Double Spatial Modulation: A High-Rate Index Modulation Scheme for MIMO Systems

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***Abstract*—In this paper, a new multiple-input multiple-output (MIMO) transmission technique, which is called double spatial modulation (DSM), is proposed as a new high-rate generalized spatial modulation (SM) scheme. DSM scheme aims to improve the spectral efficiency of classical SM by increasing the number of active transmit antennas. In the DSM scheme, incoming data bits determine two modulated symbols as well as their corresponding activated transmit antenna indices. One of the modulated symbols is directly transmitted over its corresponding activated transmit antenna, while the other one is transmitted with a rotation angle, which is optimized for M-ary quadrature amplitude modulation (M-QAM) signal constellation, over the second activated transmit antenna. The error performance of the proposed DSM scheme is compared with the recently proposed emerging SM schemes such as quadrature SM (QSM) and enhanced SM (ESM). Our computer simulations show that the DSM scheme provides considerably better error performance than QSM and ESM schemes for different spectral efficiency values. In addition, the pairwise error probability (PEP) of DSM is derived and the average bit error probability (ABEP) over uncorrelated Rayleigh fading channels is obtained for different M-QAM constellations.**

***Index Terms*—MIMO systems, spatial modulation (SM), index modulation, quadrature SM, enhanced SM.**

I. Introduction

Multiple-input multiple-output (MIMO) transmission technology has achieved a significant breakthrough in the reliability and capacity of wireless communication systems compared to single-input single-output (SISO) systems. To satisfy the increasing demand for higher data rates in wireless networks, traditional MIMO transmission techniques such as spatial multiplexing and space-time block codes (STBC) have been developed in order to achieve spatial multiplexing and diversity gains, respectively. STBCs [1], [2] aim to transmit multiple copies of the data symbols to the receive antennas in different time slots in order to achieve transmit diversity. One of the typical spatial multiplexing techniques is the Vertical Bell Labs layered space-time (V-BLAST) architecture [3], which linearly improves the spectral efficiency with the number of transmit antennas. In V-BLAST, all available transmit antennas are activated and they simultaneously transmit their own information, that results in severe inter-channel interference (ICI) and receiver complexity. The high receiver complexity and energy consumption of the traditional MIMO systems lead the researchers to develop new MIMO transmission techniques.

Index modulation (IM) techniques have recently received considerable attention as possible candidates for next generation wireless systems [4]. IM improves the spectral efficiency of a considered MIMO system by conveying extra information bits through the fundamental components of the considered MIMO transmission scheme. Spatial modulation (SM) [5] is a promising IM scheme for MIMO systems, in which the IM technique is used for the transmit antenna indices to transmit additional information bits. SM scheme is proposed to be an energy efficient implementation of MIMO systems, which avoids ICI by using only one radio frequency (RF) chain at the transmitter. In SM, extra information bits are used to determine the active transmit antenna index besides the M-ary constellation symbol, where M denotes the modulation order of the M-ary quadrature amplitude modulation or phase shift keying (M-QAM/PSK) constellations. In the SM scheme, only one of the available transmit antennas is activated through which the corresponding M-ary symbol is transmitted. In terms of the spectral efficiency, though SM achieves a significant increase, it cannot still compete with the V-BLAST technique. For this reason, in order to improve the spectral efficiency of the conventional SM, researchers have proposed variety of SM techniques.

Generalized spatial modulation (GSM) systems are proposed to further improve the spectral efficiency of SM by increasing the number of active transmit antennas in each time slot. Unlike SM, in GSM systems, a group of transmit antennas are activated to simultaneously transmit the same symbol [6] or multiple independent M-ary constellation symbols [7]. In GSM, the information bits select a combination of transmit antennas, in which each combination consists of at least two active transmit antennas. The remainder bits select M-ary constellation symbol(s) for the activated transmit antennas.

