Performance Analysis of Cooperative Spatial Modulation with Multiple-Antennas at Relay

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***Abstract*—Spatial modulation (SM) is a novel and promising approach that has been introduced as an alternative to classical multiple-input multiple-output (MIMO) spatial multiplexing techniques. Cooperative communications, on the other hand, provides additional diversity gains and high data rates by improving coverage. Combining the advantages of SM and cooperative communications would then further improve efficiency. Most of the studies in the literature of cooperative SM systems consider the space shift keying (SSK) modulation, which is a special case of SM, and single receive/transmit antenna relay (R) and destination (D). In this work, we investigate the average bit error probability (ABEP) of a decode-and-forward (DF) cooperative SM system where all nodes have multiple transmit and/or receive antennas which has not been studied before. It is shown that the derived analytical expressions for the ABEP are in close match with the computer simulation results. Furthermore, it is demonstrated that the cooperative SM scheme provides 4 dB SNR gain compared to classical *M*-ary modulated cooperative systems.**

I. Introduction

Multiple-input multiple-output (MIMO) transmission techniques provide significiant improvements in channel capacity and error performance for modern communication systems. Two main MIMO strategies in the literature are space time block coding (STBC) and spatial multiplexing. The former is proposed to improve reliability providing transmit diversity while extending the conventional two dimensional signal constellation into space and time dimensions [1]. However, for more than two transmit antennas, the symbol rate of an orthogonal STBC is upper bounded by $3/4$ symbols per channel use. The latter has been introduced for high spectral efficiency to satisfy the increasing demand for higher data rates. The Bell Labs layered space-time (BLAST) schemes are well-known forms of spatial multiplexing. In vertical-BLAST (V-BLAST) [2], the multiple data streams are transmitted over multiple transmit antennas to increase the capacity. As a result of simultaneous transmission over all antennas, a high level inter channel interference (ICI), which increases the complexity of the receiver, occurs. Spatial modulation (SM), on the other hand, is a new approach for MIMO systems and an interesting alternative to classical transmission techniques (such as V-BLAST and STBC systems) where information bits are carried with both antenna indices and conventional two-dimensional signal constellations [3]. In SM systems, $\log_2(N_t M)$ information bits are mapped to an SM symbol where N_t is the number of transmit antennas and M is the constellation size for conventional PSK/QAM modulations. The first $\log_2(N_t)$ bits are allocated for the transmit antenna index and the remaining bits are used for M-PSK/QAM modulations. Since a single transmit antenna is activated during each symbol transmission, ICI is completely eliminated in SM systems. A special case of SM, called space shift keying (SSK), activates only one transmit antenna and uses this activated antenna index to convey information by using simple carrier signal rather than the classical PSK/QAM modulated signals [4]. The SSK technique simplifies the transceiver design and reduces the decoding complexity. However, this simplification reduces the data rate of SSK compared to SM for the same number of transmit antennas. In addition to the advantages of SM over V-BLAST, SM and STBC is combined in [5] to achieve transmit diversity gains.

Cooperative communications has been intensively studied by the researchers over the past decade. In cooperative communications, a source (S) transmits its own data to a relay (R) and a destination (D) in the first time slot and R forwards the received signal either decoding (decode-and-forward, DF) or amplifying it (amplify-and-forward, AF) in the second time slot. This forwarding concept forms a virtual MIMO system to combat fading and provides a larger coverege area [6].

Combining the advantages of SM and cooperative communications has been recently studied in the literature [7]-[15]. The first study is performed by Serafimovski *et.al.* in [7] in which a dual-hop SM system is proposed (where there is no direct link between S and D). In this multi antenna dual-hop system, R uses DF protocol to support the communication between S and D. In [8], the SSK technique is utilized for a dual-hop system. A tight upper bound for the bit error rate (BER) is introduced for this multi antenna S and single antenna R and D system using the AF strategy. A real cooperative scenario in which S sents its information to R and D in the first time slot is considered in [9]. In this system, the multi antenna S transmits its data using SSK to N relays and D (all nodes have single transmit and receive antennas) in the first time slot and N relays amplify the incoming signal and retransmit to D in the following N time slots. In the same study, the use of DF strategy is investigated when the relays which correctly detect the source symbol are permitted to forward. Since the relays have single antenna, communication between R and D can not be performed with SSK. In [10], the same authors enhanced the dual-hop SSK system in [8] to an N-relay system considering opportunistic relaying to

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increase the spectral efficiency. A multi-antenna S and single antenna multiple-R and D cooperative system using SM with DF is considered in [11]. The first cooperative system in which multi antenna nodes use SSK with DF is introduced in [12]. However, the exact BER analysis is derived only for S and R with two transmit antennas with incremental relaying and selection combining at D. The combination of SM/SSK with physical layer network coding (PLNC), which is proposed to increase the spectral efficiency of cooperative communications where different users share the same relay to communicate with each other at the same time, can be found in [13]-[15].

