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Layered spatial modulation

Salim Abdelkareem Alkhawaldeh

Abstract

In this paper, we propose a layered spatial modulation (L-SM) scheme that combines a multi-layered coding scheme with the spatial modulation. At each antenna selection, the number of active transmit antennas equals the number of layers. The proposed L-SM scheme maximizes the diversity order and coding gain at each antenna selection. The exact pairwise and upper bound bit error probabilities are derived. Several examples of different spatial modulation schemes and the proposed L-SM scheme are simulated with the same number of transmit antennas and same spectral efficiency. As expected, the proposed L-SM scheme satisfies significant increase in the performance compared to all existing spatial modulation schemes.

Keywords: MIMO, Diversity, Spatial multiplexing, Layered spatial modulation, STBC, SM, L-SM

1 Introduction

Significant improvements in the bandwidth efficiency and notable reduction in the probability of error can be obtained by using multiple input multiple output (MIMO) technology [1, 2]. This technology uses multiple transmit and multiple receive antennas where space and time diversities and spatial multiplexing are applied. Several space-time trellis and block coding schemes that improve the diversity and coding gains were proposed [3–9]. On the other hand, a number of coding schemes were introduced to improve the spatial multiplexing gain [10–17]. All the above schemes use more than one transmit antenna in the same time. Simultaneous activation of multiple transmit antennas causes the inter-channel interference. To avoid this problem, spatial modulation (SM) scheme was presented [18, 19]. This scheme uses one transmit antenna at each time period depending on the first group of input bits. The second group of bits is used to determine which symbol is selected from the constellation set. Unfortunately, this scheme needs large number of transmit antennas to increase the spectral efficiency of wireless system. To reduce the number of transmit antennas, generalized spatial modulation scheme was proposed [20]. This scheme uses more than one transmit antenna at each time period. However, the transmit diversity is not exploited in this scheme which yields significant degradation in the performance. To overcome this problem, a

scheme that combines spatial modulation and space-time block coding (STBC) referred as STBC-SM was proposed [21]. This scheme takes the advantages of both spatial modulation and space-time block coding. Also, it maximizes the diversity order and multiplexing gain. This scheme suffers from degradation of the spectral efficiency offered by the spatial dimension compared with the conventional spatial modulation. To improve the spectral efficiency, high-rate STBC-SM (H-STBC-SM) scheme and spatial modulation STBC scheme with cyclic structure (STBC-CSM) were introduced [22, 23]. The number of codewords provided by these schemes is twice the number of codewords provided by the STBC-SM in [21]. The transmit diversity order achieved by both schemes is equal to two. However, the H-STBC-SM suffers from small degradation in the performance. At the same spectral efficiency and with transmit antennas less than those of the STBC-SM scheme, the performance of STBC-CSM approaches that of the STBC-SM. The authors in [24] proposed the complex interleaved orthogonal design SM with the high degree of spatial modulation (CIOD-SM-H). The spectral efficiency of this scheme is as that of the H-STBC-SM scheme, and its performance is less than that of the STBC-SM. To further increase the spectral efficiency and the performance, cyclic temporally and spatially modulated STBC (STBC-TSM) scheme was proposed [25]. In this scheme, Alamouti STBC is rotated over four symbol periods to ensure a transmit diversity order of 2.

In this paper, we propose a layered spatial modulation (L-SM) scheme that avoids large number of transmit

Correspondence: skhawaldeh@bau.edu.jo; skhawaldeh@yahoo.com
Communication Engineering Department, Faculty of Engineering
Technology, Albalqa Applied University, Amman, Jordan

antennas and provides high spectral efficiency. The proposed L-SM scheme achieves significant improvement in the performance compared to that of the all above spatial modulation schemes. The proposed L-SM scheme is based on a multi-layered coding scheme combined with the spatial modulation scheme in [18, 19]. At each antenna selection, the proposed L-SM scheme is used with transmit diversity order equals the number of active transmit antennas and maximum coding gain based on specific codeword matrices. The number of layers of the proposed scheme is equal to the number of active transmit antennas at each antenna selection.

The exact pairwise and upper bound bit error probabilities of the proposed L-SM scheme are derived. Simulation results are demonstrated with several examples of the proposed L-SM scheme and recent spatial modulation schemes combined with STBC. All schemes are compared with the same number of transmit antennas and comparable spectral efficiency. These results show that the proposed L-SM scheme significantly outperforms all other spatial modulation schemes.

This paper is organized as follows: In Section 2, the methods that we used are presented. Conventional spatial modulation scheme is presented in Section 3. In Section 4, we propose the L-SM scheme. We derive the pairwise and bit error probabilities of the proposed L-SM scheme in Section 5. In Section 6, numerical results of the proposed L-SM and different spatial modulation schemes are demonstrated. Finally, the conclusions of this paper are inserted in Section 7.

2 Methods

The proposed L-SM scheme is a combination of a multi-layered coding scheme and the spatial modulation. The codeword of the multi-layered coding scheme contains a number of layers with the same number of active transmit antennas. A number of phase shifts are inserted in the codeword among the layers and symbols to maximize the diversity and coding gains. When all transmit antennas are active, one codeword is transmitted over one codeword period. When the total number of transmit antennas is greater than or equals twice the number of active transmit antennas, two codewords are transmitted from different active transmit antennas over two different codeword periods at each antenna selection case. Several examples of the proposed L-SM and the state-of-the-art schemes are simulated using Matlab software. The channel is modeled by using the Monte Carlo method. The schemes are compared to each other with the same number of transmit and receive antennas and same spectral efficiency.

3 Conventional spatial modulation scheme

The SM scheme in [18, 19] is described in this section as shown in Fig. 1. This scheme uses two groups of bits. The first group of k bits is used to select one active transmit antenna i out of N_{all} antennas at each time period, and the second group of u bits is used to select the symbol c from the constellation set that has 2^u elements. This results in transmission rate of $(k + u)$ bits per channel use. The advantage of this approach is that it avoids the problem of inter-channel interference.