Quadrature spatial modulation (QSM) is one of the recently proposed SM schemes [8], which provides a considerable improvement in the spectral efficiency compared to classical SM by increasing the number of active transmit antennas. In QSM, the total number of transmitted information bits is $\log_2 M + 2\log_2 N_t$ and $\log_2 M$ bits of which determine the complex constellation symbol, where N_t denotes the number of the transmit antennas, which should be an integer power of two. This complex symbol is decomposed into its in-phase and quadrature components. In QSM, SM technique is independently applied to those in-phase and quadrature parts i.e., each component is transmitted through a specific antenna whose index is determined by $\log_2 N_t$ bits. Since the in-phase and quadrature parts of the data symbol are orthogonal to each other, ICI is avoided at the receiver of the QSM system.

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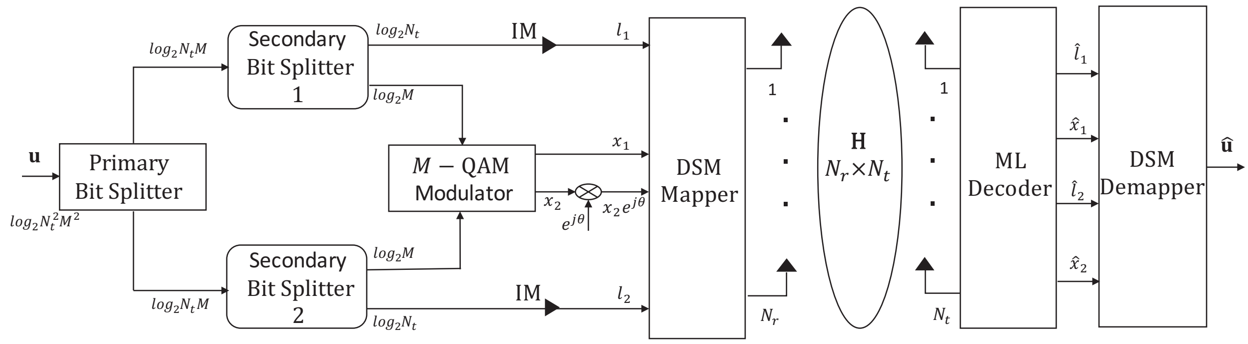

Fig. 1. System Model of DSM scheme

Enhanced spatial modulation (ESM) is one of the most recent SM techniques [9], which combines conventional SM with generalized SM schemes. In ESM, incoming information bits not only determine active antenna indices but also select the transmitted data symbols and their corresponding M-ary constellation diagrams. The active transmit antenna combinations of the ESM scheme are constructed for one or two active transmit antenna indices. In the ESM scheme, when single transmit antenna is activated, primary constellation is used, and when two transmit antennas are activated, secondary constellations are used. In order to transmit the same number of information bits in each antenna combination, the size of the secondary constellations is selected as half of the size of the primary constellation.

The aim of this paper is to introduce a new high-rate SM scheme, called double spatial modulation (DSM), which provides two-fold spectral efficiency compared to classical SM. In DSM, two independent SM transmission vectors are superimposed using constellation rotation. In other words, the DSM transmitter independently constructs two SM transmission vectors. It selects one of the N_t available transmit antennas and an M-QAM data symbol for each SM transmission vector and constructs the overall transmission vector by superimposition of these two SM transmission vectors. In order to distinguish the two different data symbols from each other, we determine a rotation angle, which is optimized for M-QAM constellations. One of the data symbols is directly transmitted through its corresponding activated transmit antenna, while the other one is rotated with an optimum angle before the transmission. For different spectral efficiencies and constellations, the bit error rate (BER) performance of DSM is compared to QSM and ESM schemes. Simulation results show that DSM exhibits better error performance than the reference MIMO transmission structures. Additionally, analytical bit error probability (ABEP) of the DSM system is obtained and it is validated using Monte Carlo simulations for uncorrelated Rayleigh fading channels and different M-QAM constellations.

The remaining parts of this paper are organized as follows. In Section II, the system model of the DSM scheme is given. In Section III, performance analysis of the proposed system is performed. Monte Carlo simulation results are given in Section IV and the paper is concluded in Section V.

II. Double Spatial Modulation System Model

The system model of the DSM scheme is shown in Fig.1. An $N_r \times N_t$ MIMO configuration is considered where N_r and N_t denote the number of receive and transmit antennas, respectively.

