A Survey on Spatial Modulation OFDM: Optimal Detection and Performance Analysis

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Abstract—Spatial modulation is a novel modulation scheme that aims to acquire a trade-off between the two adverse purposes in wireless communications, namely the improvements of data rate and data reliability, by adjuncting the operational transmit antenna index in the emitted bits. To fight against inter-symbol interference (ISI) present in frequency selective channels, orthogonal frequency division multiplexing (OFDM) has become a extensively accepted and used mechanism. We investigate in this work the performance of SM-OFDM modulation over frequency selective MIMO channel using quadrature amplitude modulation (QAM) scheme. At the receiver side, a group of detectors is proposed to recover the active transmit antenna index (Tx-antenna) and the emitted data sequence. In this paper, a new SM-OFDM-based scheme is proposed, which adds another element of information in the transmitted SM-data block consisting of a chosen constellation among the available rotated set. To attain this, an additional index is used to select the specific constellation. At the receiver, a set of detectors is proposed to jointly estimate the transmitted symbol, as well as the used constellation and the active transmit antenna indices. The comparison of the performance of this new scheme against the conventional SM-OFDM shows an increased spectral efficiency at the price of a slight degradation in bit error rate. The proposed scheme permits a trade-off between the quality of the communication and the achieved spectral efficiency. Some concluding remarks are drawn over simulation results.

***Keywords*—Spatial modulation, orthogonal frequency division multiplexing, MIMO, inter-symbol interference, optimal detector.**

I. INTRODUCTION

Wireless Communication has invaded nowadays all the fields of aspects of modern life. Accessing the global network has become the most important behavior of our life style. Wireless communication is an ever developing field that still holds many possibilities in this area. Up to the current communications standards, demand for an increased throughput of wireless communication systems, has been fulfilled by the aid of multiple antenna systems at the transceiver block, the so called MIMO-Systems, or by combination of these latter with techniques such as OFDM [1]. In [2,3], A.R. Kaye and D.A. George proved that transmitting over single antenna systems, could be extended to multiple antenna case. Since then, the efforts are focused on looking for methods that enhance the spectral efficiency, and low hardware and software complexities. MIMO communication systems offer higher data rates and enhanced BER performance, compared to single-antenna transmissions, at the cost of:

1. An increased level of complexity at the receiver, induced by the interchannel interference emanating from the simultaneous transmission of many data sequences from multiple antennas;
2. The transmit-antenna elements need to be synchronized to exploit the advantages of multiple access MIMO communications;
3. To have the ability to convey many data symbols simultaneously, multiple RF chains are required at the transmitter side.

Motivated by these aspects, SM has been coined recently. Therefore, SM has been investigated for flat fading channels using multiple antennas in [4], and for OFDM transmission [5] .

Moreover, a set of SM-based detectors have been introduced. First, an iterative maximum ratio combining (i-MRC) detector is used in [4], in order to retrieve both the emitted data stream and the TX-antenna index. Due to the sub-optimality of i-MRC-based demodulator, Jeganathan et a1. have derived in [6] an optimal detector (OD) for SM system that utilizes ML metrics. It was illustrated that OD offers a high performance with a reasonable complexity.

An alternative multiple antenna-frequency selective transmission approach, called spatial modulation-OFDM (SM-OFDM), that eliminates interchannel interference (ICI) was introduced in [5], [7]. Furthermore, better performance can be achieved when applying soft-decision ML detector discussed in [8]. A low-complexity soft output DBD algorithm and a distance-based ordered detection (DBD) for

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SM-MIMO schemes are proposed in [9]. In the aim to reduce the complexity of OD approach at a viable BER performance, sphere decoder (SD) detector was also investigated in SM schemes in [10]. Generalized SM (G-SM) was afterwards proposed in [11], [12], where more than one transmit antenna are active simultaneously, to exploit the advantages of MIMO configuration. Furthermore, we analyse in this letter the performance of SM-OFDM-based scheme using a group of detectors, and a new cosine-rule-based detector is also proposed .

The paper is organized as follows. Section II describes the mapping paradigm of SM-MIMO based scheme. Design guidelines for SM systems are given in section III. Section IV details the operating principle of SM-OFDM based architecture. SM-OFDM detectors are described in sections V, including some numerical results. A new SM-OFDM-based detector is proposed in section VI. Conclusions are presented in the last section.