The signal at receive antenna j can be written as

$$y_j = \sqrt{E_s} a_{ji} c_i + v_j \tag{1}$$

where E_s is the average symbol energy, c_i is the symbol c transmitted from antenna i, and a_{ji} is the path gain between transmit antenna i and receive antenna j. It is assumed that the path gains are samples of a zero mean complex Gaussian random variable with variance of 0.5 per dimension. The additive noise v_j at the receive antenna j is assumed to be independent samples of a zero mean complex Gaussian random variable with variance of $N_0/2$ per dimension.

The exact pairwise error probability of transmitting c_i and deciding $\tilde{c}_{\tilde{i}}$ is given by [20]

$$P_r\left(c_i \rightarrow \tilde{c}_{\tilde{i}}\right) = I_{\frac{N_0}{N_0 + \tilde{N}_0}}(N_r, N_r) \quad i \neq \tilde{i}, \ i$$
$$= 1, 2, \cdots, N_t, \tilde{i} = 1, 2, \cdots, N_t \tag{2}$$

where $\tilde{N}_0 = N_0 + E_s|c|^2 + E_s|\tilde{c}|^2$ and $I_x(w_1, w_2)$ is the regularized beta function given by

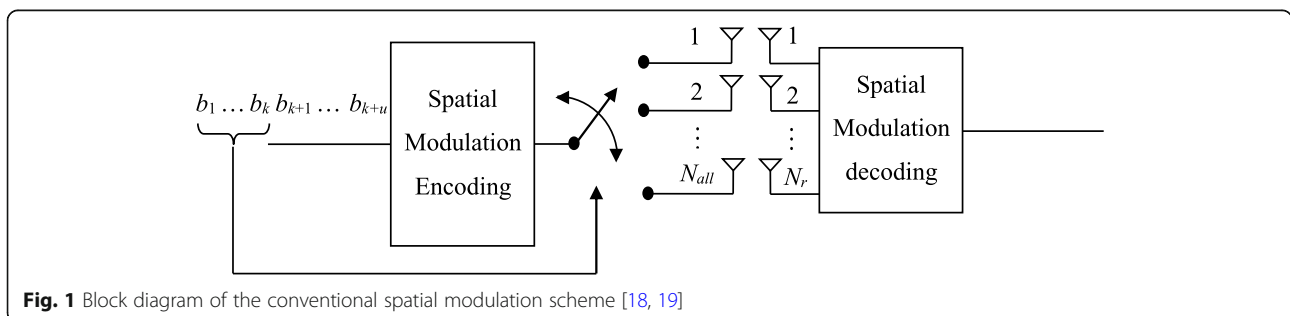$$I_x(w_1, w_2) = \frac{1}{R(w_1, w_2)} \int_{t=0}^{x} t^{(w_1-1)} (1-t)^{(w_2-1)} dt \tag{3}$$

with

Fig. 1 Block diagram of the conventional spatial modulation scheme [18, 19]

$$R(w_1, w_2) = \int_{t=0}^{1} t^{(w_1-1)}(1-t)^{(w_2-1)} dt \qquad (4)$$

The bit error probability of spatial modulation scheme is given by

$$P_{\text{bit}} \le \sum_{c,i} \sum_{\tilde{c},\tilde{i}} \frac{N(c_i, \tilde{c}_{\tilde{i}}) I_{\frac{N_0}{N_0+N_0}}(N_r, N_r)}{(k+u) \, 2^{k+u}} \qquad (5)$$

where $N(c_i, \tilde{c}_{\tilde{i}})$ is the number of bits in error between c_i and $\tilde{c}_{\tilde{i}}$.

As an example of this scheme is to apply 3 bits per channel use. The first 2 bits are used to select the active transmit antenna out of four antennas, and the third bit is used to select the symbol from the binary phase shift keying (BPSK) constellation set. The transmission and encoding of this example is shown in Table 1.

4 Proposed L-SM scheme
4.1 Proposed multi-layered coding scheme without spatial modulation

In this subsection, we present a multi-layered coding scheme that maximizes the diversity order and spatial multiplexing gain as shown in Fig. 2.

In this scheme, multi layers with the same number of transmit antennas are applied. Each layer contains a number of symbols. The received signal matrix is given as

$$\mathbf{Y} = \sqrt{\frac{E_s}{N_t}} \mathbf{A} \mathbf{C} + \mathbf{V} \qquad (6)$$

where $\mathbf{V}$ is $N_r \times N_t$ noise matrix at the receive antennas whose entries are independent samples of a zero mean complex Gaussian random variable with variance of $N_0/2$ per dimension. $\mathbf{A}$ is $N_r \times N_t$ channel matrix whose entry a_{ji} is the path gain between transmit antenna i and receive antenna j, and it is given as

Table 1 The transmission and encoding of SM scheme with 3 bits/channel use, four transmit antennas, and BPSK modulation

Message bits $b_1 b_2 b_3$	Active antennas	Transmitted symbol c
000	1	−1
010	2	−1
100	3	−1
110	4	−1
001	1	1
011	2	1
101	3	1
111	4	1

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N_t} \\ a_{21} & a_{22} & \cdots & a_{2N_t} \\ \vdots & & & \\ a_{N_r 1} & a_{N_r 2} & \cdots & a_{N_r N_t} \end{bmatrix} \qquad (7)$$