As seen from the previous studies in the literature, the SSK technique is generally considered instead of the SM and single transmit antennas are assumed at relay(s) and destination. As known, the SM/SSK uses at least two transmit antennas. Therefore, a cooperative SM system in which the relay(s) operating with DF and having only one transmit antenna is not a complete SM system since the relay(s) can not re-encode the decoded data into the SM symbols. Moreover, an SM system needs at least two receive antennas for the error performance improvement. To the best of our knowledge, a comprehensive work in cooperative SM/SSK systems that suggests multiple transmit and receive antenna nodes has not been given in the literature yet. In this study, we consider a cooperative scenario in which the S, R and D have more than two transmit/receive antennas. S maps the information bits into an SM symbol and sends it to R and D in the first phase. R decodes the received signal using maximum likelihood (ML) detection and re-encodes the estimated signal to an SM symbol and forwards to D in the second phase. At D, the ML detection is employed to determine the transmitted signal. We derive an analytical expression for the bit error probability (BEP) of the above system. Furthermore, we compare the cooperative SM scheme with the classical cooperative *M*-ary modulation techniques. Our computer simulations and analytical expressions show that the proposed system provides error performance improvement over conventional systems.

The rest of the paper is organized as follows. In Sections II, the system model is given. In Section III, BEP analysis of cooperative SM system with AF and DF relaying is given. The theoretical results and computer simulations are presented in Section IV. Section V concludes the paper.

The notation used throughout the paper is as follows: A vector and a matrix will respectively be denoted by a lower-case boldface and an upper-case boldface letter. $(\cdot)^T$, $(\cdot)^H$ and $\|\cdot\|$ represent transpose, Hermitian transpose and Euclidean/Frobenius norm of a vector/matrix, respectively. $\mathbb{C}^{m\times n}$ represents the dimensions of a complex-valued matrix. $\Pr\{\cdot\}$ and $E\{\cdot\}$ denote the probability of an event and the expectation operation, respectively. $\Re(x)$ represents the real part of complex variable x. $\mathcal{CN}(0,\sigma^2)$ denotes the circularly symmetrical zero-mean complex Gaussian distribution with variance σ^2.

II. System Model

A cooperative communications system consisting of an S, an R and a D is given in Fig. 1. S and R have N_t^S and N_t^R transmit antennas while R and D have N_r^R and N_r^D receive

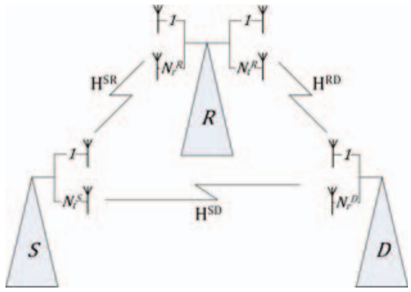

Fig. 1. Cooperative scenario.

antennas, respectively. Each element of the MIMO channel matrices between S and R, $\mathbf{H}^{SR}\in\mathbb{C}^{N_r^R\times N_t^S}$, S and D, $\mathbf{H}^{SD}\in\mathbb{C}^{N_r^D\times N_t^S}$, and R and D, $\mathbf{H}^{RD}\in\mathbb{C}^{N_r^D\times N_t^R}$, are modeled as $\mathcal{CN}(0,1)$ and obeys the flat Rayleigh fading channel model. A unit energy SM symbol with $E[\mathbf{x}^H\mathbf{x}]=1$ can be given as $\mathbf{x}=[\underbrace{0,\ 0,\ \ldots,\ 0,}_{l-1}\ x_q,\ \underbrace{0,\ \ldots,\ 0}_{N_t-l}]^T=[l,x_q]$, where l is the active antenna index and x_q is the M-PSK/QAM constellation symbol. In the first time slot, S transmits an SM symbol to R and D as