II. SPATIAL MODULATION (SM)

Spatial modulation (SM) is a novel mapping paradigm, where the antenna index is utilized as an additional source to send the information bits. At the transmitter, the information bits are divided into blocks, each one of them has the length:

$$b_{SM} = log_2(N_t) + log_2(M) \tag{1}$$

with $log2(N_t)$ presents the number of bits utilized to identify the activated transmit antenna among the possible ones in the antenna-array which are kept silent meanwhile, and $log_2(M)$ is the number of bits used to indicate the symbol in the signal constellation emitted by the selected antenna as shown in Fig. 2. This idea was introduced for the first time in [4].

An example of SM is shown in figure 2, with $N_t = 2$ that uses $4QAM$ modulation, thereby using 3bits/symbol for each transmitted SM symbol. Assuming that the input data bits is $[1 \quad 0 \quad 0]^T$, which corresponds in SM mapping to the transmission of the symbol $-1.0000 + 1.0000i$ from the second transmit antenna.

The resulted signal is transmitted through the wireless channel using the following equation:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \tag{2}$$

where: $\mathbf{y}$ is the complex received vector; $\mathbf{H}$ is the complex channel matrix; $\mathbf{w}$ is the complex AWGN noise vector; and $\mathbf{x}$ is the complex modulated transmitted vector.

The channel matrix $\mathbf{H}(k)$ can be presented as a group of complex coefficients between the transmit and receive antennas as illustrated in the following equation:

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} & \dots & h_{1N_t} \\ h_{21} & h_{22} & \dots & h_{2N_t} \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r1} & h_{N_r2} & \dots & h_{N_rN_t} \end{pmatrix} \tag{3}$$

III. DESIGN GUIDELINES FOR SM-MIMO SYSTEMS

SM is a new modulation concept that aims to offer some benefits in terms of:

- **Rate:** due to the introduction of the spatial-position and the adoption of the three-dimensional constellation diagram, SM-MIMO can offer a high throughput and an increased SE, compared to SISO system. Hence, this design should be tuned accurately since the data rate could further enhanced by a proper data streams encoding ensuring ICI mitigation, but at the cost of an additional receiver complexity [13].
- **Capacity:** depends on the number of transmit antenna elements (N_t) [14].
- **Error performance :** it was shown in most of research papers that SM can provide a better BER performance than SISO counterpart, especially, when the number of TX-antennas is higher than four and the number of receive antennas is more than one [15].
- **Channel fading:** the BER performance of SM-based scheme is affected by the distribution of the wireless channel fading [15]. Thus, more bits can be encoded and transmitted if there is less channel fading or equivalently a higher Nakagami fading parameter [15].
- **Channel State Information:** based on the assumption that adequate channel estimators are used, it was illustrated that SM is robust to imperfect channel state information (CSI) [16, 17].
- **Demodulation:** the selection of the best demodulator depends on the offered performance and the detection complexity level at the receiver.
- **Energy-Efficiency:** SM-MIMO scheme uses one RF chain at each time instant, thus providing a better energy efficiency and minimizing the complexity [18].

IV. SM-OFDM BASED SCHEME

In the current and future generations of wireless communication networks, and for many applications, ISI resulted when using a frequency selective wireless channel. For a frequency-selective fading channel, OFDM is a popular modulation mechanism, which is utilized to eliminate ISI and to take advantages of the frequency diversity. Subsequently, coupling SM and OFDM is favourable to deal with frequency selective channels.

The operating principle of SM-OFDM is described in Figure. 3. After insertion of error correction codes in the original interleaved data to combat channel errors, the bit stream is mapped with SM. In general, the number of bits/symbol/sub-carrier or sub-channel b_{SM} that SM-OFDM based scheme can transmit for each block is given earlier in “(1)”.