It is assumed that the path gains in $\mathbf{A}$ are samples of a zero mean complex Gaussian random variable with variance of 0.5 per dimension. In (6), $\mathbf{C}$ is the codeword matrix given by

$$\mathbf{C} = \begin{bmatrix} s_{1,1} & s_{2,1} & \cdots & s_{N_t,1} \\ s_{N_t,2} & s_{1,2} & \cdots & s_{N_t-1,2} \\ \vdots & & & \\ s_{2,N_t} & & \cdots & s_{1,N_t} \end{bmatrix} \qquad (8)$$

$$s_{i,t} = \begin{bmatrix} c_{1,i} & c_{2,i} & \cdots & c_{N_t,i} \end{bmatrix} \mathbf{p} e^{j\alpha_i} \ , i = 1, 2, \cdots, N_t, \ t = 1, 2, \cdots, N_t \qquad (9)$$

$$\mathbf{p} = \begin{bmatrix} e^{j\beta_1} & e^{-j\frac{2\pi(t-1)}{N_t}} e^{j\beta_2} & e^{-j\frac{4\pi(t-1)}{N_t}} e^{j\beta_3} \cdots e^{-j\frac{2(N_t-1)\,\pi(t-1)}{N_t}} e^{j\beta_{N_t}} \end{bmatrix} \qquad (10)$$

where $c_{j,\,i}$ is the ith symbol of the jth layer. The symbols $c_{j,\,i}s$ are selected by the bits $b_1 b_2 \ldots b_u$. In (9) and (10), $\alpha_1, \alpha_2, \cdots, \alpha_{N_t}$ and $\beta_1, \beta_2, \cdots, \beta_{N_t}$ are the phase shifts among transmitted symbols and layers, respectively. It is worthy of noting that this scheme provides spectral efficiency of N_t symbols per channel use.

The upper bound of the average probability of codeword matrix $\mathbf{C}_m$ and the decoder decided $\mathbf{C}_n$ is given in [13] as

$$P(\mathbf{C}_m \rightarrow \mathbf{C}_n) \le \frac{1}{\left| \mathbf{I}_{N_r \times N_r} + \frac{E_s}{4N_0 N_t} \mathbf{R} \otimes \mathbf{I}_{N_r} \right|} \qquad (11)$$

where $\mathbf{R} = (\mathbf{C}_m - \mathbf{C}_n)(\mathbf{C}_m - \mathbf{C}_n)^H$ and the superscript H denotes Hermitian transpose. This result was derived by using the Chernoff's upper bound [26].

In the case of high signal to noise ratio, (11) can be written as

$$P(\mathbf{C}_m \rightarrow \mathbf{C}_n) \le (\lambda_1 \lambda_2 \cdots \lambda_r)^{-N_r} \left(\frac{E_s}{4N_0 N_t} \right)^{-rN_r} \qquad (12)$$

where r and $\lambda_1, \lambda_2, \cdots, \lambda_r$ are the rank and the eigenvalues of matrix $\mathbf{R}$, respectively.

The angles $\alpha_1, \cdots, \alpha_{N_t}, \beta_1, \cdots, \beta_{N_t}$ have to be chosen to increase the upper bound of (11). This can be obtained by maximizing the rank r to become N_t and the product of eigenvalues $(\lambda_1 \lambda_2 \cdots \lambda_r)$ of $\mathbf{R}$.

It is worthy of noting that this coding scheme achieves diversity order of $N_t \times N_r$ and maximum coding gain $(\lambda_1 \lambda_2 \cdots \lambda_{N_t})^{\frac{1}{N_t}}$ under specific values of $\alpha_1, \cdots, \alpha_{N_t}, \beta_1, \cdots, \beta_{N_t}$.
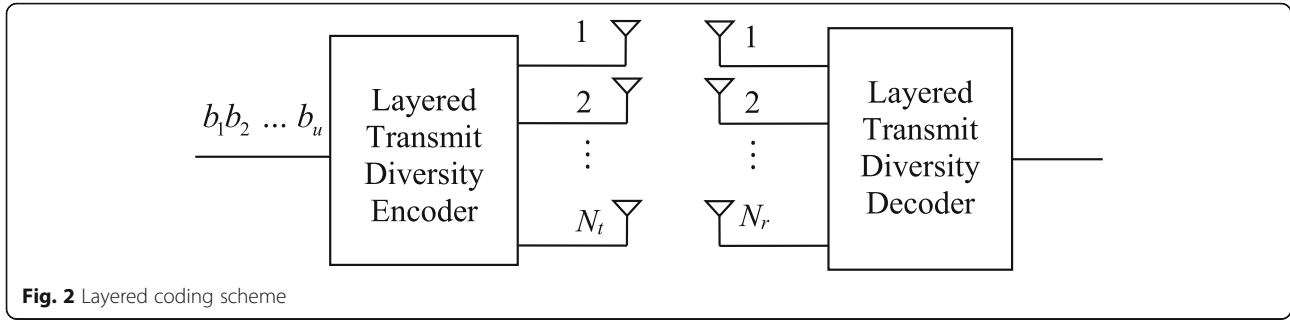
Fig. 2 Layered coding scheme

4.2 Proposed L-SM scheme

In this section, we combine the proposed layered coding scheme presented in Section 4.1 with the spatial modulation scheme presented in [18, 19] to form a layered spatial modulation (L-SM) scheme. Assume that the total number of antennas = N_{all} and the number of active transmit antennas at each antenna selection = N_t. In Section 4.1, $N_{all} = N_t$ and one codeword matrix is transmitted over N_t symbol periods (one codeword period) with diversity order equals $N_t \times N_r$. In this case, there is no antenna selection and the proposed scheme uses N_t^2 symbols per N_t channel use. For $N_{all} \geq 2N_t$, two different codewords are transmitted from different active transmit antennas over two different codeword periods at each antenna selection case. Depending on the antenna selection case, each codeword is transmitted circularly from N_t active antennas along the total number of transmit antennas. This produces $N = \frac{2N_{all}!}{(N_{all}-N_t)!N_t!} + N_{all}$ antenna selections and the number of bits related to these selections = $k = \log_2 N$. The proposed L-SM scheme achieves diversity order of $N_t \times N_r$ and maximum coding gain at each case of the antenna selections. Since each codeword contains N_t^2 symbols, the proposed L-SM scheme uses (k bits + $2N_t^2$ symbols) per $2N_t$ channel use which is equivalent to ($\frac{k}{2N_t}$ bits + N_t symbols) per channel use. Note that N_t symbols = $N_t \log_2 M$ bits. This yields ($\frac{k}{2N_t} + N_t \log_2 M$) bits per channel use. For the proposed L-SM scheme, the received signal matrix over the two codeword periods is sent to the maximum likelihood decoder to estimate the k bits ($b_1, b_2,..., b_k$) related to antenna selections and the $2N_t^2 \log_2 M$ bits related to the symbols in the two codeword matrices. Two different examples are introduced to explain the concept of the L-SM scheme.

