD})s$ takes 16 RVMS,
4. $|\cdot|^2$ takes 2 RVMS.

Considering the above products, $\mathcal{O}_{\text{C-MRC}}$ can be written as follows:

$$\mathcal{O}_{\text{C-MRC}} = 18M + 8. \quad (35)$$

Note that the product $w_{SD}\tilde{y}_{SD}^{\hat{\ell}}$ and $w_{RD}\tilde{y}_{RD}$ are calculated only once since it is independent of s . Also, since only one receiver antenna is active in DT, the complexity analysis is not multiplied by \mathcal{N}_D . This significantly reduces the complexity of DT.

As a result, the overall complexity of the AS-CSM system can be expressed final form as follows:

$$\mathcal{O}_{\text{AS-CSM}} = (6\mathcal{N}_D + 3)\mathcal{N}_S + 24M + 8. \quad (36)$$

The C-MRC based combining method used in DT is not as optimal as ML detector. However, it gives a near-optimal result.⁴² On the other hand, ML detector is performed for data detection in RT. However, ML detector uses $\hat{\ell}$ in the decision rule while decoding the data. $\hat{\ell}$ is obtained with a near-optimal estimate. Therefore, the symbol decoded in RT is obtained with near-optimal accuracy. As a result, the estimated data decoded from the symbols and indices is obtained with a near-optimal accuracy in DT.

4 | SIMULATION RESULTS

In this section, we present simulation results for DF based AS-CSM system with different numbers of antennas ($\mathcal{N}_S, \mathcal{N}_R, \mathcal{N}_D$) for the source, relay and destination terminals and make comparisons with AS-CSM with traditional MRC combining technique. Furthermore, SNR-based antenna selection cooperative MIMO (AS-Coop MIMO) relaying system curves (without SM) with C-MRC and MRC are given and depicted in some figures for comparison. The end-to-end BER performance of the proposed system is evaluated by Monte-Carlo simulation for M -QAM over both independent and identically distributed (from Figures 2 to 5) and independent and nonidentically distributed (Figures 6 and 7) Rayleigh fading channels. The SNR term given in the figures is $\text{SNR}_{dB} = 10\log_{10}(E_s/N_0)$, where E_s is the transmitted symbol energy of the signal and all performance comparisons are made at a BER of 10^{-5} values.

From Figures 2 to 5, it has been assumed that $\mu_{SD_i} = \mu_{SR_j} = \mu_{R_jD_i} = \mu$ and $E_S = E_R = E_s$, where $i = 1, 2, \dots, \mathcal{N}_D$ and $j = 1, 2, \dots, \mathcal{N}_R$. It has been also assumed that every fading coefficient of the channel between nodes is fixed within

FIGURE 2 Theoretical and simulation BER performance curves of AS-CSM scheme at 4 bits/s/Hz for 4-QAM constellation with $N_S = 4$