Let arbitrary $m = \log_2 N_t^2 M^2$ incoming data bits are to be transmitted at any particular time instance. Then, m is split into two equal parts, which contains $\log_2 N_t M$ bits. Each part determines its own data symbol and the corresponding active transmit antenna index. Each data symbol is modulated by $\log_2 M$ bits and each active transmit antenna index is determined by $\log_2 N_t$ bits. The first data symbol x_1 is directly transmitted through active transmit antenna with the index l_1, and the second data symbol x_2 is rotated with an angle θ

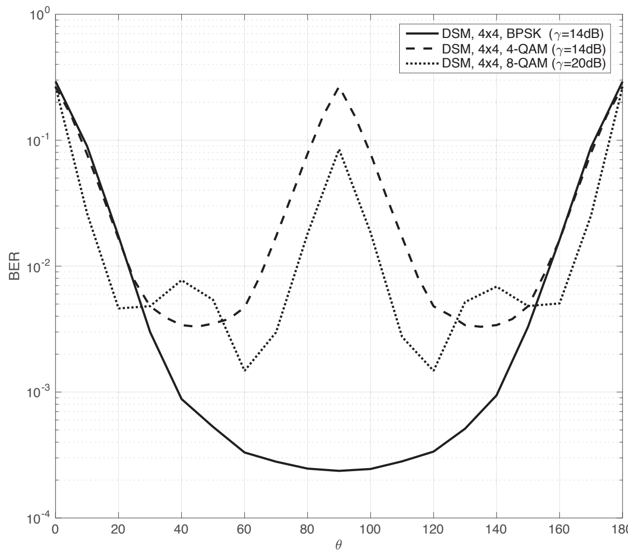

Fig. 2. Optimum rotation angle of DSM scheme for BPSK, 4-QAM and 8-QAM

before transmission through the second active antenna index l_2 in order to be distinguishable from data symbol x_1. This rotation angle is optimized for M-QAM signal constellations to minimize the BER. In Fig. 2, the optimum rotation angles are determined for different constellations by performing a search between $0^o - 180^o$ at certain signal to noise ratio (SNR) values. The angle which gives the best error performance is determined as the optimum rotation angle of data symbol x_2. The optimum rotation angle θ is respectively found as 90^o, 45^o and 30^o for BPSK, 4-QAM and 8-QAM constellations. For BPSK and 4-QAM, the SNR is taken as 14 dB, while it is taken as 20 dB for 8-QAM constellation. Therefore, the transmission vector $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ of the DSM scheme can be given as

$$\mathbf{x} = [0 \cdots 0 \underbrace{x_1}_{l_1} 0 \cdots 0 \underbrace{x_2 e^{j\theta}}_{l_2} 0 \cdots 0]^T \tag{1}$$

where $l_1, l_2 \in \{1, 2, \ldots, N_t\}$ stand for the positions of x_1 and $x_2 e^{j\theta}$, respectively. It should be noted that it is possible to have $l_1 = l_2$ for the DSM scheme, while due to the use of a rotation angle, the corresponding two data symbols can be distunguished at the receiver.

Assume that we want to transmit the following bit sequence $\{0\,1\,1\,1\,0\,1\}$ for a given time instance using a 4×4 MIMO system with BPSK modulation, where $m = 6$. The first $\log_2 M$ bit $\{0\}$ modulates a BPSK symbol $(x_1 = -1)$ and the following $\log_2 N_t$ bits $\{1\,1\}$ determine the active transmit antenna index $l_1 = 4$ for the transmission of x_1 , whose resulting transmission vector is $\mathbf{s_1} = \begin{bmatrix}0 & 0 & 0 & 1\end{bmatrix}^T$. In the same way, the first $\log_2 M$ bit of the remaining bits, which is $\{1\}$, modulates a second BPSK symbol $(x_2 = 1)$ and the last $\log_2 N_t$ bits $\{0\,1\}$ determine a second active antenna index $l_2 = 2$. Before the transmission through the transmit antenna with the index l_2, x_2 is rotated by the optimum BPSK rotation angle 90^o as given in Fig. 2, which results in the second transmission vector $\mathbf{s_2} = \begin{bmatrix}0 & j & 0 & 0\end{bmatrix}^T$. The overall transmission vector is constructed by the superimposition of $\mathbf{s_1}$ and $\mathbf{s_2}$ vectors as $\mathbf{x} = \mathbf{s_1} + \mathbf{s_2}$.