Then, the output vectors from the SM mapping $\mathbf{R}(t)$ are converted to the time domain by using the inverse fast

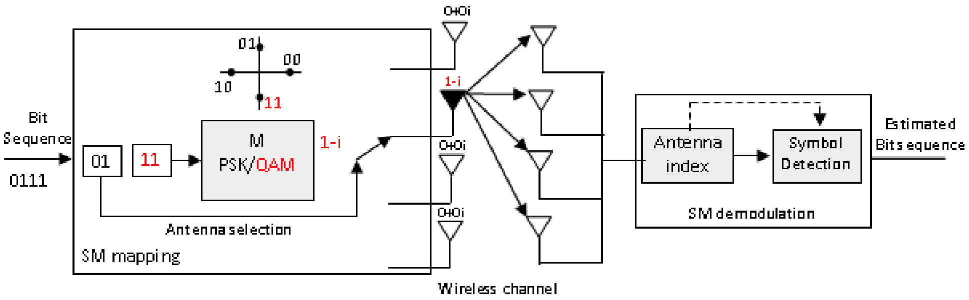
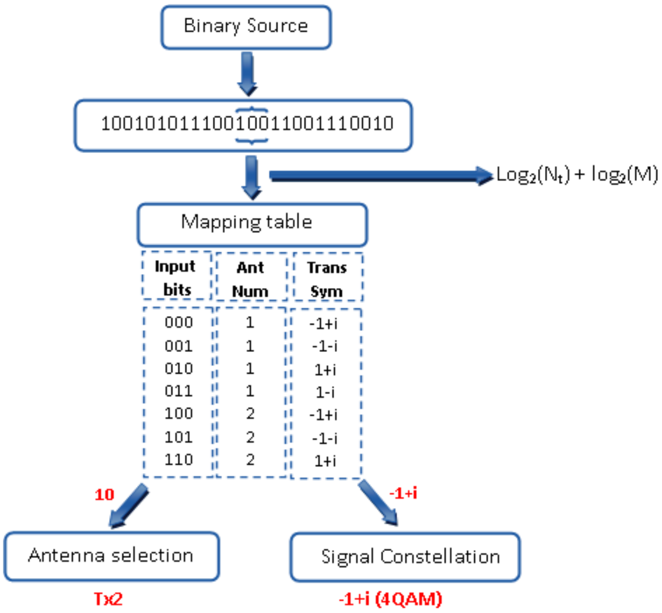


Fig. 1: Spatial modulation transceiver block diagram.



Input bits	Ant Num	Trans Sym
000	1	-1+i
001	1	-1-i
010	1	1+i
011	1	1-i
100	2	-1+i
101	2	-1-i
110	2	1+i

Fig. 2: SM: How it works "The Transmitter".

Fourier transform (*IFFT*). Afterwards, a cyclic prefix (CP) is inserted, to avoid the ISI between the OFDM symbols.

After that, the resultant vectors $\mathbf{R}(t)$ are conveyed simultaneously from the N_t active transmit antennas over the MIMO channel, denoted $\mathbf{H}(t)$, using the following equation:

$$\mathbf{Y}(t) = \mathbf{H}(t) \otimes \mathbf{R}(t) + \mathbf{W}(t) \tag{4}$$

$\mathbf{H}(t)$ sets to:

$$\mathbf{H}(t) = \begin{pmatrix} \mathbf{h}_{1,1}(t) & \mathbf{h}_{1,2}(t) & \dots & \mathbf{h}_{1,N_t}(t) \\ \mathbf{h}_{2,1}(t) & \mathbf{h}_{2,2}(t) & \dots & \mathbf{h}_{2,N_t}(t) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{h}_{N_r,1}(t) & \mathbf{h}_{N_r,2}(t) & \dots & \mathbf{h}_{N_r,N_t}(t) \end{pmatrix} \tag{5}$$

Each vector of $\mathbf{H}(t)$ refers to the multipath channel gains between each ν^{th} transmit and ϱ^{th} receive antennas as follows:

$$\mathbf{h}_{\varrho\nu}(t) = \left[h_{\varrho\nu}(t)^1 \quad h_{\varrho\nu}(t)^2 \cdots h_{\varrho\nu}(t)^L\right] \tag{6}$$

where L is the number of paths. The satages are simply reversed at the receiver. The indices of transmit antenna and the emitted data stream can be recovered using one of the detectors that will be described in the next section.

V. SM-OFDM DETECTORS

The detection algorithms of SM-MIMO system could be divided into four fundamental categories as described in [19]: matched filter (MF) based detection in [7], maximum likelihood (ML) detection in [6, 8], sphere decoding (SD) [10, 20], and other detectors as signal vector based list detection (SVD) in [21]. SM-based detection techniques are presented in Fig. 4.