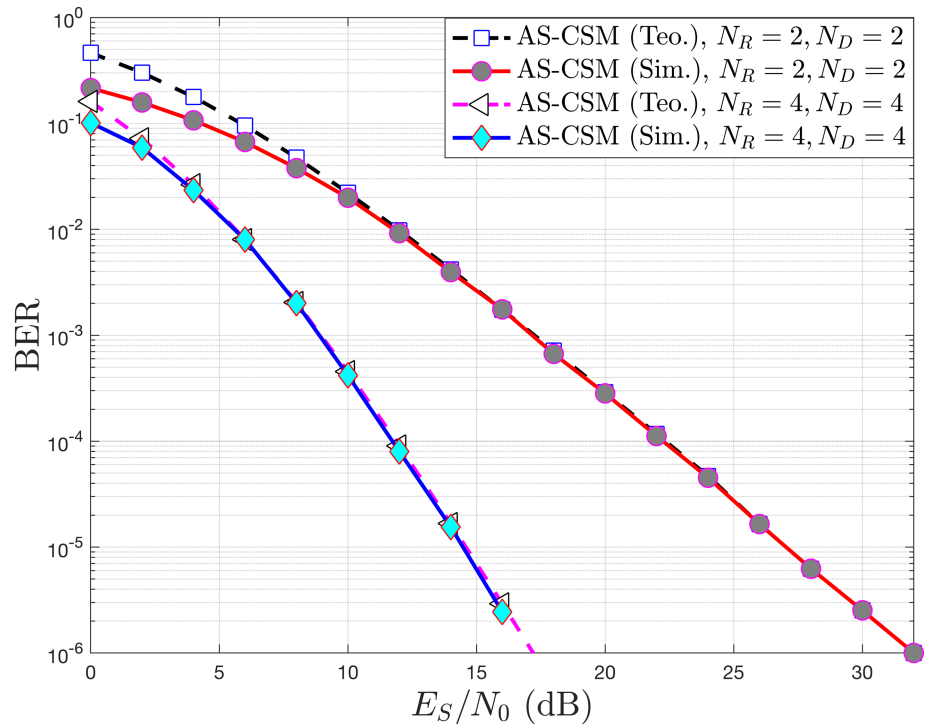
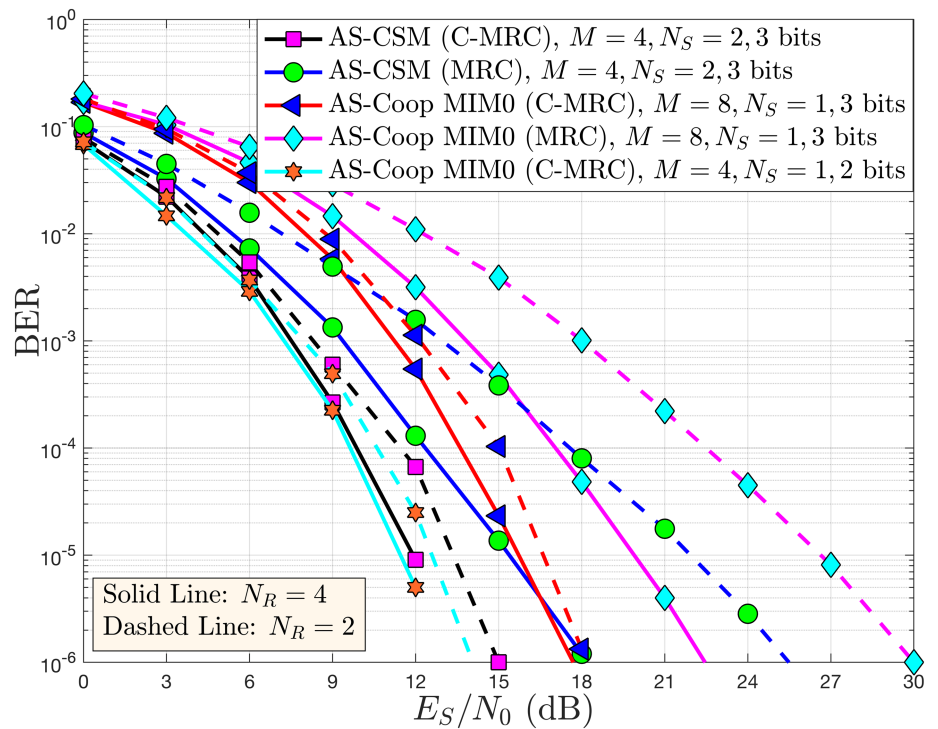


FIGURE 3 BER performance at 2 and 3 bits/s/Hz for AS-CSM and AS-Coop MIMO schemes using C-MRC and MRC when $N_D = 4$



coherence time interval and experiences slow and flat fading. The simulation results are obtained for 4-QAM, 8-QAM, 16-QAM, 64-QAM, and 256-QAM modulations.

We first present the theoretical and simulation BER performance curves of the proposed AS-CSM scheme with C-MRC at 4 bits/s/Hz for 4-QAM with $N_S = 4$ in Figure 2 when the number of relay and destination antennas are $N_R = 2, 4$ and $N_D = 2, 4$, respectively. It can be seen from this figure that the derived theoretical results become very tight to simulation results with increasing the number antennas of RT and DT as well as SNR values for all cases.