$\mathbf{x}$ is transmitted over a wireless MIMO channel, which is characterized by $\mathbf{H}$ with $N_r \times N_t$ dimensions while experiencing additive white Gaussian noise (AWGN) $\mathbf{n} \in \mathbb{C}^{N_r \times 1}$. The channel entries are assumed to be independent and identically distributed (i.i.d), circularly symmetric, complex Gaussian random variables with zero mean and unit variance. Similarly, the entries of the complex Gaussian noise vector $\mathbf{n}$ are assumed to be i.i.d with zero mean and N_0 variance. Therefore, the received signal vector $\mathbf{y} \in \mathbb{C}^{N_r \times 1}$ is given as

$$\begin{aligned}\mathbf{y} &= \mathbf{H}\mathbf{x} + \mathbf{n} \\ &= \mathbf{h}_{l_1} x_1 + \mathbf{h}_{l_2} x_2 e^{j\theta} + \mathbf{n}.\end{aligned} \tag{2}$$

where $\mathbf{h}_{l_1}$ and $\mathbf{h}_{l_2}$ denote the l_1th and l_2th column vectors of $\mathbf{H}$, respectively.

At the receiver side, maximum likelihood (ML) detector is used to obtain the optimum BER performance for the DSM scheme with the assumption of perfect channel state information (P-CSI). ML detector considers all possible realizations of the antenna indices l_1 and l_2 and M-QAM constellation symbols x_1 and x_2 to jointly decide the antenna indices $\hat{l}_1$ and $\hat{l}_2$ along with the data symbols $\hat{x}_1$ and $\hat{x}_2$ by calculating $N_t^2 M^2$ decision metrics. For this purpose, the ML detector considers

$$\left[\hat{x}_1, \hat{x}_2, \hat{l}_1, \hat{l}_2\right] = \arg \min_{x_1, x_2, l_1, l_2} \left\| \mathbf{y} - (\mathbf{h}_{l_1} x_1 + \mathbf{h}_{l_2} x_2 e^{j\theta}) \right\|^2 \tag{3}$$

where $\|\cdot\|$ shows vector norm.

III. Double Spatial Modulation Performance Analysis

In this section, theoretical BER analysis of the proposed DSM system is performed. We first calculate the conditional pairwise error probability (CPEP) of the DSM system, and by averaging CPEP over all realizations of the complex channel coefficients, we evaluate the unconditional pairwise error probability (UPEP) and then obtain an upper bound for the ABEP of the system.

When $\mathbf{x}$ is transmitted and it is erroneously detected as $\hat{\mathbf{x}}$, the CPEP is calculated as

$$\begin{aligned} &P\left(\mathbf{x} \to \hat{\mathbf{x}} | \mathbf{H}\right) \\ &\quad = P(\|\mathbf{y} - \mathbf{H}\mathbf{x}\|^2 > \|\mathbf{y} - \mathbf{H}\hat{\mathbf{x}}\|^2) \\ &\quad = P(\|\mathbf{H}\mathbf{x}\|^2 - \|\mathbf{H}\hat{\mathbf{x}}\|^2 - 2\Re\left\{\mathbf{y}^H(\mathbf{H}\mathbf{x} - \mathbf{H}\hat{\mathbf{x}})\right\} > 0) \\ &\quad = P(D > 0). \end{aligned} \tag{4}$$

where D is a Gaussian distributed random variable whose mean and variance values are respectively given as $-\|\mathbf{H}(\mathbf{x} - \hat{\mathbf{x}})\|^2$ and $2N_0 \|\mathbf{H}(\mathbf{x} - \hat{\mathbf{x}})\|^2$. Therefore we obtain

$$P(\mathbf{x} \to \hat{\mathbf{x}} | \mathbf{H}) = Q\left(\sqrt{\frac{\|\mathbf{H}(\mathbf{x} - \hat{\mathbf{x}})\|^2}{2N_0}}\right). \tag{5}$$