Example 1 We consider the proposed scheme with $N_{all} = N_t = 2$. In this case, there is no antenna selection. Therefore, one codeword with two layers is transmitted from two antennas over one codeword period of time. Assume that the symbols c_{11} and c_{12} are related to layer 1 and the symbols c_{21} and c_{22} are related to layer 2. According to (8), (9), and (10), the transmitted codeword matrix $\mathbf{C}$ of this example is given by

$$\mathbf{C} = \begin{bmatrix} e^{j\alpha_1}\left(e^{j\beta_1}c_{11} + e^{j\beta_2}c_{21}\right) & e^{j\alpha_2}\left(e^{j\beta_1}c_{12} + e^{j\beta_2}c_{22}\right) \\ e^{j\alpha_2}\left(e^{j\beta_1}c_{12} - e^{j\beta_2}c_{22}\right) & e^{j\alpha_1}\left(e^{j\beta_1}c_{11} - e^{j\beta_2}c_{21}\right) \end{bmatrix}$$

$$(13)$$

The spectral efficiency of this case is equal to 2 symbols/s/Hz = (2 $\log_2 M$) bits/s/Hz. For the case of BPSK modulation, we assume that $\alpha_1 = \beta_1 = 0$ as reference. The phase shifts α_2 and β_2 have to be chosen to increase the upper bound of (11). This can be obtained by maximizing the rank r and the product of eigenvalues ($\lambda_1 \lambda_2$) of $\mathbf{R}$. A rank r of 2 and maximum product of eigenvalues ($\lambda_1 \lambda_2$) occur when $\alpha_2 = \beta_2 = \frac{\pi}{2}$. For the case of quadrature phase shift keying (QPSK) modulation, $\alpha_1 = \beta_1 = 0$, $\alpha_2 = \frac{\pi}{6}$, and $\beta_2 = \frac{\pi}{4}$ and the spectral efficiency = 4 bits/s/Hz. For the case of 8-QAM modulation, $\alpha_1 = \beta_1 = 0$, $\alpha_2 = 0.21\pi$, and $\beta_2 = \frac{3\pi}{16}$ and the spectral efficiency = 6 bits/s/Hz. For the case of 16-QAM modulation, $\alpha_1 = \beta_1 = 0$, $\alpha_2 = 0.1\pi$, and $\beta_2 = \frac{\pi}{4}$ and the spectral efficiency = 8 bits/s/Hz.

Example 2 We consider the proposed L-SM scheme with $N_{all} = 4$, $N_t = 2$ and 2 transmitted codewords $\mathbf{C}$ and $\mathbf{E}$. The transmission approach of this example is demonstrated in Table 2. Note that the two codewords are transmitted from different active transmit antennas over two different codeword periods at each antenna selection case. The rotation of the two codeword matrices is different than that in [21–25]. The number of antenna selections $N = \frac{2 \times 4!}{(4-2)!2!} + 4 = 16$ as shown in Table 2 and $k = 4$. For BPSK, QPSK, 8-QAM, and 16-QAM modulation, the angles α_1, β_1, α_2, and β_2 are the same as those in Example 1 whereas the angles θ_1, θ_2, θ_3, θ_4, and θ_5 are selected to maximize the diversity order to $2N_r$ and multiplexing gain and they are equal to $\frac{\pi}{12}, \frac{2\pi}{12}, \frac{4\pi}{12}, \frac{5\pi}{12}$, and $\frac{3\pi}{12}$, respectively. The spectral efficiency of this example = ($\frac{k}{2N_t}$ bits + N_t symbols) per channel use = ($1 + 2\log_2 M$) bits/s/Hz.

5 Performance analysis of the proposed L-SM scheme

The performance of the proposed L-SM scheme is derived in this section. At antenna selection related to b_1, $b_2,..., b_k$, the received signal matrices $\mathbf{Y}_m$ and $\mathbf{Y}_p$ related

Table 2 The transmission and encoding of the proposed L-SM scheme with $N_{all} = 4$, $N_t = 2$, and $(1 + 2\log_2 M)$ bits/s/Hz

