A Spatial Modulation Scheme with Full Diversity for Four Transmit Antennas

Tien Dong Nguyen*, Xuan Nam Tran*, Vu Duc Ngo†, and Minh Tuan Le‡
*Le Quy Don Technical University, 236 Hoang Quoc Viet, Cau Giay, Ha Noi, Vietnam
Email: qttdong@gmail.com, namtx@mta.edu.vn
†Hanoi University of Science and Technology, 1 Dai Co Viet, Hanoi, Vietnam
E-mail: duc.ngovu@hust.edu.vn
‡Hanoi Department of Science and Technology, 5 Nguyen Trai Str., Ha Dong, Hanoi, Vietnam
E-mail: tuan.hdost@gmail.com

***Abstract*—In this paper, we propose a Spatial Modulation (SM) with full diversity for 4 transmit antennas, called DS-SM, by designing SC codewords and incorporating them with a Diagonal Space Time Block Code. Similar to the conventional SM scheme, the proposed scheme only activates an antenna element at a time for signal transmission. However, it is different from the conventional SM in that it is able to achieve full diversity. In order to attain low detection complexity, an ML detector based on sphere decoding is presented. Computer simulation shows that the proposed DS-SM scheme outperforms some existing STBC-SM techniques in terms of both bit error rate (BER) performance and effective throughput.**

***Keywords*—multi-input multi-output systems, spatial modulation, spatial constellation, space time block code.**

I. Introduction

An innovative Multiple-Input Multiple-Output (MIMO) technique, called Spatial Modulation (SM), which overcomes many disadvantages of spatial multiplexing MIMO systems was proposed by Mesleh $et\ al.$ in [1] and [2]. Besides the two conventional signal dimensions, i.e., the in-phase and quadrature components, the SM scheme utilizes the third one which is the indices of transmit antennas, hence the name "*spatial modulation*". Since modulated signals are transmitted from an active antenna at a time, inter-antenna synchronization (IAS) at the transmitter and inter-channel interference (ICI) at the receiver can be completely avoided in the SM scheme. As a result, a low-complexity maximum likelihood (ML) detector can be implemented at the receiver. Furthermore, an extended case from the SM scheme, called Space Shift Keying (SSK) in [3], only conveys information bits by the antenna positions. Though it is demonstrated in [2] and [3] that the two techniques potentially outperform some MIMO schemes, they actually can not achieve transmit diversity gain [4].

Recently, different methods have been proposed to attain transmit diversity in the SM system. In [5], Sugiura *et al.* proposed the Coherent Space-Time Shift Keying (CSTSK) which achieved second-order transmit diversity. In the CSTSK scheme, all transmit antennas are activated at any transmission period. Consequently, it requires N_t radio frequency (RF) chains at the tranmitter. Another method that has the same transmit diversity order is the Time-Orthogonal-Signal-Design Space Shift Keying (TOSD-SSK) in [6]. To achieve higher diversity order, a different scheme called the Space-Time-Shift-Keying (STSK) was proposed in [7]. However, it requires high complexity in encoding and decoding processes. Space Time Block Coded Spatial Modulation (STBC-SM) in [8] is another technique to increase transmit diversity by integrating Space Time Block Codes in SM systems. This scheme has the second transmit diversity order and obtains a spectral efficiency of $m = \frac{1}{2}\log_2 c + \log_2 M$ bits per channel use (bpcu), where c is the total number of STBC-SM codewords and M is the modulation level of the symbols encoded in an STBC code matrix. In addition, by using Alamouti's STBC structure in the transmitter, a low-complexity maximum likelihood detector can be implemented at its receiver. Later, a high rate STBC-SM scheme (HR-STBC-SM) for 4 and 6 transmit antennas has been proposed in [9] by introducing the concept of spatial constellation (SC) matrices. Since the number of SC matrices is larger than the number of the codewords in STBC-SM for the same number of transmit antennas, HR-STBC-SM system has higher spectral efficiency than its STBC-SM counterpart. To improve the spectral efficiency of STBC-SM, a technique based on cyclic structure and complex signal constellation rotation, called STBC-CSM, was proposed in [10]. Recently, based on multiplication of SC matrices and Alamouti code matrices, Le $et\ al.$ proposed the so-called spatially modulated orthogonal space time block coding (SM-OSTBC) scheme [11]. The SM-OSTBC method obtains the maximum spectral efficiency of $n_T - 2 + \log_2 M$ bpcu when $n_A = n_T$, i.e., when all transmit antennas are activated. n_T and n_A respectively denotes the numbers of transmit antennas and the numbers of active antennas. Both STBC-CSM and SM-OSTBC method have higher spectral efficiency than existing SM schemes. However, they only achieve second order transmit diversity. Although the latest scheme based on Diagonal Space Time Block Codes and the SC matrices proposed in [11], called SM-DC [17], provides higher spectral efficiency than SM-OSTBC one, it only obtains the same transmit diversity order as the SM-OSTBC does.