$$\mathbf{y}^{SD} = \mathbf{h}_l^{SD}x_q+\mathbf{n}^{SD} \quad (1)$$

$$\mathbf{y}^{SR} = \mathbf{h}_l^{SR}x_q+\mathbf{n}^{SR}, \quad (2)$$

respectively, where $N_r^{D(R)}\times 1$, $\mathbf{h}_l^{SD(SR)}$ vector is the l^{th} column of the corresponding MIMO channel matrix, $\mathbf{H}^{SD(SR)}=\begin{bmatrix}\mathbf{h}_1^{SD(SR)} & \mathbf{h}_2^{SD(SR)} & \ldots & \mathbf{h}_{N_t}^{SD(SR)}\end{bmatrix}$, with each element being independent and identically distributed (i.i.d) as $\mathcal{CN}(0,1)$ and $\mathbf{n}$ is the $N_r^{R,D}\times 1$ additive white Gaussian noise vector whose entries are modeled as $\mathcal{CN}(0,N_0)$ with noise spectral density $N_0/2$ per dimension. At R, the detector which has the perfect channel state information (CSI), estimates the antenna index, $\tilde{l}$, and the M-PSK/QAM symbol, $\tilde{x}_q$, with ML decision rule as,

$$[\tilde{l},\tilde{x}_q]=\arg\min_{l,q}\left\|\mathbf{y}^{SR}-\mathbf{h}_l^{SR}x_q\right\|^2 \quad (3)$$

and re-encodes to an SM signal and sends to D, which is received as

$$\mathbf{y}^{RD}=\mathbf{h}_{\tilde{l}}^{RD}\tilde{x}_q+\mathbf{n}^{RD}. \quad (4)$$

The ML detection rule at D is,

$$[\hat{l},\hat{x}_q]=\arg\min_{l,q}\left(\left\|\mathbf{y}^{SD}-\mathbf{h}_l^{SD}x_q\right\|^2+\left\|\mathbf{y}^{RD}-\mathbf{h}_l^{RD}x_q\right\|^2\right). \quad (5)$$

III. Average Bit Error Probability (ABEP) Derivation

The average bit error probability (ABEP) of the cooperative SM system where S and R have equal number of transmit antennas ($N_t^S=N_t^R=N_t$) and the modulation orders ($M^S=M^R=M$) can be evaluated using the union-bound method

$$APEP(D \mid R^c) = E\left\{\Pr\left\{\left\|\mathbf{y}^{SD} - \mathbf{h}_l^{SD} x_q\right\|^2 + \left\|\mathbf{y}^{RD} - \mathbf{h}_l^{RD} x_q\right\|^2 \geq \left\|\mathbf{y}^{SD} - \mathbf{h}_k^{SD} x_p\right\|^2 + \left\|\mathbf{y}^{RD} - \mathbf{h}_k^{RD} x_p\right\|^2 \mid \mathbf{H}^{SD}, \mathbf{H}^{RD}\right\}\right\}$$

$$= E\left\{\Pr\left\{\left\|\left(\mathbf{h}_l^{SD} x_q + \mathbf{n}^{SD}\right) - \mathbf{h}_l^{SD} x_q\right\|^2 + \left\|\left(\mathbf{h}_{\tilde{l}}^{RD} \tilde{x}_q + \mathbf{n}^{RD}\right) - \mathbf{h}_l^{RD} x_q\right\|^2 \right.\right.$$
$$\left.\left. \geq \left\|\left(\mathbf{h}_l^{SD} x_q + \mathbf{n}^{SD}\right) - \mathbf{h}_k^{SD} x_p\right\|^2 + \left\|\left(\mathbf{h}_{\tilde{l}}^{RD} \tilde{x}_q + \mathbf{n}^{RD}\right) - \mathbf{h}_k^{RD} x_p\right\|^2 \mid \mathbf{H}^{SD}, \mathbf{H}^{RD}\right\}\right\} \quad (9)$$

$$= E\left\{\Pr\left\{\left\|\mathbf{h}_l^{SD} x_q - \mathbf{h}_k^{SD} x_p\right\|^2 + \left\|\mathbf{h}_l^{RD} x_q - \mathbf{h}_k^{RD} x_p\right\|^2 \right.\right.$$
$$\left.\left. \geq 2\Re\left\{\left(\mathbf{y}^{SD}\right)^H \left(\mathbf{h}_l^{SD} x_q - \mathbf{h}_k^{SD} x_p\right) + \left(\mathbf{y}^{RD}\right)^H \left(\mathbf{h}_l^{RD} x_q - \mathbf{h}_k^{RD} x_p\right)\right\} \mid \mathbf{H}^{SD}, \mathbf{H}^{RD}\right\}\right\} \quad (10)$$

$$= E\left\{Q\left(\sqrt{\frac{\left\|\mathbf{h}_l^{SD} x_q - \mathbf{h}_k^{SD} x_p\right\|^2 + \left\|\mathbf{h}_l^{RD} x_q - \mathbf{h}_k^{RD} x_p\right\|^2}{2N_0}}\right)\right\} \quad (11)$$