A. *Minimum Mean Square Error (MMSE) detection*

MMSE algorithm describes the approach which minimizes the mean square error (MSE) between two entities as described in the following equation.

$$\tilde{\mathbf{z}}^c(k) = (\mathbf{h}_j^c(k))^H[(\mathbf{h}_j^c(k))^H * \mathbf{h}_j^c(k) + \sigma_w^2\mathbf{I}]^{-1}\mathbf{y}^c(k) \tag{7}$$

Then, the TX-antenna index is computed by:

$$\hat{j}^c = arg\max_j |\tilde{\mathbf{z}}^c(k)| \tag{8}$$

Finally, the transmitted symbol is computed using the following quantization function:

$$\hat{q}^c = Q(\tilde{\mathbf{z}}^c(k)_{(j=\hat{j})}) \tag{9}$$

B. *Optimal detection (OD)*

This detector follows a different rule compared to the detectors mentioned above. Assuming that the conveyed signals are probably equally likely, as in [6], the indices $\hat{j}, \hat{q}$ are computed as follows:

$$[\hat{j}, \hat{q}] = arg\max_{j,q} p_y(\mathbf{y}|\mathbf{x}_{j,q}, \mathbf{H}) \tag{10}$$

$$= arg\min_{j,q}(\|\mathbf{g}_{jq}\|_F^2 - 2Re\{\mathbf{y}^H\mathbf{g}_{jq}\}) \tag{11}$$

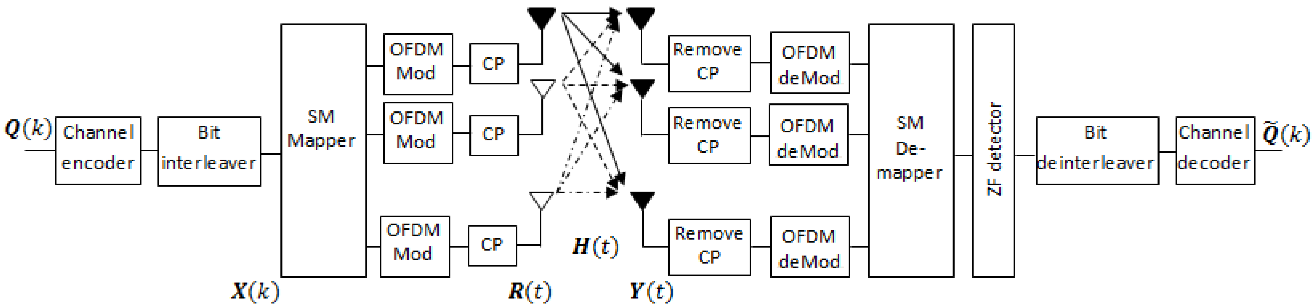


Fig. 3: SM-OFDM System model.

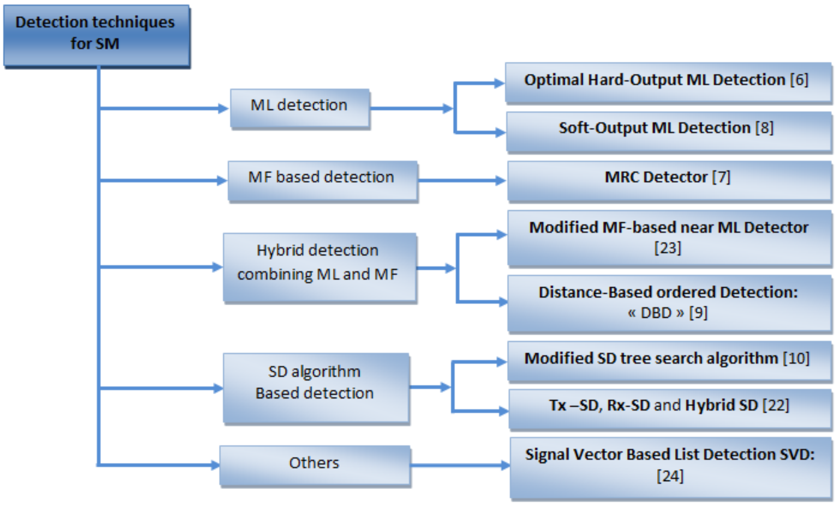


Fig. 4: Overview of SM detectors.

where $\mathbf{g}_{jq} = \mathbf{h}_j\mathbf{x}_{j,q}$, $1 < j < N_t$, $1 < q < M$, M being the modulation order and $p_y(\mathbf{y}|\mathbf{x}_{j,q}, \mathbf{H}) = \pi^{-N_r} exp(-\|\mathbf{y} - \mathbf{H}x_{jq}\|_F^2)$ is the PDF of $\mathbf{y}$, conditioned on $\mathbf{x}_{jq}$ and $\mathbf{H}$.