The first codeword period				The second codeword period			
Ant.1	Ant.2	Ant.3	Ant.4	Ant.1	Ant.2	Ant.3	Ant.4
$C(1,1)$	$C(2,1)$	0	0	0	0	$E(1,1)$	$E(2,1)$
$C(1,2)$	$C(2,2)$	0	0	0	0	$E(1,2)$	$E(2,2)$
0	0	$C(1,1)$	$C(2,1)$	$E(1,1)$	$E(2,1)$	0	0
0	0	$C(1,2)$	$C(2,2)$	$E(1,2)$	$E(2,2)$	0	0
$C(1,1)e^{j\theta_1}$	0	$C(2,1)e^{j\theta_1}$	0	0	$E(1,1)e^{j\theta_2}$	0	$E(2,1)e^{j\theta_2}$
$C(1,2)e^{j\theta_1}$	0	$C(2,2)e^{j\theta_1}$	0	0	$E(1,2)e^{j\theta_2}$	0	$E(2,2)e^{j\theta_2}$
0	$C(1,1)e^{j\theta_2}$	0	$C(2,1)e^{j\theta_2}$	$E(1,1)e^{j\theta_1}$	0	$E(2,1)e^{j\theta_1}$	0
0	$C(1,2)e^{j\theta_2}$	0	$C(2,2)e^{j\theta_2}$	$E(1,2)e^{j\theta_1}$	0	$E(2,2)e^{j\theta_1}$	0
$C(1,1)e^{j\theta_3}$	0	0	$C(2,1)e^{j\theta_3}$	0	$E(1,1)e^{j\theta_4}$	$E(2,1)e^{j\theta_4}$	0
$C(1,2)e^{j\theta_3}$	0	0	$C(2,2)e^{j\theta_3}$	0	$E(1,2)e^{j\theta_4}$	$E(2,2)e^{j\theta_4}$	0
0	$C(1,1)e^{j\theta_4}$	$C(2,1)e^{j\theta_4}$	0	$E(1,1)e^{j\theta_3}$	0	0	$E(2,1)e^{j\theta_3}$
0	$C(1,2)e^{j\theta_4}$	$C(2,2)e^{j\theta_4}$	0	$E(1,2)e^{j\theta_3}$	0	0	$E(2,2)e^{j\theta_3}$
$C(1,1)e^{j\theta_5}$	$C(2,1)e^{j\theta_5}$	0	0	0	0	$E(1,1)e^{j\theta_5}$	$E(2,1)e^{j\theta_5}$
$C(1,2)e^{j\theta_5}$	$C(2,2)e^{j\theta_5}$	0	0	0	0	$E(1,2)e^{j\theta_5}$	$E(2,2)e^{j\theta_5}$
0	0	$C(1,1)e^{j\theta_5}$	$C(2,1)e^{j\theta_5}$	$E(1,1)e^{j\theta_5}$	$E(2,1)e^{j\theta_5}$	0	0
0	0	$C(1,2)e^{j\theta_5}$	$C(2,2)e^{j\theta_5}$	$E(1,2)e^{j\theta_5}$	$E(2,2)e^{j\theta_5}$	0	0
0	0	$E(1,1)$	$E(2,1)$	$C(1,1)$	$C(2,1)$	0	0
0	0	$E(1,2)$	$E(2,2)$	$C(1,2)$	$C(2,2)$	0	0
$E(1,1)$	$E(2,1)$	0	0	0	0	$C(1,1)$	$C(2,1)$
$E(1,2)$	$E(2,2)$	0	0	0	0	$C(1,2)$	$C(2,2)$
0	$E(1,1)e^{j\theta_2}$	0	$E(2,1)e^{j\theta_2}$	$C(1,1)e^{j\theta_1}$	0	$C(2,1)e^{j\theta_1}$	0
0	$E(1,2)e^{j\theta_2}$	0	$E(2,2)e^{j\theta_2}$	$C(1,2)e^{j\theta_1}$	0	$C(2,2)e^{j\theta_1}$	0
$E(1,1)e^{j\theta_1}$	0	$E(2,1)e^{j\theta_1}$	0	0	$C(1,1)e^{j\theta_2}$	0	$C(2,1)e^{j\theta_2}$
$E(1,2)e^{j\theta_1}$	0	$E(2,2)e^{j\theta_1}$	0	0	$C(1,2)e^{j\theta_2}$	0	$C(2,2)e^{j\theta_2}$
0	$E(1,1)e^{j\theta_4}$	$E(2,1)e^{j\theta_4}$	0	$C(1,1)e^{j\theta_3}$	0	0	$C(2,1)e^{j\theta_3}$
0	$E(1,2)e^{j\theta_4}$	$E(2,2)e^{j\theta_4}$	0	$C(1,2)e^{j\theta_3}$	0	0	$C(2,2)e^{j\theta_3}$
$E(1,1)e^{j\theta_3}$	0	0	$E(2,1)e^{j\theta_3}$	0	$C(1,1)e^{j\theta_4}$	$C(2,1)e^{j\theta_4}$	0
$E(1,2)e^{j\theta_3}$	0	0	$E(2,2)e^{j\theta_3}$	0	$C(1,2)e^{j\theta_4}$	$C(2,2)e^{j\theta_4}$	0
0	0	$E(1,1)e^{j\theta_5}$	$E(2,1)e^{j\theta_5}$	$C(1,1)e^{j\theta_5}$	$C(2,1)e^{j\theta_5}$	0	0
0	0	$E(1,2)e^{j\theta_5}$	$E(2,2)e^{j\theta_5}$	$C(1,2)e^{j\theta_5}$	$C(2,2)e^{j\theta_5}$	0	0
$E(1,1)e^{j\theta_5}$	$E(2,1)e^{j\theta_5}$	0	0	0	0	$C(1,1)e^{j\theta_5}$	$C(2,1)e^{j\theta_5}$
$E(1,2)e^{j\theta_5}$	$E(2,2)e^{j\theta_5}$	0	0	0	0	$C(1,2)e^{j\theta_5}$	$C(2,2)e^{j\theta_5}$

to codeword matrices $\mathbf{C}_m$ and $\mathbf{C}_p$ transmitted from two different active antenna combinations over different symbol periods through two codeword periods are given by

$$\mathbf{Y}_m = \sqrt{\frac{E_s}{N_t}} \mathbf{A}_l \mathbf{C}_m e^{j\theta_l} + \mathbf{V}_1 \tag{14}$$

$$\mathbf{Y}_p = \sqrt{\frac{E_s}{N_t}} \mathbf{A}_f \mathbf{C}_p e^{j\theta_f} + \mathbf{V}_2 \tag{15}$$

where the active channel matrices $\mathbf{A}_l$ and $\mathbf{A}_f$ and the angles θ_l and θ_f are related to active antenna combinations l and f which are different in all antenna elements.