In (5), $Q(x)$ denotes the Q-function, which can be alternatively shown as $Q(x) = \frac{1}{\pi}\int_0^{\pi/2} \exp\left(-x^2/\sin^2\theta\right) d\theta$ and in this case, CPEP can be calculated as

$$P(\mathbf{x} \to \hat{\mathbf{x}} | \mathbf{H}) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \exp\left(\frac{\|\mathbf{H}(\mathbf{x} - \hat{\mathbf{x}})\|^2}{4N_0 \sin^2\theta}\right) d\theta. \tag{6}$$

UPEP is calculated by averaging (6) over the channel matrix $\mathbf{H}$ using a moment generating function (MGF)-based approach as

$$P\left(\mathbf{x} \to \hat{\mathbf{x}}\right) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} \left(\frac{\sin^2\theta}{\sin^2\theta + \frac{\|\mathbf{x} - \hat{\mathbf{x}}\|^2}{4N_0}}\right)^{N_r} d\theta. \tag{7}$$

The closed form expression of (7) is given in [10] as

$$P\left(\mathbf{x} \to \hat{\mathbf{x}}\right) = \frac{1}{2}\left[1 - \mu\left(c\right)\sum_{k=0}^{N_r - 1}\binom{2k}{k}\left(\frac{1 - \mu^2\left(c\right)}{4}\right)^k\right] \tag{8}$$

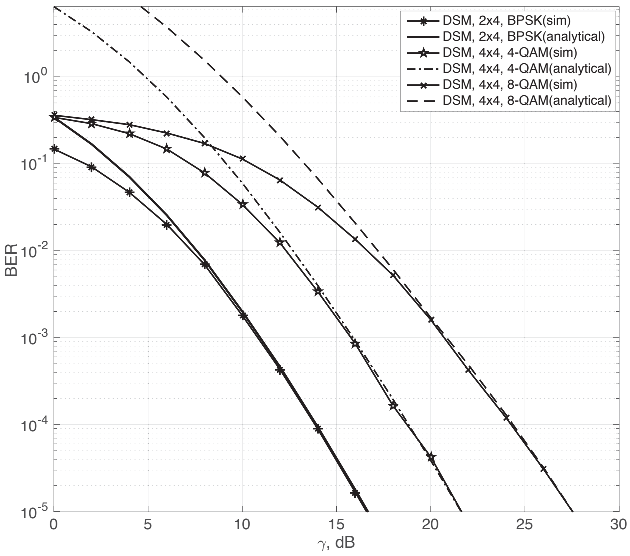

Fig. 3. Analytical and simulatated BER performance of 2×4 DSM with BPSK, 4×4 DSM with 4-QAM and 8-QAM

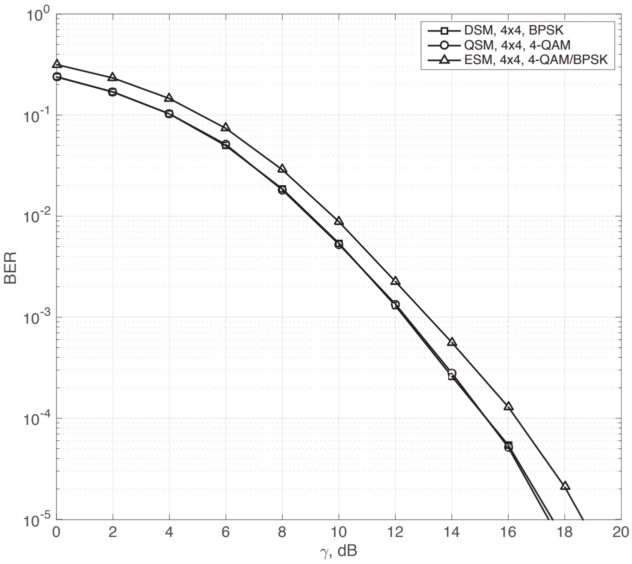

Fig. 4. BER performance of 4×4 DSM, QSM and ESM systems for $m = 6$ bpcu spectral efficiency

where $c = \dfrac{\left\|\mathbf{x} - \hat{\mathbf{x}}\right\|^2}{4N_0}$ and $\mu\left(c\right) \triangleq \left(\dfrac{c}{1+c}\right)$.