In this paper, motivated by previous works in [9] and [17], we focus on improving the diversity order of the SM system by combining SC matrices with a diagonal space time block code. The proposed SM scheme offers following advantages: 1) It achieves 4th order transmit diversity while requiring only an RF chain at the transmitter; 2) For the same number of transmit antennas, the proposed scheme outperforms several existing SM schemes at comparable spectral efficiency, as shown by simulation results; 3) Low decoding complexity is achievable with the aid of sphere decoding technique. More importantly, like in the conventional SM, IAS and ICI are completely avoided in the proposed scheme since it requires only one activated antenna at a symbol time.

The remainder of the paper is organized as follows. The proposed SM scheme is briefly described in section II. Section III presents SC codeword design and section IV introduces signal detection. Finally, we provide some simulation results and make conclusions in Sections V and VI, respectively.

II. The Proposed SM System Model

In Fig.1, we propose the system model with $n_T = 4$ transmit antennas and n_R receive antennas. Assume that at

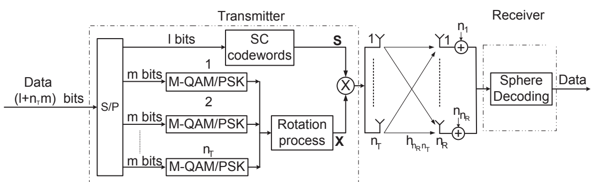

Fig. 1. Block diagram of the DS-SM scheme

every T symbol periods, a block of $(l+n_T m)$ data bits are fed into the transmitter, where l bits are mapped into a $n_T \times n_T$ SC codeword $\mathbf{S}$, out of K SC codewords ($l = \log_2 K$) in the spatial constellation Ω_S. The remaining $n_T m$ bits are modulated in M-QAM or M-PSK modulators to get a 4×1 modulated symbol vector $\mathbf{u} = [\begin{array}{cccc} u_1 & u_2 & u_3 & u_4 \end{array}]^T$ with $M = 2^m$. After that, using the rotation matrix $\mathbf{L}$ in [13], we get the rotated signal vector $\tilde{\mathbf{u}}$ as follows

$$\tilde{\mathbf{u}} = \mathbf{L} \cdot [\begin{array}{cc} \Re(\mathbf{u}) & \Im(\mathbf{u}) \end{array}]^T \tag{1}$$

where $\Re(\mathbf{a})$ and $\Im(\mathbf{a})$ denotes the real and imaginary part of vector $\mathbf{a}$ respectively. The rotation matrix $\mathbf{L}$ is explicitly expressed as follows [13]

$$\mathbf{L} = \sqrt{\frac{2}{n}} \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \ldots & \ldots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \tag{2}$$

where $w_{tk} = \cos\left(\frac{\pi}{4n}(4t-1)(2k-1)\right)$, for $1 \le t, k \le n$ and $n = 2n_T = 8$.