In Figure 3, BER performance curves of AS-CSM with $N_S = 2$, 4-QAM and AS-Coop MIMO with $N_S = 1$, 8-QAM and 4-QAM are presented when $N_R = 2$ (dashed line), $N_R = 4$ (solid line) and $N_D = 4$. In AS-CSM, the transmission

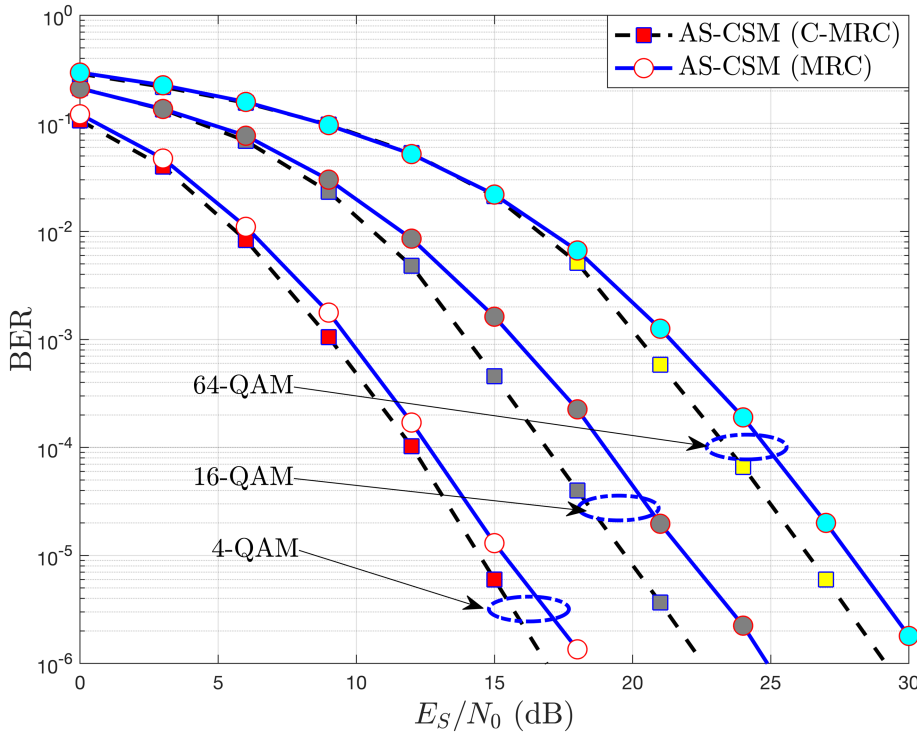


FIGURE 4 BER performance of AS-CSM scheme with C-MRC and MRC at 4, 6, and 8 bits/s/Hz for 4-QAM, 16-QAM, 64-QAM modulation with $\mathcal{N}_S = \mathcal{N}_R = \mathcal{N}_D = 4$

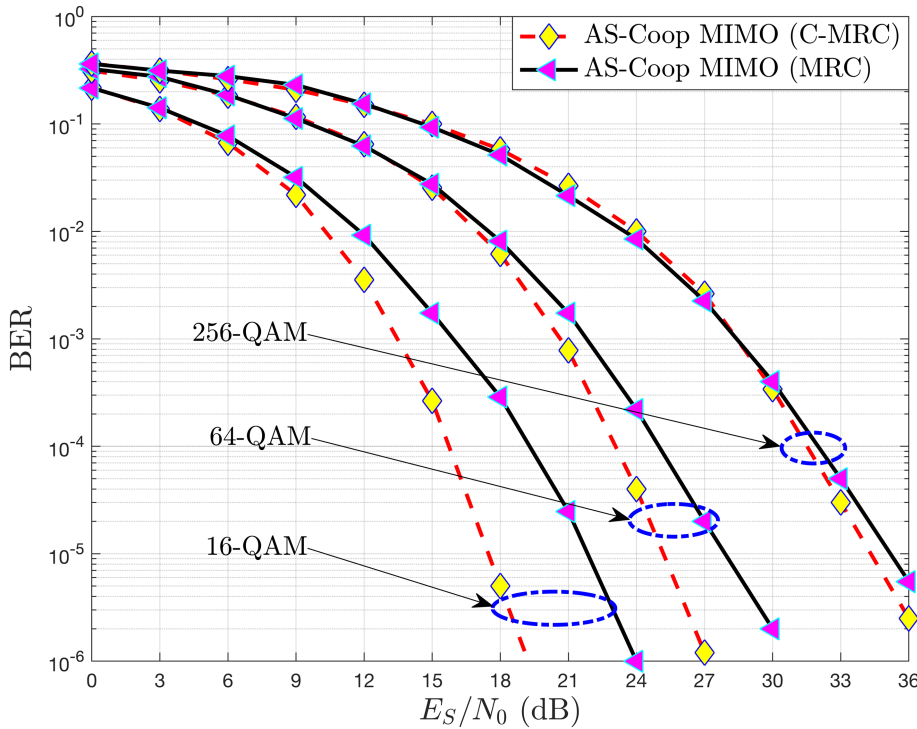


FIGURE 5 BER performance of AS-Coop MIMO scheme with C-MRC and MRC at 4, 6, and 8 bits/s/Hz for 16-QAM, 64-QAM, 256-QAM modulation with $\mathcal{N}_S = 1, \mathcal{N}_R = \mathcal{N}_D = 4$