(Ch.12 in [16]) as follows,

$$ABEP \leq \frac{1}{N_t M \log_2(N_t M)} \times \sum_{l=1}^{N_t} \sum_{q=1}^{M} \sum_{k=1}^{N_t} \sum_{p=1}^{M} N\left([l, x_q] \to [k, x_p]\right) APEP \quad (6)$$

where $N\left([l, x_q] \to [k, x_p]\right)$ is the number of bit errors between the SM symbols $[l, x_q]$ and $[k, x_p]$, and APEP is the average pairwise error probability when $[l, x_q]$ is transmitted and it is erroneously detected as $[k, x_p]$, which is computed next.

A. Average Pairwise Error Probability Analysis

The average pairwise error probability (APEP) at D for the cooperative SM system can be given as,

$$APEP \approx APEP(R) \times APEP(D \mid R^e) + (1 - APEP(R)) \times APEP(D \mid R^c) \quad (7)$$

where $APEP(R)$ is the APEP at the relay, $APEP(D \mid R^e)$ is the APEP at the destination when R makes a decision error and $APEP(D \mid R^c)$ is the APEP at the destination when R detects the SM symbol correctly. When R makes a decision error, this cause an error propagation and D will make an erroneous decision with a high probability. As a result of this error propagation, $APEP(D \mid R^e)$ approximates to a certain value which is independent of the SNR. This value is determined via Monte Carlo simulations and used in (7) (see Fig. 2).

The $APEP(R)$ is the APEP of the conventional SM and can be calculated as [17],

$$APEP(R) = E\left\{\Pr\left([l, x_q] \longrightarrow [k, x_p] \mid \mathbf{H}\right)\right\} = E\left\{Q\left(\sqrt{\frac{\left\|\mathbf{h}_l^{SR} x_q - \mathbf{h}_k^{SR} x_p\right\|^2}{2N_0}}\right)\right\} \quad (8)$$

where $Q(.)$ is the Q-function.

$APEP(D \mid R^c)$ can be calculated as in (9) which is given at the top of the page. Since (9) is the APEP when R detects the signal correctly, the antenna index and the symbol are estimated correctly, i.e. $\tilde{l} = l$ and $\tilde{x}_q = x_q$. Hence, $APEP(D \mid R^c)$ will be as in (10), where the right hand side is a random variable (r.v.) with $\mathcal{CN}\left(0, 2N_0\left(\left\|\mathbf{h}_l^{SD} x_q - \mathbf{h}_k^{SD} x_p\right\|_2^2 + \left\|\mathbf{h}_l^{RD} x_q - \mathbf{h}_k^{RD} x_p\right\|_2^2\right)\right)$ distribution.

To obtain the APEP, the probability density functions (pdf) of the random variables in Q-function of (8) and (11) have to be computed. Let $\kappa = \frac{\gamma}{2}\left\|\mathbf{h}_l^{SR} x_q - \mathbf{h}_k^{SR} x_p\right\|^2$ where $\gamma = \frac{1}{N_0}$ and pdf of κ be $p_\kappa(\kappa)$. The APEP at R can be calculated as

$$APEP(R) = \int_0^\infty Q\left(\sqrt{\kappa}\right) p_\kappa(\kappa) d\kappa \quad (12)$$

which can be computed with Craig's formula yielding the well-known moment generating function (MGF) approach [16],

$$APEP(R) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} M_\kappa\left(-\frac{1}{2\sin^2(\theta)}\right) d\theta. \quad (13)$$

For flat Rayleigh fading channel model, κ follows gamma distribution (in our special case, it is actually Erlang distribution) with *Gamma*$\left(N_r^R, \overline{\gamma}\right)$ where

$$\overline{\gamma} = \begin{cases} \frac{\gamma}{2}\left|x_q - x_p\right|^2 & \text{if } l = k \\ \frac{\gamma}{2}\left(\left|x_q\right|^2 + \left|x_p\right|^2\right) & \text{if } l \neq k. \end{cases} \quad (14)$$