Then, the signal vector $\tilde{\mathbf{u}}$ is re-arranged to get

$$\tilde{\mathbf{x}} = [\begin{array}{cccc} \tilde{u}_1 + j\tilde{u}_5 & \tilde{u}_2 + j\tilde{u}_6 & \tilde{u}_3 + j\tilde{u}_7 & \tilde{u}_4 + j\tilde{u}_8 \end{array}]^T. \tag{3}$$

After that, the $n_T \times T$ transmitting matrix is formed as $\mathbf{X} = \mathrm{diag}(\tilde{\mathbf{x}})$, where $\mathrm{diag}(\mathbf{a})$ represents a diagonal matrix with the elements of vector $\mathbf{a}$ lying in the main diagonal of the matrix.

Finally, the $n_T \times T$ transmitted codeword $\mathbf{C}$ is created simply by multiplying $\mathbf{S}$ and $\mathbf{X}$, i.e., $\mathbf{C} = \mathbf{S}.\mathbf{X}$. The codeword $\mathbf{C}$ will be transmitted from n_T antennas within T symbol periods.

Under the assumption that the receiver is equipped with n_R receive antennas, the $n_R \times T$ received signal matrix $\mathbf{Y}$ is given by

$$\mathbf{Y} = \sqrt{\frac{\gamma}{E_s}}\mathbf{HC} + \mathbf{N} = \sqrt{\frac{\gamma}{E_s}}\mathbf{HSX} + \mathbf{N} \tag{4}$$

where $\mathbf{H}$ and $\mathbf{n}$ denote $n_R \times n_T$ channel matrix and $n_R \times T$ noise vector respectively. It is assumed that the entries of $\mathbf{H}$ and $\mathbf{n}$ are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance. E_s is the average symbol energy of M-QAM/M-PSK modulated signal. γ is the average signal to noise ratio (SNR) at each receive antenna.

At the receiver, transmitted signals $(\mathbf{S}, \mathbf{X})$, or equivalently, $(\mathbf{S}, \mathbf{u})$, are detected with the aid of the sphere decoding in [13]-[15] to reduce complexity under the assumption that the receiver perfectly knows channel state information.

III. SC Codeword Design

As can be seen from the previous section, the SC codewords play an important role in the design of an SM scheme. Inspired by the SC concept in [9], we propose a set of 4 SC codewords as follows

$$\mathbf{S}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{S}_2 = \begin{bmatrix} 0 & e^{j\theta} & 0 & 0 \\ e^{j\theta} & 0 & 0 & 0 \\ 0 & 0 & 0 & e^{j\theta} \\ 0 & 0 & e^{j\theta} & 0 \end{bmatrix},$$

$$\mathbf{S}_3 = \begin{bmatrix} 0 & 0 & 0 & e^{j2\theta} \\ 0 & 0 & e^{j2\theta} & 0 \\ e^{j2\theta} & 0 & 0 & 0 \\ 0 & e^{j2\theta} & 0 & 0 \end{bmatrix},$$

$$\mathbf{S}_4 = \begin{bmatrix} 0 & 0 & e^{j3\theta} & 0 \\ 0 & 0 & 0 & e^{j3\theta} \\ 0 & e^{j3\theta} & 0 & 0 \\ e^{j3\theta} & 0 & 0 & 0 \end{bmatrix}.$$

In order for the proposed scheme to obtain full diversity, the rotation angle θ is optimized based on the rank and determinant criteria as stated in [16]. By using exhaustive computer search for $\theta \in [0, \pi/2]$, we are able find its optimal values that maximize the following minimum determinant

$$d_{\min} = \min_{\mathbf{C} \neq \mathbf{C}'} \det(\mathbf{C} - \mathbf{C}')^H (\mathbf{C} - \mathbf{C}'). \tag{5}$$

The results are summarized in the Table I for different modulation techniques.