rate is $\tilde{m} = \log_2 \mathcal{N}_S + \log_2 M = 3$ bits/s/Hz. As a reference, BER performance curves of AS-CSM and AS-Coop MIMO schemes with C-MRC are also compared with traditional MRC combining technique and depicted in the same figure. When the number of antennas of ST increases from $\mathcal{N}_S = 1$ to $\mathcal{N}_S = 2$, the bit-based achievable throughput of the AS-CSM scheme increases from 2 to 3 bits/s/Hz. The results obtained clearly show that when number of antennas of RT increases, where only the best one is active during the entire transmission period, the proposed method approximates successfully the BER results obtained with AS-Coop MIMO at 2 bits/s/Hz ($M = 4, \mathcal{N}_S = 1$) as shown in Figure 3. SNR differences between the proposed AS-CSM scheme with C-MRC and AS-Coop MIMO with C-MRC at 3

FIGURE 6 BER performance of AS-CSM scheme with C-MRC at 4 and 6 bits/s/Hz with $\mathcal{N}_S = \mathcal{N}_R = \mathcal{N}_D = 4$, 4-QAM and 16-QAM over i.n.d. Rayleigh fading channels

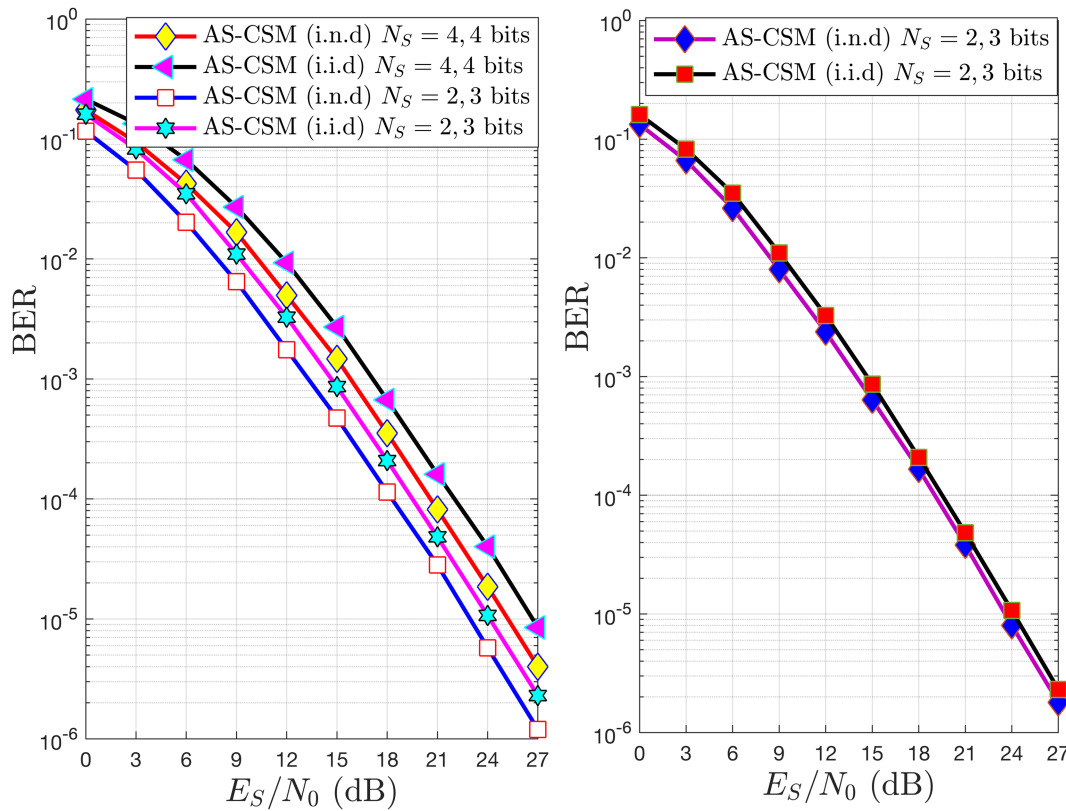
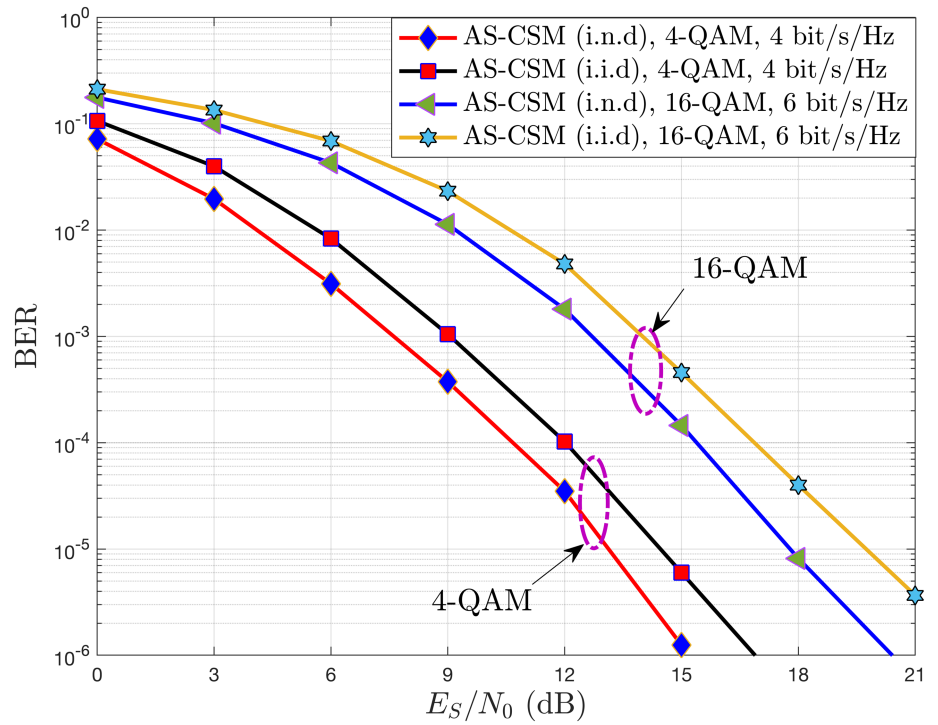