C. Signal Vector-Based Detector (SVD)

SVD principle is based on the observation that the received vector $\mathbf{h}_j\mathbf{x}_q$ and $\mathbf{h}_j$ have the same direction, as described in [21]. The direction is found by estimating the angle θ_j^c between $\mathbf{h}_j$ and $\mathbf{y}$, as follows:

$$\theta_j^c = arccos\frac{\|\langle\mathbf{h}_j^c(k), \mathbf{y}^c(k)\rangle\|_F}{\|\mathbf{h}_j^c(k)\|_F\|\mathbf{y}^c(k)\|_F} \tag{12}$$

Then, the TX-antenna index can be calculated using the following equation:

$$\hat{j}_{SVD}^c = arg\min_j \theta_j^c \qquad j = \{1, ..., N_t\} \tag{13}$$

Finally, the emitted symbol can be estimated as:

$$\hat{q}_{SVD}^c = arg\min_q \|\mathbf{y}^c(k) - \mathbf{h}_{\hat{j}SVD}^c(k)x_q\|_F^2 \quad q = \{1, ..., M\} \tag{14}$$

D. Distance-Based ordered Detection (DBD)

The DBD algorithm calculates the distances between the estimated symbols and their demodulation constellations [21]. First, for DBD principle, the received vector $\mathbf{y}$ is multiplied by the pseudo-inverse of $\mathbf{h}$ as:

$$\mathbf{z}^c(k) = (\mathbf{H}^\dagger)^c(k)\mathbf{y}^c(k) \quad j = \{1, 2, ..., N_t\} \quad c = \{1, 2, ..., N\} \tag{15}$$

Then the estimated symbol $\hat{x}_q$ is obtained by the demodulator as described in the following expression.

$$\hat{x}_q^c = Q(z^c(k)) \tag{16}$$

Let $d_{j,q}$ denotes the distance between $\hat{x}_q$ and all possibly values of the transmitted sequences x_q by applying this following equation:

$$d_{j,q} = \|\mathbf{h}_j^c(k)\||\hat{x}_q^c - x_q| \tag{17}$$

Hence the TX-index $\hat{j}$ and the corresponding modulated symbol x_q are estimated by:

$$[\hat{j}^c, \hat{q}^c] = \min_{j,q}(d_{j,q}) \tag{18}$$

VI. Proposed detector for SM-OFDM scheme

Two processing steps are involved in this detector, resulting from the merging of two approaches in the estimation of the TX-antenna index, the selected rotated constellation, and the emitted symbol. It is performed by using MRC technique and cosine rule principle.

1— Antenna index estimation: First, the antenna index should be computed. Hence, MRC is used as expressed in the following equation:

$$\tilde{z}_j^c(k) = \frac{(\mathbf{h}_j^c(k))^H}{\|\mathbf{h}_j^c(k)\|_F^2}\mathbf{y}^c(k) \quad for \quad c = \{1, 2, ..., N\} \tag{19}$$

where $\mathbf{h}_j^c(k)$ refers to the j^{th} channel vector, corresponding to the c^{th} subcarrier, and $\mathbf{y}^c(k)$ is the received vector on each c^{th} subcarrier. Therefore, the TX-antenna index $\hat{j}^c$ will be calculated by:

$$\hat{j}^c = arg \max_j |\tilde{\mathbf{z}}^c(k)| \tag{20}$$

Based on “19”, the vector $\mathbf{z}^c(k)$ could be presented as:

$$\mathbf{z}^c(k) = [z_1^c(k), z_2^c(k), ..., z_{N_t}^c(k)]^T \tag{21}$$

2— Constellation and symbol indices estimation: At the receiver side, based on the assumption that a perfect channel knowledge is available, and that one transmit antenna being activated at the c^{th} subcarrier and is transmitting the q^{th} symbol mapped to the p^{th} constellation, the transmitted vector $\tilde{\mathbf{z}}_j^c(k)$ can be defined as:

$$\tilde{\mathbf{z}}_j^c(k) \quad = \quad \boldsymbol{\chi}_q^{p,c}(k) + \mathbf{n}(k) \tag{22}$$