Using the 4 SC codewords above, the spectral efficiency of DS-SM scheme is given by

$$\mu = \frac{1}{4}\left(\log_2 4 + \log_2 M^4\right) = \left(\frac{1}{2} + \log_2 M\right) \text{ [bpcu]}. \tag{6}$$

TABLE I. OPTIMAL VALUES OF θ AND THE CORRESPONDING MINIMUM DETERMINANTS FOR DIFFERENT MODULATION SCHEMES

Modulation	BPSK	4QAM	8QAM
θ	1.35	0.18	1.38
$d_{\min}$	0.017	0.0082	$3.82 \cdot 10^{-4}$

IV. SIGNAL DETECTION OF THE SCHEME

For a given matrix $\mathbf{S}_q, q = 1, \ldots, 4$, we are able to construct the $n_R \times 4$ equivalent matrix $\tilde{\mathbf{H}}_q = \sqrt{\frac{\gamma}{E_s}}\mathbf{H}\mathbf{S}_q$. Therefore, the system equation in (4) can be re-written as

$$\mathbf{Y} = \tilde{\mathbf{H}}_q\mathbf{X} + \mathbf{N}. \quad (7)$$

The diagonal structure of the STBC codeword $\mathbf{X}$ allows us to re-express (7) as

$$\mathbf{y} = \mathbf{H}_{e,q}\tilde{\mathbf{x}} + \mathbf{n} \quad (8)$$

where $\mathbf{H}_{e,q} = \left[\ \text{diag}(\tilde{\mathbf{h}}_1) \quad \text{diag}(\tilde{\mathbf{h}}_2) \quad \cdots \quad \text{diag}(\tilde{\mathbf{h}}_{n_R})\ \right]^T$, $\tilde{\mathbf{h}}_k$, $(k = 1, 2, \cdots, n_R)$, is the kth row of $\tilde{\mathbf{H}}_q$. $\mathbf{y} = \text{vec}(\mathbf{Y}^T), \mathbf{n} = \text{vec}(\mathbf{N}^T)$. $\text{vec}(\mathbf{A})$ denotes the column-vectorial stacking operation of a matrix $\mathbf{A}$.

Converting equation (8) into the equivalent real system-equation and using (1) and (4), we obtain

$$\mathbf{v} = \mathbf{M}_q\mathbf{s} + \mathbf{w} \quad (9)$$

where $\mathbf{s} = \left[\ \Re(\mathbf{u}) \quad \Im(\mathbf{u})\ \right]^T$, $\mathbf{w} = \left[\ \Re(\mathbf{n}) \quad \Im(\mathbf{n})\ \right]^T$. $\mathbf{v} = \left[\ \Re(\mathbf{y}) \quad \Im(\mathbf{y})\ \right]^T$, $\mathbf{M}_q = \begin{bmatrix} \Re(\mathbf{H}_{e,q}) & -\Im(\mathbf{H}_{e,q}) \\ \Im(\mathbf{H}_{e,q}) & \Re(\mathbf{H}_{e,q}) \end{bmatrix}\mathbf{L}$. Equation (9) is now similar to the system equation of a conventional spatial multiplexing scheme. Therefore, the sphere decoders (SD) in [13]-[15] can be used to detect $\mathbf{s}$ for a given $\mathbf{S}_q$ as follows

$$(\hat{\mathbf{s}})_q = \arg\min_{\mathbf{s}} \|\mathbf{t}_q - \mathbf{R_q}\mathbf{s}\|^2 \quad (10)$$

where $\mathbf{t}_q = \mathbf{Q}_q^T\mathbf{v}$, and $\mathbf{Q}_q\mathbf{R}_q$ is the QR decomposition of $\mathbf{M}_q$, i.e., $\mathbf{M}_q = \mathbf{Q}_q\mathbf{R}_q$.