FIGURE 7 BER performance of AS-CSM scheme with C-MRC at 3 and 4 bits/s/Hz with $\mathcal{N}_R = \mathcal{N}_D = 2$ and 4-QAM over i.n.d. Rayleigh fading channels

bits/s/Hz are 3.5 and 4 dB when $\mathcal{N}_R = 2, 4$, respectively. It is seen from this figure that AS-CSM with MRC provides SNR gains of 4 dB over AS-Coop MIMO with MRC when $\mathcal{N}_R = 4$. We also observe that AS-Coop MIMO with C-MRC at 2 bits/s/Hz provides SNR gains of 0.8 and 0.4 dB over AS-CSM with C-MRC at 3 bits/s/Hz when $\mathcal{N}_R = 2, 4$.

TABLE 1 Comparison of throughput with AS-CSM and AS-Coop MIMO

		Comparison of Throughput	
		AS-Coop MIMO, bits/s/Hz	AS-CSM, bits/s/Hz
$\mathcal{N}_S = 2$	4-QAM	2	3
	16-QAM	4	5
	64-QAM	6	7
$\mathcal{N}_S = 4$	4-QAM	2	4
	16-QAM	4	6
	64-QAM	6	8
$\mathcal{N}_S = 16$	4-QAM	2	6
	16-QAM	4	8
	64-QAM	6	10

In Figure 4 with $\mathcal{N}_S = 4$ and Figure 5 with $\mathcal{N}_S = 1$, the average BER curves of the AS-CSM scheme with C-MRC and MRC for 4-QAM, 16-QAM, 64-QAM and AS-Coop MIMO with C-MRC and MRC for 16-QAM, 64-QAM and 256-QAM are depicted for 4, 6, and 8 bits/s/Hz when $\mathcal{N}_R = \mathcal{N}_D = 4$, respectively. We can see from Figure 4 that the bit-based achievable throughput of the proposed system increases from 2 to 4 bits/s/Hz, 4 to 6 bits/s/Hz, and 6 to 8 bits/s/Hz when the number of antennas of ST increases from $\mathcal{N}_S = 2$ to $\mathcal{N}_S = 4$ according to AS-Coop MIMO system, respectively. For BER results with C-MRC given in Figures 4 and 5, SNR differences between AS-CSM and AS-Coop MIMO at 4, 6, and 8 bits/s/Hz are 3, 5.35, and 8 dB.