After evaluating the UPEP, by considering well-known upper bounding technique, ABEP of the DSM system can be obtained by

$$P_b \approx \frac{1}{m2^m} \sum_{\mathbf{x}} \sum_{\substack{\hat{\mathbf{x}} \\ \hat{\mathbf{x}} \neq \mathbf{x}}} P(\mathbf{x} \rightarrow \hat{\mathbf{x}}) e(\mathbf{x}, \hat{\mathbf{x}}) \tag{9}$$

where m is total number of bits for each transmitted DSM vector $\mathbf{x}$ and $e(\mathbf{x}, \hat{\mathbf{x}})$ is the total number of bit errors for the corresponding pairwise error event $P(\mathbf{x} \rightarrow \hat{\mathbf{x}})$.

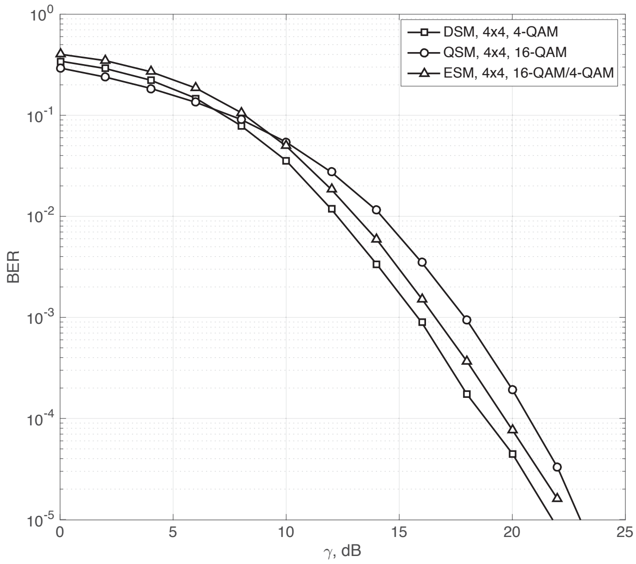

Fig. 5. BER performance of 4×4 DSM, QSM and ESM systems for $m = 8$ bpcu spectral efficiency

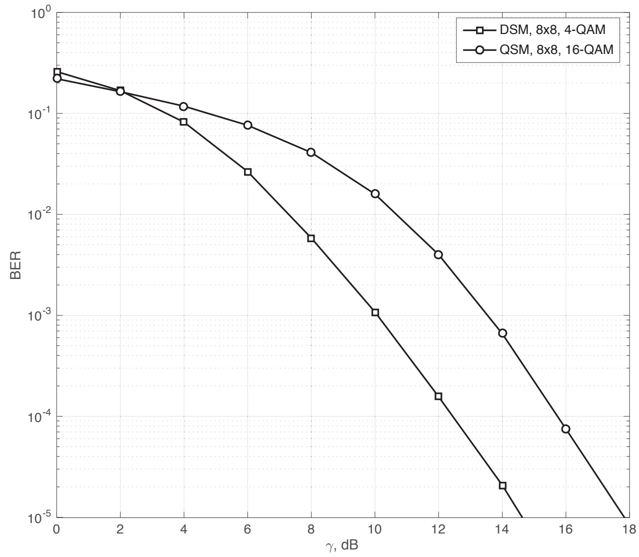

Fig. 6. BER performance of 8×8 DSM and QSM systems for $m = 10$ bpcu spectral efficiency

IV. Simulation Results

In this section, for different spectral efficiency values, analytical BER performance of the proposed DSM system is analyzed and verified through Monte Carlo simulation results. In addition, the BER performance of the DSM scheme is compared with QSM and ESM MIMO transmission schemes for different spectral efficiency values. BER results are depicted as a function of γ, where γ is defined as the received SNR at each received antenna. We consider natural mapping for IM and M-QAM symbols.