After that, the index q of the transmitted SC codeword is determined as follows [11]

$$\hat{q} = \arg\min_{q} \left\|\mathbf{t}_q - \mathbf{R}_q(\hat{\mathbf{s}})_q\right\|^2 + \mathbf{y}^T\mathbf{y} - \mathbf{t}_q^T\mathbf{t}_q. \quad (11)$$

Finally, information bits are recovered from the detected SC codeword $\mathbf{S}_{\hat{q}}$ and detected signal vector $\hat{\mathbf{s}}_{\hat{q}}$ at the receiver.

V. SIMULATION RESULTS

In this section, the BER performance of the proposed DS-SM scheme is presented and compared with several existing SM-based MIMO schemes such as SM [1], STBC-SM [8], STBC-CSM [10], SM-OSTBC [11], DC-SM [17] for different n_R. For the sake of convenience, an SM-based MIMO scheme with n_T transmit antennas, n_R receive antennas, and n_A simultaneously activated antennas is denoted as (n_T, n_R, n_A). We further assume that ML detectors are applied to all SM-based MIMO schemes .

Fig. 2 and Fig. 3 respectively show the BER curves of the DS-SM $(4, n_R, 1)$ in comparison with those of the SM $(4, n_R, 1)$, the STBC-SM $(4, n_R, 2)$, the STBC-CSM $(4, n_R, 2)$, and of the DC-SM $(4, n_R, 1)$ for $n_R = 1$ and

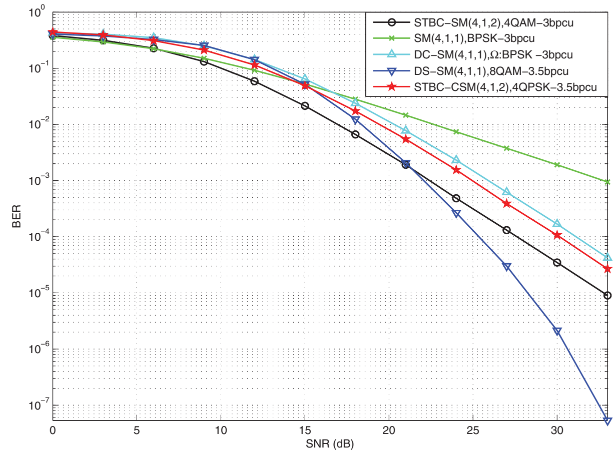

Fig. 2. BER performances of the SM, STBC-SM, STBC-CSM, and DS-SM schemes when $n_R = 1$.

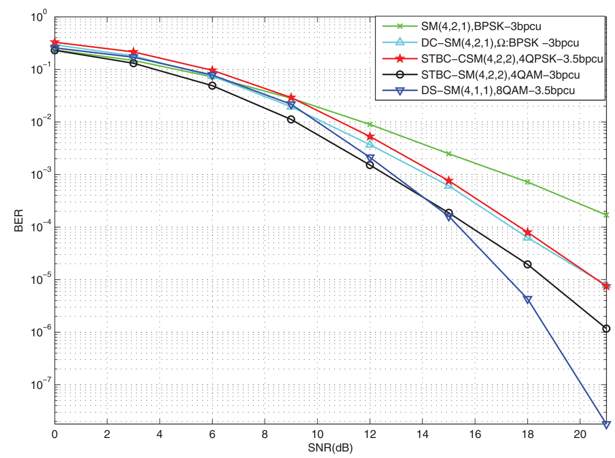

Fig. 3. BER performances of the SM, STBC-SM, STBC-CSM, and DS-SM schemes when $n_R = 2$.

$n_R = 2$. Appropriate modulation techniques are applied to the MIMO schemes in order to achieve the equivalent spectral efficiencies of 3 and 3.5 bpcu. It is clearly observed from the two figures that the DS-SM attains the fourth order transmit diversity. In these figures, the proposed DS-SM scheme not only provides higher spectral efficiency but also outperforms all existing SM-based MIMO ones as the SNR is sufficiently high. Specifically, at $\text{BER} = 10^{-3}$, the proposed scheme offers about 0.3 dB, 3 dB, 3.5 dB and 10 dB SNR gain over the STBC-SM, the STBC-CSM, the DC-SM and the SM, respectively at $n_R = 1$.