The MGF of κ is obtained as [16],

$$M_\kappa(s) = (1 - \overline{\gamma} s)^{-N_r^R}. \quad (15)$$

(13) can be computed using ([16], Eq.5A.4b) as

$$APEP(R) = \frac{1}{2}\left[1 - \mu \sum_{j=0}^{N_r^R - 1} \binom{2j}{j} \left(\frac{1 - \mu^2}{4}\right)^j\right] \quad (16)$$

where $\mu = \sqrt{\frac{\overline{\gamma}/2}{\overline{\gamma}/2 + 1}}$ and $\binom{\cdot}{\cdot}$ denotes the binomial coefficient.

Same approach can be followed for $APEP(D \mid R^c)$. Consider, $\kappa' = \left\|\mathbf{h}_l^{SD} x_q - \mathbf{h}_k^{SD} x_p\right\|^2 + \left\|\mathbf{h}_l^{RD} x_q - \mathbf{h}_k^{RD} x_p\right\|^2$.

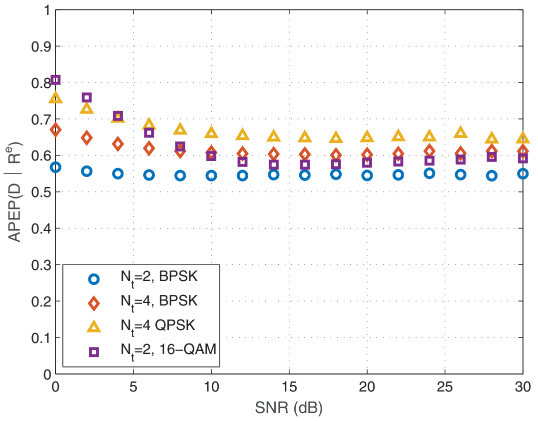

Fig. 2. Average pairwise error probability at D when R makes a decision error for different kinds of SM symbols.

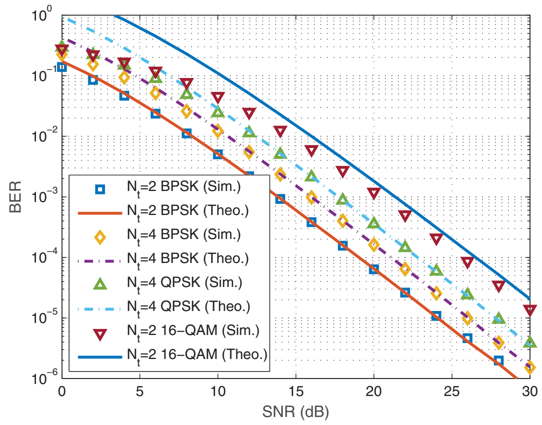

Fig. 3. BER performance of cooperative SM system with DF relaying for different number of transmit antennas and different modulations. Note that $N_t^S = N_t^R = N_t$ and $N_r^R = N_r^D = 2$.

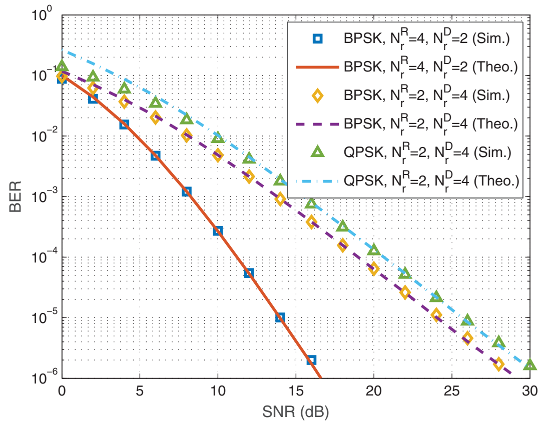

Fig. 4. BER performance of cooperative SM system with DF relaying for $N_t^S = N_t^R = N_t = 2$, different modulation orders with respect to different number of receive antennas at R and D.

Then, the pdf of κ' will be $Gamma(2N_r^D, \overline{\gamma})$. Therefore, its MGF is given as

$$M_{\kappa'}(s) = (1 - \overline{\gamma}s)^{-2N_r^D} . \tag{17}$$

Hence, $APEP(D \mid R^c)$ will become,

$$APEP(D \mid R^c) = \frac{1}{2}\left[1 - \mu \sum_{j=0}^{2N_r^D-1} \binom{2j}{j} \left(\frac{1-\mu^2}{4}\right)^j\right] \tag{18}$$

where μ is as defined in (16).