The comparisons of throughput for bits/s/Hz according to some values of M and \mathcal{N}_S are given in Table 1. The results obtained from Figures 2 to 5 and Table 1 clearly show that when the number of antennas \mathcal{N}_S of ST and the value of M increase, the proposed method significantly provides high achievable data rate despite a single active antenna of ST.

The average BER performance curves of the proposed AS-CSM scheme with C-MRC technique at 4 and 6 bits/s/Hz over the i.n.d. Rayleigh fading channels in case of $\mathcal{N}_S = \mathcal{N}_R = \mathcal{N}_D = 4$, 4-QAM and 16-QAM are shown in Figure 6. In this figure, corresponding to the i.n.d. channel parameters from the active antenna of ST to DT and RT as well as the best antenna of RT to DT are chosen as $\mu_{S_eD} = [1.2 \ 0.8 \ 1.4 \ 0.6]^T$, $\mu_{S_eR} = [1.3 \ 0.7 \ 1.5 \ 0.5]^T$ and $\mu_{R^*D} = [1.1 \ 0.8 \ 1.4 \ 0.7]^T$, respectively. In Figure 7A, with $\mathcal{N}_S = 2, 4$, $\mathcal{N}_R = \mathcal{N}_D = 2$, 4-QAM at 3 and 4 bits/s/Hz, the results, where corresponding to the i.n.d. channel parameters are chosen as $\mu_{S_eD} = [0.6 \ 1.4]^T$, $\mu_{S_eR} = [0.6 \ 1.4]^T$ and $\mu_{R^*D} = [0.8 \ 1.2]^T$, respectively, are shown. If values of μ for both the active antenna of ST and the best antenna of RT are chosen better than other inactive antennas of ST and RT terminals by arranging the power of ST→DT, ST→RT and RT→DT links, performance of the proposed AS-CSM scheme increases sufficiently (see Figures 2,3,6, and 7A). In addition, even the total power of proposed system is reduced, we can still obtain the same BER performance or better than the system which has fixed power (see Figures 2,3, and 7B). In Figure 7B with 4-QAM at 3 bits/s/Hz, i.n.d. channel parameters are chosen as $\mu_{S_eD} = [0.8 \ 1.2]^T$, $\mu_{S_eR} = [0.7 \ 1.3]^T$ and $\mu_{R^*D} = [0.8 \ 1.2]^T$, respectively. In Figures 6 and 7, the average BER performance of the AS-CSM system with different power values of ST→DT, ST→RT and RT→DT channels are shown while other channel power values are fixed.

5 | CONCLUSIONS AND FUTURE WORK

In this study, we have introduced a new high-rate, high spectral efficiency, low power, and low complexity cooperative relaying technique called AS-CSM by using the C-MRC combining technique. The proposed new relaying scheme consists of the combination of SM at ST and antenna selection technique at RT. A general method has been presented for construction of the AS-CSM scheme for any number antennas of ST and RT. Exact closed-form BER expression of the considered system with C-MRC methods over i.n.d and i.i.d. Rayleigh fading channels has been obtained using M -QAM modulation. We have also made comparisons with AS-CSM with MRC technique as well as SNR-based antenna

selection cooperative MIMO relaying system. It has been shown via theoretical BER analysis and also supported by computer simulations that the AS-CSM scheme offers significant improvements spectral efficiency. On the other hand, in our proposed scheme, since the number of required RF chains at ST-DT and RT-DT nodes is only two, ICI and necessity for synchronization of all antennas are completely avoided for cooperative relaying networks. Thus, power consumption, complexity and therefore cost have been reduced. We conclude that the AS-CSM scheme can be useful for high-rate, high spectral efficiency, low power and low complexity emerging wireless cooperative communication systems.

For future work, we plan to apply the proposed AS-CSM to the QSM technique. We also consider combining the index modulation technique, which is popular recently, with the proposed technique. Thus, we plan to introduced a new technique that has faster and better error performance than the proposed technique.