Considering the effective throughput η defined as $\eta = (1 - \text{FER}).\mu$ where μ is the spectral efficiency, and FER denotes the frame error rate. We simulate the throughput for the DS-SM, the SM, the STBC-SM, the DC-SM, the STBC-CSM, and the SM-OSTBC assuming that a frame consists of 168 bits[1] and a channel matrix is unchanged within a frame. Fig. 4 shows the effective throughput as a function of SNR for $n_R = 1$. We observe that the range of effective throughput

[1]This is the lowest common multiple of the numbers of bits conveyed by transmit codewords of these schemes.

from 1 to 3 the DS-SM surpasses all comparing techniques. Particularly, at 2.5 bpcu, the proposed scheme achieves an SNR gain of approximately 2 dB compared with the SM-OSTBC. At $n_R = 2$, the proposed DS-SM even has higher effective throughput than the remaining ones as clearly demonstrated in Fig. 5.

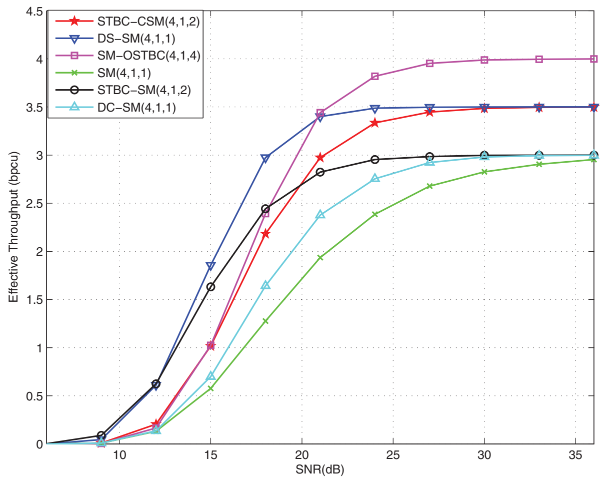

Fig. 4. Effective throughput versus SNR for various SM-based MIMO schemes with $n_T = 4$ transmit antennas, $n_R = 1$ receive antenna.

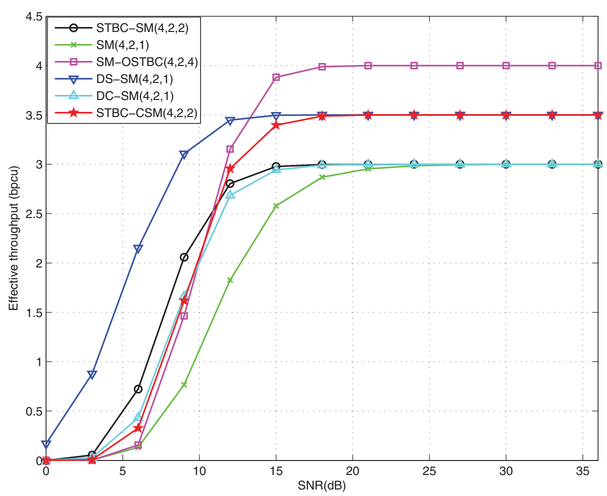

Fig. 5. Effective throughput versus SNR for various SM-based MIMO schemes with $n_T = 4$ transmit antennas, $n_R = 2$ receive antennas.

VI. Conclusions

In this paper, we have proposed a new SM scheme, called DS-SM, via the combination of a diagonal space-time block code with SC codewords. The proposed scheme requires only one activated antenna at a time and is designed based on the rank and determinant criteria to guarantee full transmit diversity. A sphere-decoding-based detector has been presented for low-complexity signal detection at the receiver without degrading the system performance. Analytic and simulation results show that the DS-SM outperforms existing SM-based MIMO schemes in terms of both BER and effective throughput. A limitation of the proposed scheme is that it has not been optimized for high modulation order, i.e., for large M due to extensive computer search. In future works, we will try to address this issue in order to improve the spectral efficiency of the DS-SM.