IV. Performance Evaluation

In this section, we present analytical and computer simulation results for the BEP of cooperative SM systems. Monte Carlo simulations are realized for at least 10^6 channel uses as a function of the received SNR and compared with the analytical results. In order to obtain the same spectral efficiency, the number of transmit antennas and the modulation orders are taken identical for S-R and R-D links, i.e. $N_t^S = N_t^R = N_t$ and $M^S = M^R = M$. Additionally, the distances from one node to other nodes are equal.

As mentioned in the previous section, when R makes a decision error, this cause an error propagation and D will make an erroneous decision with a high probability. As a result of this error propogation, $APEP(D \mid R^e)$ approximates to a certain value which is independent of the SNR. This is depicted in Fig. 2 where this value is calculated via Monte Carlo simulations as an average (over at least 10^6 channel uses) of the erroneously detected symbols at D when R makes a decision error. In Fig. 2, $APEP(D \mid R^e)$ is computed for different SM parameters as a function of received SNR.

In Fig. 3, BER performance of cooperative SM system with DF relaying is given where the number of receive antennas for R and D are the same, i.e., $N_r^R = N_r^D = N_r$. The computer simulations are evaluated for different number of transmit antennas, different types of modulations and as a result for different spectral efficiencies. As seen from Fig. 3, the theoretical curves and computer simulation results have exact match.

In Fig. 4, the impact of the amount of receive antenna on BER is investigated. The computer simulation results and theoretical curves for the same number of transmit antennas, different modulation orders and different N_r^R and N_r^D values are depicted in Fig. 4 where the analytical curves and computer simulation results are in close match. On the other hand, the slope of the curves, i.e., the diversity order, depends on the S-R link and the location of the R for the DF cooperative communications.

The BER performance comparison of cooperative SM and classical cooperative M-ary modulated systems is given in Figs. 5 and 6 where $R = 3$, 4 and 5 bits/s/Hz spectral efficiency values are considered for both figures. The only difference between the two figures is the number of receive antennas of R and D. In Fig. 5, two receive antennas are considered at R and D, i.e. $N_r^R = N_r^D = N_r = 2$ while in Fig. 6, four receive antennas are considered, i.e., $N_r^R =$

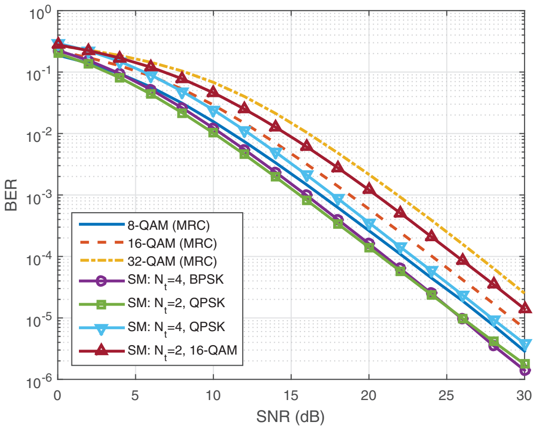

Fig. 5. BER performance comparison of cooperative SM with classical cooperative M-ary modulation for DF relaying systems. ($N_r^R = N_r^D = N_r = 2$)

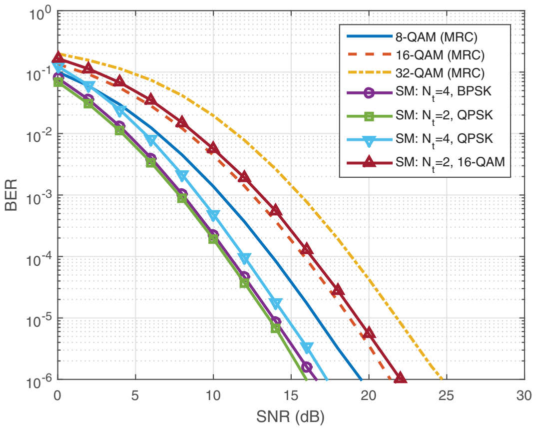

Fig. 6. BER performance comparison of cooperative SM with classical cooperative M-ary modulation for DF relaying systems. ($N_r^R = N_r^D = N_r = 4$)

$N_r^D = N_r = 4$. As seen from Fig. 5, cooperative SM system provides approximately 2 dB SNR gain over corresponding classical cooperative system when R and D has two receive antennas. When they have four receive antennas as in Fig. 6, the SNR gain increases to 4 dB.