In Fig. 3, ABEP of the DSM system is analytically analyzed for different MIMO configurations and constellations. We obtain the analytical BER performance of 2×4 DSM with BPSK, 4×4 DSM with 4-QAM and 4×4 DSM with 8-QAM systems, which achieve spectral efficiencies $m = 4$, 8 and 10 bits per channel use (bpcu), respectively. The comparisons with the Monte Carlo simulations indicate that, analytical results show consistency with simulation results at high SNR values.

In Fig. 4, for 4×4 MIMO configuration, DSM technique is compared with the QSM and ESM systems. In order to achieve $m = 6$ bpcu spectral efficiency, DSM uses BPSK, QSM uses 4-QAM and ESM uses 4-QAM as the primary constellation and two BPSK constellations $(\pm 1, \pm j)$ as the secondary constellations. The simulation results show that DSM and QSM systems exhibit exactly the same BER performance, which is considerably better than the ESM scheme. For the DSM scheme, since the optimum rotation angle of BPSK is 90^o, the second transmission data symbol is $(\pm j)$, while the first data symbol, which is a plain BPSK symbol (± 1), and superimposition of these two symbol gives 4-QAM constellation as $(\pm 1 \pm j)$. Similarly, in QSM with 4-QAM, the conventional SM scheme is independently applied to the real and imaginary parts of a 4-QAM symbol. Therefore, the BER performance of the DSM with BPSK and QSM with 4-QAM are identical.

In Fig. 5, BER performance comparison of DSM with QSM and ESM is given for a 4×4 MIMO configuration and $m = 8$ bpcu spectral efficiency. In this case, 4-QAM, 16-QAM and 16-QAM primary constellation with 4-QAM secondary constellations are respectively used by DSM, QSM and ESM schemes. DSM exhibits 1 dB better error performance than ESM while it is 2 dB better than QSM scheme.

In Fig. 6, a 8×8 MIMO configuration is used and DSM system is only compared with QSM, since ESM [9] does not have any realizations for 8×8 MIMO system. In order to achieve $m = 10$ bpcu spectral efficiency, DSM and QSM use 4-QAM and 16-QAM constellations, respectively. It is clear from Fig. 6 that, DSM exhibits significantly better error performance than QSM scheme.

It is important to note that, these improvements in spectral efficiency and error performance of DSM scheme cost higher receiver complexity than compared MIMO schemes.

V. Conclusion

In this paper, a new high-rate index modulation scheme called DSM is proposed, whose spectral efficiency doubles as that of the conventional SM. The DSM is based on the application of double independent SM techniques, which can be differentiated from each other by a rotation angle optimizing for M-QAM constellations. In this paper, the theoretical analysis of the DSM system has been derived and the ABEP of the system has been depicted for different M-QAM constellation orders and spectral efficiencies. In addition, it has been shown by computer simulations that the BER of the proposed DSM system exhibits considerably better performance than the newly proposed reference SM techniques QSM and ESM for the same spectral efficiency values.

References

[1] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Sel. Areas Commun*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[2] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, Jul. 1999.

[3] G. J. Foschini, "Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas," *Bell Lab. Tech. J.*, vol. 1, no. 2, pp. 41–59, 1996.

[4] E. Basar, "Index modulation techniques for 5G wireless networks," *IEEE Commun. Mag.*, vol. 54, no. 7, 2016.

[5] 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.

[6] A. Younis, N. Serafimovski, R. Mesleh, and H. Haas, "Generalised spatial modulation," in *Proc. Signals, Sys. Comput.*, 2010, pp. 1498–1502.

[7] J. Fu, C. Hou, W. Xiang, L. Yan, and Y. Hou, "Generalised spatial modulation with multiple active transmit antennas," in *Proc. IEEE Globecom Workshops*, 2010, pp. 839–844.

[8] R. Mesleh, S. S. Ikki, and H. M. Aggoune, "Quadrature spatial modulation," *IEEE Trans. Veh. Technol.*, vol. 64, no. 6, pp. 2738–2742, Jun. 2015.

[9] C.-C. Cheng, H. Sari, S. Sezginer, and Y. T. Su, "Enhanced spatial modulation with multiple signal constellations," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2237–2248, Jun. 2015.

[10] M. K. Simon and M.-S. Alouini, *Digital communication over fading channels*. John Wiley & Sons, vol. 95, 2005.