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REFERENCES

- Buzzi S, Chih-Lin I, Klein TE, Poor HV, Yang C, Zappone A. A survey of energy-efficient techniques for 5G networks and challenges ahead. *IEEE J Sel Areas Commun*. 2016;34(4):697-709.
- Sharma SK, Woungang I, Anpalagan A, Chatzinotas S. Toward tactile internet in beyond 5G era: recent advances, current issues, and future directions. *IEEE Access*. 2020;8:56948-56991. <http://doi.org/10.1109/ACCESS.2020.2980369>
- Chen X, Yu W, Larsson EG, Al-Dhahir N, Ng DWK, Schober R. Massive access for 5g and beyond. arXiv preprint arXiv:2002.03491; 2020.
- Aydin E, Cogen F, Basar E. Code-index modulation aided quadrature spatial modulation for high-rate MIMO systems. *IEEE Trans Veh Technol*. 2019;68(10):10257-10261.
- Telatar IE. Capacity of multi-antenna Gaussian channels. *European Trans Telecommun*. 1999;10:585-595.
- Boccardi F, Clerckx B, Ghosh A, et al. Multiple-antenna techniques in LTE-advanced. *IEEE Commun Mag*. 2012;50(3):114-121.
- Loa K, Wu CC, Sheu ST, et al. IMT-advanced relay standards [WiMax/LTE update]. *IEEE Commun Mag*. 2010;48(8):40-48.
- Ding Z, Krikidis I, Rong B, Thompson JS, Wang C, Yang S. On combating the half-duplex constraint in modern cooperative networks: protocols and techniques. *IEEE Wireless Commun*. 2012;19(6):20-27.
- Yang Y, Hu H, Xu J, Mao G. Relay technologies for WiMax and LTE-advanced mobile systems. *IEEE Commun Mag*. 2009;47(10):100-105.
- Ilhan H. The performance of MIMO system using MRT scheme in vehicular systems. *Int J Commun Syst*. 2017;30(9):e3188. e3188 IJCS-16-0046.R1. <https://doi.org/10.1002/dac.3188>
- Aydin E, Ilhan H. SNR-based relay selection scheme for cooperative relay networks. *2015 International Wireless Commun. and Mobile Computing Conf (IWCMC)*. Dubrovnik, Croatia; 2015:448-453.
- Kumbhani B, Kshetrimayum RS. Error performance of two-hop decode and forward relaying systems with source and relay transmit antenna selection. *Electron Lett*. 2015;51(6):530-532.
- Mesleh RY, Haas H, Sinanovic S, Ahn CW, Yun S. Spatial modulation. *IEEE Trans Veh Technol*. 2008;57(4):2228-2241.
- Basar E. Index modulation techniques for 5G wireless networks. *IEEE Commun Mag*. 2016;54(7):168-175.
- Serafimovski N, Sinanovic S, Di Renzo M, Haas H. Dual-hop spatial modulation (Dh-SM). *2011 IEEE 73rd Vehicular Technology Conference (VTC Spring)*. Yokohama, Japan; 2011:1-5.
- Mesleh R, Ikki S, Alwakeel M. Performance analysis of space shift keying with amplify and forward relaying. *IEEE Commun Lett*. 2011;15(12):1350-1352.
- Mesleh R, Ikki SS. Space shift keying with amplify and forward MIMO relaying. *Trans Emerging Tel Tech*. 2015;26(4):520-531.
- Mesleh R, Ikki SS, Aggoune EHM, Mansour A. Performance analysis of space shift keying (SSK) modulation with multiple cooperative relays. *EURASIP J Adv Signal Process*. 2012;2012(1):1-10.
- Mesleh R, Ikki SS. Performance analysis of spatial modulation with multiple decode and forward relays. *IEEE Wireless Commun Lett*. 2013;2(4):423-426.
- Mesleh R, Ikki SS. Analysis of cooperative communication spatial modulation with imperfect channel estimation. *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*. London, UK; 2013:2023-2027. <https://doi.org/10.1109/PIMRC.2013.6666477>
- Yang P, Zhang B, Xiao Y, et al. Detect-and-forward relaying aided cooperative spatial modulation for wireless networks. *IEEE Trans Commun*. 2013;61(11):4500-4511.
- Som P, Chockalingam A. Bit error probability analysis of SSK in DF relaying with threshold-based best relay selection and selection combining. *IEEE Commun Lett*. 2014;18(1):18-21.
- Maheswaran P, Selvaraj MD. Cooperative time successive SSK-M-ary modulation for decode-and-forward relay systems. *IEEE Trans Veh Technol*. 2020;69(1):537-551.