Define matrices $\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)$ and $\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p)$ as

$$\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m) = \mathbf{Y}_m - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_l \mathbf{C}_m e^{j\theta_l} = \mathbf{V}_1 \tag{16}$$

$$\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p) = \mathbf{Y}_p - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_f \mathbf{C}_p e^{j\theta_f} = \mathbf{V}_2 \tag{17}$$

$$\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n) = \mathbf{Y}_m - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}} \tag{18}$$

$$\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q) = \mathbf{Y}_p - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_{\tilde{f}} \mathbf{C}_q e^{j\theta_{\tilde{f}}} \qquad (19)$$

where $\mathbf{C}_n$ and $\mathbf{C}_q$ are different than $\mathbf{C}_m$ and $\mathbf{C}_p$. The pairwise error probability of $(b_1, b_2, ..., b_k, \mathbf{C}_m, \mathbf{C}_p)$ and the decoder decided $(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q)$ is given by

$$P_r(b_1, b_2, ..., b_k, \mathbf{C}_m, \mathbf{C}_p \to \tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q) =$$
$$P_r\left(\|\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)\|_F^2 > \|\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)\|_F^2 \right)$$
$$+ P_r\left(\|\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p)\|_F^2 > \|\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q)\|_F^2 \right)$$
$$(20)$$

where the subscript F denotes the Frobenius norm of the matrix.

The mean and variance matrices of $\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)$ are given by

$$\overline{\mathbf{G}}(b_1, b_2, ..., b_k, \mathbf{C}_m) = E[\mathbf{V}_1] = \mathbf{0}_{N_r \times N_t} \qquad (21)$$

$$\sigma^2_{\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)} = E|\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)$$
$$-\overline{\mathbf{G}}(b_1, b_2, ..., b_k, \mathbf{C}_m)|^2 = N_0 I_{N_r \times N_t} \qquad (22)$$

where $\mathbf{0}_{N_r \times N_t}$ is $N_r \times N_t$ zero matrix and E is the expectation.

In a similar manner,

$$\overline{\mathbf{G}}(b_1, b_2, ..., b_k, \mathbf{C}_p) = \mathbf{0}_{N_r \times N_t} \qquad (23)$$

$$\sigma^2_{\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p)} = N_0 I_{N_r \times N_t} \qquad (24)$$

The mean and variance matrices of $\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)$ are given by

$$\overline{\mathbf{G}}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n) = E\left[\mathbf{Y}_m - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}\right] = \mathbf{0}_{N_r \times N_t}$$
$$(25)$$

$$\sigma^2_{\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)} = E|\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n) - \overline{\mathbf{G}}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)|^2$$
$$= E\left|\mathbf{Y}_m - \sqrt{\frac{E_s}{N_t}} \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}\right|^2$$
$$(26)$$

$\mathbf{V}_1$ is independent of $\mathbf{A}_l \mathbf{C}_m e^{j\theta_l}$ and $\mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}$, then

$$\sigma^2_{\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)} = E|\mathbf{V}_1|^2 + \frac{E_s}{N_t} E\left(|\mathbf{A}_l \mathbf{C}_m e^{j\theta_l} - \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}|^2 \right)$$
$$= N_0 I_{N_r \times N_t} + \frac{E_s}{N_t} E\left(|\mathbf{A}_l \mathbf{C}_m e^{j\theta_l} - \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}|^2 \right)$$
$$(27)$$

In a similar manner,

$$\overline{\mathbf{G}}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q) = \mathbf{0}_{N_r \times N_t} \qquad (28)$$

$$\sigma^2_{\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q)} = N_0 I_{N_r \times N_t} + \frac{E_s}{N_t} E\left(\left|\mathbf{A}_f \mathbf{C}_p e^{j\theta_f} - \mathbf{A}_{\tilde{f}} \mathbf{C}_q e^{j\theta_{\tilde{f}}}\right|^2 \right)$$
$$(29)$$

Let,

$$\mathbf{D}(b_1, b_2, ..., b_k, \mathbf{C}_m) = \mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)./\left(\sqrt{N_t}\, \sigma_{\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_m)}\right)$$
$$(30)$$

$$\mathbf{D}(b_1, b_2, ..., b_k, \mathbf{C}_p) = \mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p)./\left(\sqrt{N_t}\sigma_{\mathbf{G}(b_1, b_2, ..., b_k, \mathbf{C}_p)}\right)$$
$$(31)$$

$$\mathbf{D}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n) = \mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)./\left(\sqrt{N_t}\sigma_{\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)}\right)$$
$$(32)$$

$$\mathbf{D}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q) = \mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q)./\left(\sqrt{N_t}\sigma_{\mathbf{G}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q)}\right)$$
$$(33)$$

where the operation ./ is Hadamard division (element by element of the numerator and denominator matrices).
$\|\mathbf{D}(b_1, b_2, ..., b_k, \mathbf{C}_m)\|_F^2$, $\|\mathbf{D}(b_1, b_2, ..., b_k, \mathbf{C}_p)\|_F^2$, $\|\mathbf{D}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n)\|_F^2$, and $\|\mathbf{D}(\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_q)\|_F^2$ are central chi-square random variables with $2N_r$ degrees of freedom. By using the approach in [20], the pairwise error probability can be obtained as

$$P_r\left((b_1, b_2, ..., b_k, \mathbf{C}_m, \mathbf{C}_p) \to (\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q)\right)$$
$$= I_{\frac{N_0}{2N_0 + \frac{z_1}{N_t^2}}}(N_r, N_r) + I_{\frac{N_0}{2N_0 + \frac{z_2}{N_t^2}}}(N_r, N_r)$$
$$(34)$$

In (34), z_1 and z_2 are given by

$$z_1 = \frac{E_s}{N_t} E\left\|\mathbf{A}_l \mathbf{C}_m e^{j\theta_l} - \mathbf{A}_{\tilde{l}} \mathbf{C}_n e^{j\theta_{\tilde{l}}}\right\|_F^2 \qquad (35)$$

$$z_2 = \frac{E_s}{N_t} E\left\|\mathbf{A}_f \mathbf{C}_p e^{j\theta_f} - \mathbf{A}_{\tilde{f}} \mathbf{C}_q e^{j\theta_{\tilde{f}}}\right\|_F^2 \qquad (36)$$