In a noiseless environment, $\tilde{\mathbf{z}}_j^c(k)$ could be presented as:

$$\begin{aligned} \tilde{\mathbf{z}}_j^c(k) &= [Re(\tilde{z}_j^c(k)), Im(\tilde{z}_j^c(k))]^T & (23)\\ &= [Re(\chi_q^{p,c}(k)), Im(\chi_q^{p,c}(k))]^T & (24)\\ &= \mathbf{M}_p[Re(s_0^c(k)), Im(s_0^c(k))]^T & (25) \end{aligned}$$

The angle between $\tilde{\mathbf{z}}_j^c(k)$ and the emitted one, $\boldsymbol{\chi}_q^{p,c}(k)$, should be zero, in the absence of noise. In adverse, these vectors fluctuated around each other in a noisy environnement.

We propose the cosine-based rule, and is based on the observation that the emitted vector $\tilde{\mathbf{z}}_j^c(k)$ share the same direction with the rotated symbol vector $\boldsymbol{\chi}_q^{p,c}(k)$; therefore the cross-angle will be zero. Subsequently, the vector $\boldsymbol{\chi}_q^{p,c}(k)$ having the smallest angle value $\varphi_q^{p,c}$ corresponds to the expected one, and the angle can be computing using this equation:

$$\varphi_q^{p,c} = arccos\frac{\langle \tilde{\mathbf{z}}_j^c(k), \boldsymbol{\chi}_q^{p,c}(k)\rangle}{|\tilde{\mathbf{z}}_j^c(k)||\boldsymbol{\chi}_q^{p,c}(k)|} \tag{26}$$

Afterwards, the estimated p^{th} constellation and the q^{th} emitted symbol index are calculated by looking for the minimal value of the equation in “26” as described in the following equation:

$$[\hat{p}, \hat{q}] = arg \min_{p,q}(\varphi_q^{p,c}) \tag{27}$$

VII. Nakagami-m fading channel model - channel impairments

The generalized Nakagami-m distribution is adopted herein to encompass as fading scenarios as possible, and the channel envelope in such case is given by the known formula:

$$f_{|\omega_l|}(x) = \frac{2}{\Gamma(m_l)}(\frac{m_l}{\Omega_l})^{m_l} x^{2m_l-1} exp(-\frac{m_l}{\Omega_l}x^2) \quad l = 1, 2, ..., L \tag{28}$$

where $\Gamma(\cdot)$ is the gamma function defined as $\Gamma(m) = \int_0^\infty x^{m-1}e^x dx$. The parameter $m \geq \frac{1}{2}$ indicates the fading severity and $\Omega_l = \varepsilon\{|\omega_l|^2\}$ refers to the mean-square value of the l^{th} path signal where ω_l represents the multipath gain. The spatial fading correlation is taken into account, by separating the parts arising from the receive and the transmit sides, thereby adopting the so-called Kronecker model. Because of the adopted SM modulation scheme, one transmit antenna is concerned at each time instant. Therefore the transmit correlation is not of interest, which yields the following channel expression:

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H} \tag{29}$$

where $\mathbf{H}_w$ is the matrix containing the $N_r \times N_t$ channel vectors $\mathbf{h}_{\varrho\nu}$ introduced earlier. The superscript $(.)^{\frac{1}{2}}$ stands for the Hermitian square root of a matrix and the receive correlation matrix $\mathbf{R}_r \in R^{N_r \times N_r}$ has the following Toeplitz structure:

$$\mathbf{R}_r = \begin{bmatrix} 1 & \alpha & \dots & \alpha^{N_r-1} \\ \alpha & 1 & \dots & \alpha^{N_r-2} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha^{N_r-1} & \alpha^{N_r-2} & \dots & 1 \end{bmatrix} \tag{30}$$