24. Yarkin F, Altunbas I, Basar E. Cooperative space shift keying media-based modulation with hybrid relaying. *IEEE Syst J*. 2020;14(1): 500-509.
25. Altin G, Aygolu U, Basar E, Celebi ME. Outage probability analysis of cooperative spatial modulation systems. *2016 23rd International Conference on Telecommunications (ICT)*. Thessaloniki, Greece; 2016:1-5.
26. Li Q, Wen M, Basar E, Poor HV, Chen F. Spatial modulation-aided cooperative noma: performance analysis and comparative study. *IEEE J Sel Signal Process*. 2019;13(3):715-728.
27. Altin G, Basar E, Aygolu U, Celebi ME. Performance analysis of cooperative spatial modulation with multiple-antennas at relay. *2016 IEEE International Black Sea Conference on Communications and Networking (BlackSeaCom)*. Varna, Bulgaria; 2016:1-5.
28. Afana A, Erdogan E, Ikki S. Quadrature spatial modulation for cooperative MIMO 5G wireless networks. *2016 IEEE Globecom Workshops (GC Wkshps)*. Washington, DC, USA; 2016:1-5.
29. Afana A, Mesleh R, Ikki S, Atawi IE. Performance of quadrature spatial modulation in amplify-and-forward cooperative relaying. *IEEE Commun Lett*. 2016;20(2):240-243.
30. Rajesh R, Velmurugan PGS, Thiruvengadam SJ, Mallick PS. Spatial modulation and physical layer network coding based bidirectional relay network with transmit antenna selection over Nakagami-m fading channels. *Int J Commun Syst*. 2018;31(14):e3742. <https://doi.org/10.1002/dac.3742>
31. Rajashekar R, Hari KVS, Hanzo L. Antenna selection in spatial modulation systems. *IEEE Commun Lett*. 2013;17(3):521-524.
32. Pillay N, Xu H. Comments on antenna selection in spatial modulation systems. *IEEE Commun Lett*. 2013;17(9):1681-1683.
33. Ntontin K, Renzo MD, Perez-Neira A, Verikoukis C. Performance analysis of multistream spatial modulation with maximum-likelihood detection. *2013 IEEE Global Communications Conference (GLOBECOM)*. Atlanta, GA, USA; 2013:1590-1594.
34. Ntontin K, Renzo MD, Perez-Neira AI, Verikoukis C. A low-complexity method for antenna selection in spatial modulation systems. *IEEE Commun Lett*. 2013;17(12):2312-2315.
35. Aydin E, Ilhan H. A novel SM-based MIMO system with index modulation. *IEEE Commun Lett*. 2016;20(2):244-247.
36. Kumbhani B, Kshetrimayum RS. Outage probability analysis of spatial modulation systems with antenna selection. *Electron Lett*. 2014; 50(2):125-126.
37. Yarkin F, Altunbas I, Basar E. Source transmit antenna selection for space shift keying with cooperative relays. *IEEE Commun Lett*. 2017;PP(99):1-4.
38. Hanzo L, Alamri O, El-Hajjar M, Wu N. *Near-Capacity Multi-Functional Mimo Systems: Sphere-Packing, Iterative Detection and Cooperation*. Chichester, UK: John Wiley and IEEE Press; 2009.
39. Naidoo NR, Xu HJ, Quazi TAM. Spatial modulation: optimal detector asymptotic performance and multiple-stage detection. *IET Commun*. 2011;5(10):1368-1376.
40. Jeganathan J, Ghayeb A, Szczecinski L. Generalized space shift keying modulation for MIMO channels. *2008 IEEE 19th International Symposium on Personal, Indoor and Mobile Radio Communications*. Cannes, France; 2008:1-5.
41. Proakis JG. *Digital Communications*. New York: McGraw-Hill; 2001.
42. Wang T, Cano A, Giannakis GB, Laneman JN. High-performance cooperative demodulation with decode-and-forward relays. *IEEE Trans Commun*. 2007;55(7):1427-1438.
43. Cho K, Yoon D. On the general BER expression of one- and two-dimensional amplitude modulations. *IEEE Trans Commun*. 2002;50(7): 1074-1080.

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