By using the upper bound presented in [27], the average probability of bit error is given by

$$P_b \le \sum_{b_1, ..., b_k, \mathbf{C}_m, \mathbf{C}_p} \sum_{\tilde{b}_1, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q} \frac{N_e(b_1, ..., b_k, \mathbf{C}_m, \mathbf{C}_p, \tilde{b}_1, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q)}{(k + v) 2^{k+v}}$$
$$\times P_r\left((b_1, b_2, ..., b_k, \mathbf{C}_m, \mathbf{C}_p) \to (\tilde{b}_1, \tilde{b}_2, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q)\right)$$
$$(37)$$

where $v = 2N_t^2 \log_2(M)$ and $N_e(b_1, ..., b_k, \mathbf{C}_m, \mathbf{C}_p, \tilde{b}_1, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q)$ is the number of bits in error between $b_1, ..., b_k$, $\mathbf{C}_m, \mathbf{C}_p$ and $\tilde{b}_1, ..., \tilde{b}_k, \mathbf{C}_n, \mathbf{C}_q$. By substituting (34) in (37),
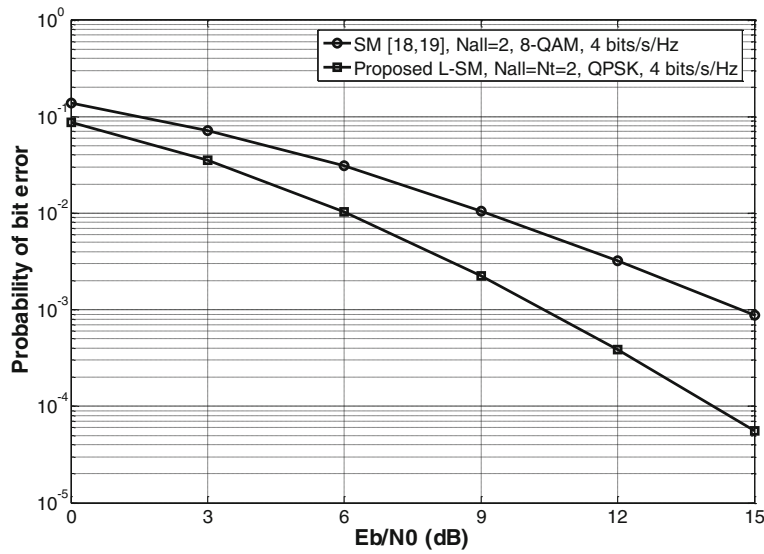
Fig. 3 Performance comparison of the SM and proposed L-SM schemes with $N_r = 2$ for 4 bits/s/Hz

$$P_b \leq \sum_{b_1,...,b_k,\mathbf{C}_m,\mathbf{C}_p} \; \sum_{\tilde{b}_1,...,\tilde{b}_k,\mathbf{C}_n,\mathbf{C}_q} \frac{N_e\left(b_1,...,b_k,\mathbf{C}_m,\mathbf{C}_p,\tilde{b}_1,...,\tilde{b}_k,\mathbf{C}_n,\mathbf{C}_q\right)}{(k+v)\,2^{k+v}}$$
$$\times \left(I_{\frac{N_0}{2N_0+\frac{z_1}{N_t^2}}}(N_r,N_r) + I_{\frac{N_0}{2N_0+\frac{z_2}{N_t^2}}}(N_r,N_r) \right)$$
$$(38)$$

6 Numerical results and comparisons

In this section, we compare the performance of the proposed L-SM scheme with the spatial modulation schemes: SM [18, 19], STBC-SM [21], STBC-CSM [23],
and STBC-TSM [25] with the same number of antennas and same spectral efficiency.

Figure 3 shows the bit error probability of the proposed L-SM scheme with two layers compared to SM scheme [18, 19] as a function of E_b/N_0 where E_b is the bit energy. The proposed L-SM and SM schemes are equipped with two transmit and two receive antennas. For the proposed L-SM scheme $N_{all} = N_t = 2$ and the codeword is transmitted over one codeword period without any antenna selection. QPSK and 8-QAM modulation are used for the proposed L-SM and SM schemes, respectively. This yields spectral efficiency of 4 bits/s/Hz for both of them. Example 1 in Section 4.2 explains the
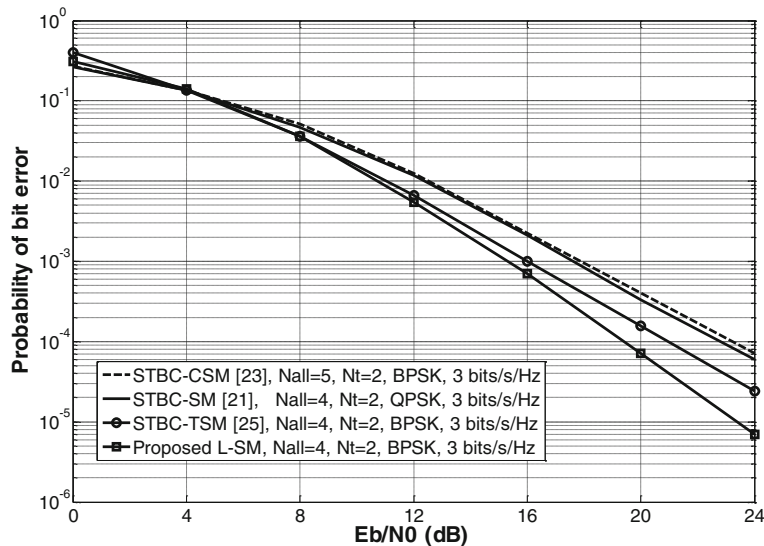