V. Conclusion

In this study, we have proposed a new cooperative SM scheme and we have investigated its ABEP performance for the DF relaying. Most of the studies on cooperative SM systems in the literature consider the SSK instead of SM and single receive antenna in R and/or D. In this work, we have derived an analytical expression for the ABEP of DF multi-antenna cooperative communications system which uses SM. In order to maintain the same spectral efficiency, we considered equal number of transmit antennas for S and R. Derived expressions for the ABEP have exact match with the computer simulation results. Moreover, computer simulations and analytical expressions show that cooperative SM system provides 2 dB and 4 dB SNR gains when R and D have two and four receive antennas, respectively. Additionally, it can be concluded that the SNR gains increase with increasing N_r. Since the relay location, i.e. distance of the relay relatively to the source and destination, is important for the error performance, the diversity order depends on the S-R link. In our system model, R has equal distance to S and D, therefore, the diversity order is not improved.

In our future studies, different number of transmit/receive antennas and different modulation orders at all nodes will be taken into account. Furthermore, different diversity and relaying protocols will be investigated.

References

[1] V. Tarokh, H. Jafarkhani and A. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 16, no. 8, pp. 1456-1467, Jul. 1999.

[2] P. Wolniansky, G. Foschini, G. Golden and R. Valenzuela, "V-BLAST: An architecture for realizing very high data rates over the rich-scattering wireless channel," in *Proc. Int. Symp. Signals, Syst., Electron. (ISSSE'98),* Pisa, Italy, pp.295-300, Sep. 1998.

[3] R. Mesleh, H. Haas, S. Sinanovic, C. Ahn and S. Yun, "Spatial modulation," *IEEE Trans. Veh. Tech.*, vol. 57, no. 4, pp. 2228-2241, Jul. 2008.

[4] J. Jeganathan, A. Ghrayeb, L. Szczecinski and A. Ceron, "Space shift keying modulation for MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, pp. 3692-3703, Jul. 2009.

[5] E. Başar, Ü. Aygölü, E. Panayırcı, and H. V. Poor, "Space-time block coded spatial modulation," *IEEE Trans. Commun.*, vol. 59, no. 3, pp. 823-832, Mar. 2011.

[6] J. N. Laneman, D. N. C. 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.

[7] N. Serafimovski, S. Sinanovic, M. Di Renzo, H. Haas, "Dual-hop spatial modulation (Dh-SM)," *IEEE Veh. Tech. Conf., Spring*, Yokohoma, Japan, 2011.

[8] R. Mesleh, S. S. Ikki ve 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.

[9] R. Mesleh, S. S. Ikki, E.-H. M. Aggoune ve A. Mansour, "Performance analysis of space shift keying (SSK) modulation with multiple cooperative relays," *EURASIP J. Advances in Signal Process.*, vol. 201, pp. 1-10, Sept. 2012.

[10] R. Mesleh ve S. S. Ikki, "Space shift keying with amplify-and-forward MIMO relaying," *Trans. Emerging Tel. Tech.*, vol. 26, no. 4, pp. 520-531, Apr. 2015.

[11] R. Mesleh ve S. 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.

[12] P. Som ve A. Chockalingam, "End-to-end BER analysis of space shift keying in decode-and-forward cooperative relaying," *IEEE Wireless Commun. Netw. Conf.*, pp. 3465-3470, Shangai, China, 2014.

[13] X. Xie, Z. Zhao, M. Peng ve W. Wang, "Spatial modulation in two-way network coded channels: Performance and mapping optimization," *IEEE Int. Symp. Personal, Indoor, Mobile Radio Commun.*, Sydney, Australia, 2012.

[14] M. Wen, X. Cheng, H. V Poor ve B. Jiao, "Use of SSK modulation in two-way amplify-and-forward relaying," *IEEE Trans. Veh. Tech.*, vol. 63, no. 3, pp. 1498-1504, Mar. 2014.

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

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

[17] J. Jeganathan, A. Ghrayep and L. Szczecinski, "Spatial modulation: Optimal detection and performance analysis," *IEEE Commun. Lett.*, vol. 12, no.8, pp.545-547, Aug. 2008.