References

[1] R. Mesleh, H. Haas, A. Chang Wook, and Y. Sangboh, "Spatial Modulation - A New Low Complexity Spectral Efficiency Enhancing Technique," in *First Conf. on Commun. and Networking,* China, 2006, pp. 1-5.

[2] R. Y. Mesleh, H. Haas, S. Sinanovic, A. Chang Wook, and Y. Sangboh, "Spatial Modulation," *IEEE Trans. Veh. Technol,* vol. 57, pp. 2228-2241, 2008.

[3] J. Jeganathan, A. Ghrayeb, L. Szczecinski, and A. Ceron, "Space shift keying modulation for MIMO channels," *IEEE Trans. on Wireless Commun.,* vol. 8, pp. 3692-3703, 2009.

[4] T. Handte, A. Muller, and J. Speidel, "BER Analysis and Optimization of Generalized Spatial Modulation in Correlated Fading Channels," in *Proc. VTC 2009-Fall,* 2009, pp. 1-5.

[5] S. Sugiura, C. Sheng, and L. Hanzo, "Coherent and Differential Space-Time Shift Keying: A Dispersion Matrix Approach," *IEEE Trans. Commun.,* vol. 58, pp. 3219-3230, 2010.

[6] M. Di Renzo and H. Haas, "Space Shift Keying (SSK) Modulation: On the Transmit-Diversity / Multiplexing Trade-Off," in *Proc. IEEE ICC,* 2011, pp. 1-6.

[7] S. Sugiura, C. Sheng, and L. Hanzo, "Generalized Space-Time Shift Keying Designed for Flexible Diversity-, Multiplexing- and Complexity-Tradeoffs," *IEEE Trans. Wireless Commun.,* vol. 10, pp. 1144-1153, 2011.

[8] E. Basar, U. Aygolu, E. Panayirci, and H. V. Poor, "Space-time block coding for spatial modulation," in *Proc. PIMRC,* 2010, pp. 803-808.

[9] Minh-Tuan Le, Vu-Duc Ngo, Hong-Anh Mai, and Xuan-Nam Tran, "High-rate Space-Time Block Coded Spatial Modulation," in *Conf. on ATC,* 2012, pp. 278-282.

[10] L. Xiaofeng and W. Lei, "High Rate Space-Time Block Coded Spatial Modulation with Cyclic Structure," *IEEE Commun. Letters,* vol. 18, pp. 532-535, 2014.

[11] Minh-Tuan Le, Vu-Duc Ngo, Hong-Anh Mai, Xuan Nam Tran, and M. Di Renzo, "Spatially Modulated Orthogonal Space-Time Block Codes with Non-Vanishing Determinants," *IEEE Trans. Commun.,* vol. 62, pp. 85-99, 2014.

[12] C. Soo Ki, P. Seung, and K. Chung Gu, "Rotated multidimensional modulation for spatial multiplexing systems," in *Proc. VTC,* 2003, pp. 246-250.

[13] E. Viterbo and J. Boutros, "A universal lattice code decoder for fading channels," *IEEE Trans. Inf. Theory,* vol. 45, pp. 1639-1642, 1999.

[14] A. M. Chan and L. Inkyu, "A new reduced-complexity sphere decoder for multiple antenna systems," in *Proc. ICC,* 2002, pp. 460-464.

[15] M. O. Damen, H. El Gamal, and G. Caire, "On maximum-likelihood detection and the search for the closest lattice point," *IEEE Trans. Inf. Theory,* vol. 49, pp. 2389-2402, 2003.

[16] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory,* vol. 45, pp. 1456-1467, 1999.

[17] L. Wang and Z. Chen, "Spatially Modulated Diagonal Space Time Codes," *IEEE Commun. Letters,* vol. PP, pp. 1-1, 2015.