Fig. 4 Performance comparison of STBC-CSM, STBC-SM, STBC-TSM, and proposed L-SM schemes with $N_r = 1$ for 3 bits/s/Hz
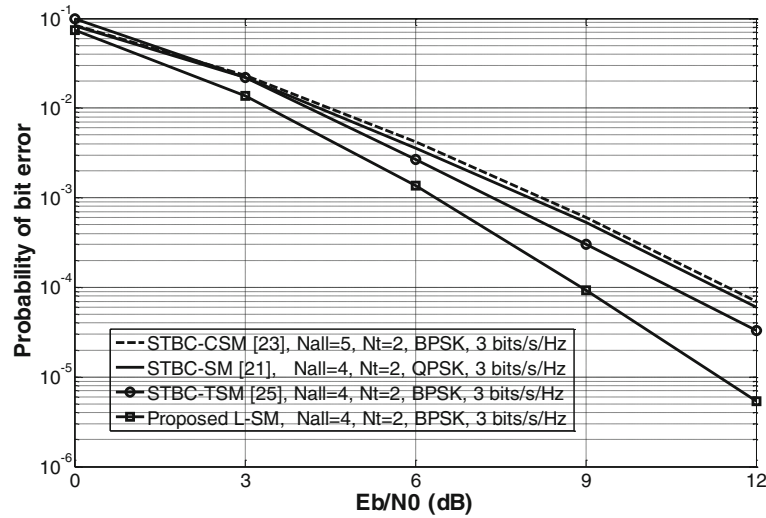
Fig. 5 Performance comparison of STBC-CSM, STBC-SM, STBC-TSM, and proposed L-SM schemes with $N_r = 2$ for 3 bits/s/Hz

proposed scheme for this case. As can be observed from the figure, the proposed scheme significantly outperforms the SM scheme.

In Figs. 4 and 5, the performance of the proposed L-SM, STBC-SM, STBC-CSM and STBC-TSM schemes is presented for $N_r = 1$ and $N_r = 2$. All these schemes except STBC-CSM are equipped with four transmit antennas, and the SM-CSM scheme is equipped with five transmit antennas. The number of active transmit antennas of all these schemes is equal to 2. To achieve spectral efficiency of 3 bits/s/Hz for all schemes, BPSK modulation is used for the proposed L-SM, STBC-CSM, and STBC-TSM schemes and QPSK is used for

STBC-SM scheme. The proposed L-SM scheme in this case is explained by example 2 of Section 4.2. In both figures, significant improvement in the performance of the proposed L-SM scheme is achieved compared to that of the all other schemes.

Figure 6 further compares the performance of the proposed L-SM scheme with SM scheme. Both schemes use eight transmit and two receive antennas. The proposed L-SM scheme uses two active transmit antennas and QPSK modulation. The total number of antenna selections $N = \frac{2 \times 8!}{(8-2)!2!} + 8 = 64$, but in this example, we use only 16 antenna selections to produce $k = 4$ which yields spectral efficiency of 5 bits/s/Hz. The SM scheme uses
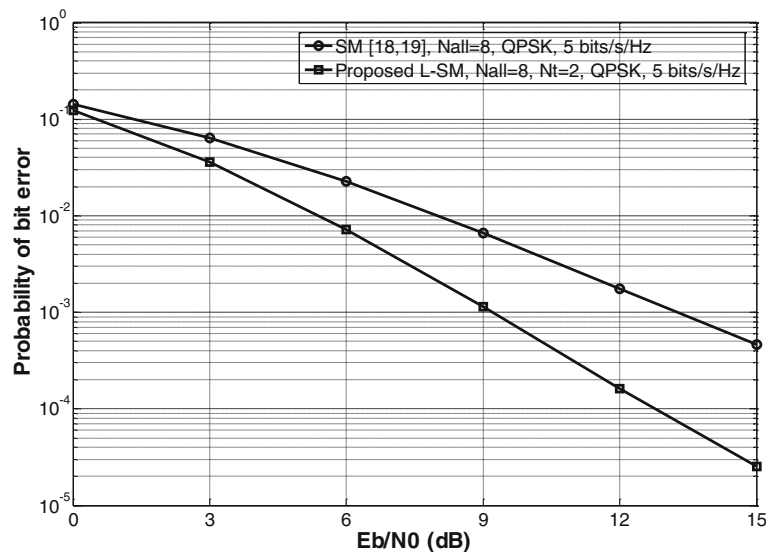

Fig. 6 Performance comparison of SM and proposed L-SM schemes with $N_r = 2$ for 5 bits/s/Hz

QPSK modulation to satisfy the same spectral efficiency of 5 bits/s/Hz. As expected, similar behavior as in the case of Fig. 3 is observed.

Note that the generalized spatial modulation scheme in [20] uses more than one active transmit antenna at each time period to increase the spectral efficiency. The performance of this scheme is slightly smaller than the performance of the spatial modulation scheme in [18, 19] with the same spectral efficiency as explained in [20]. Therefore, no need to compare this scheme with our scheme since our scheme significantly outperforms the spatial modulation scheme in [18, 19]. Also, no need to compare our scheme with the H-STBC-SM [22] and CIOD-SM-H [24] schemes because their performance is less than that of the STBC-CSM [23] and STBC-TSM [25] schemes with the same transmit antennas and same spectral efficiency as can be shown in [23, 25].

7 Conclusions

We have proposed L-SM scheme with high performance compared to all existing spatial modulation schemes. The proposed L-SM scheme uses a number of layers with the same number of active transmit antennas. At each antenna selection, the proposed L-SM scheme maximizes the diversity and coding gains. The performance of the proposed L-SM scheme was analyzed. Numerical results of the proposed L-SM and different spatial modulation schemes were presented. Significant improvement in the performance of the proposed L-SM scheme is achieved compared to that of the other schemes.

Abbreviations
BPSK: Binary phase shift keying; CIOD-SM-H: Complex interleaved orthogonal design SM with the high degree of spatial modulation; E_b/N_0: Bit energy to noise ratio; H-STBC-SM: High-rate space-time block coded spatial modulation; L-SM: Layered spatial modulation; MIMO: Multiple input multiple output; M-QAM: M-ary quadrature amplitude modulation; QPSK: Quadrature phase shift keying; SM: Spatial modulation; STBC: Space-time block coding; STBC-CSM: Spatial modulation space-time block coding scheme with cyclic structure; STBC-SM: Space-time block coded spatial modulation; STBC-TSM: Cyclic temporally and spatially modulated space-time block coding

Authors' contributions
All contributions are from the sole author SA. The author read and approved the final manuscript.

Competing interests
The author declares that he has no competing interests.

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