where $\alpha = exp(-\beta)$, with β standing for the correlation decay coefficient set to $\frac{2\pi}{\lambda}dsin\phi$, with λ being the wavelength, d the inter-element spacing and ϕ describing the angle of arrival (AoA) offset. The channel coefficients at the receive side are said to be perfectly correlated when $0 < \alpha << 1$. Moreover, in practice, obtaining perfect channel estimates is hardly feasible, therefore the availability of only imperfect channel state information (CSI) should be considered. Thus, by taking into account both spatial correlation and imperfect CSI at the receiver side in Nakagami fading, the channel estimate could be obtained as follows:

$$\hat{\mathbf{H}} = \rho\mathbf{R}_r^{1/2}\mathbf{H} + (1-\rho)\lambda^{N_r \times N_t} \tag{31}$$

where λ is a normally distributed random variable with zero mean and unit variance. The coefficient $0 < \rho < 1$ is a factor that determines the similitude of the estimated CSI to the actual one, thus leading to perfect CSI estimation scenario when $\rho = 1$.

VIII. SIMULATION RESULTS

We consider the following parameters: Rayleigh channel model with $L = 7$ taps configuration is retained, the $FFT = 128$ is used, and 4 antennas are considered at the transmitter and the receiver sides, respectively. 2PSK modulation is retained. The receive antennas are assumed separated sufficiently such that to eliminate spatial correlation. BER performance is illustrated in Fig. 5 when considering MIMO channel model. As expected, the performance of SM operated by ZF, MMSE, DBD, OD, SVD, and MRC-cosine-based rule detectors, ZF and MMSE are suboptimal detections schemes, which performances are inferior to OD, DBD, SVD and MRC-cosine-based rule detectors, mainly because antenna indices are not accurately estimated. The channel matrices in this case are not orthogonal and a linear detection, such as MMSE algorithm, which has a limitation to find antenna indices, as compared to OD and SVD and DBD detectors.

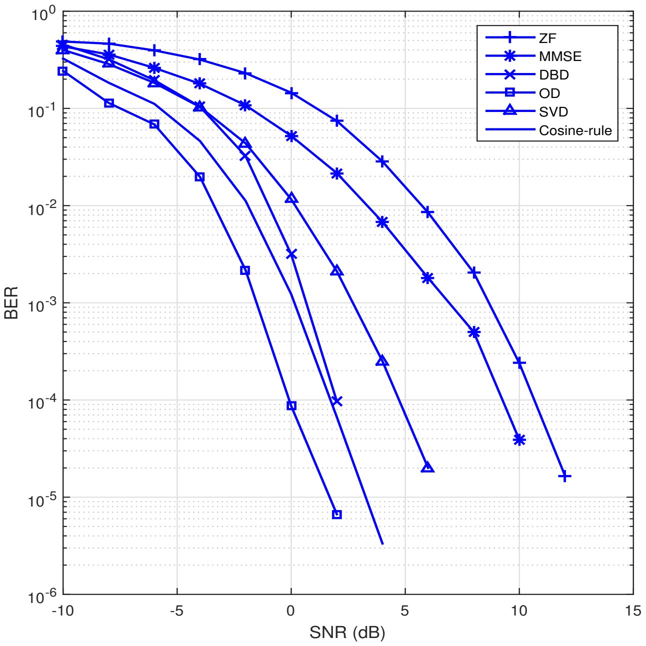


Fig. 5: Performance of SM-OFDM detectors.

Fig. 6 compares the achieved BER performance for different values of m, and different correlation and CSI conditions, when adopting the three presented detectors. Rayleigh channel scenario, obtained when $m = 1$, is compared against purely Nagakami channel, simulated with $m = 10$. Furthermore, uncorrelated ideally estimated channels are herein taken as a reference and are obtained by setting the values of ρ and α to one and zero, respectively. From this figure it can be seen that, in ideal channel conditions, Nagakami channel is more favorable to communication than Rayleigh channel, whatever is the used detector. This was expected because of the high scattering level characterizing propagation in Rayleigh channel (uncorrelated perfectly known channel). Performance gain in Nakagami channel is negligeable when opting for a given detector over the others, unlike in Rayleigh channel where OD exhibits the best performance and MMSE is the least performing, which cosolidates the observations reported in different references [22]. This is mainly due to the lack of accuracy in estimating the values of antenna indices in MMSE. The attained data reliability is quite interesting since low BER values are provided at reasonable SNR levels. However, as shown in this figure, increasing slightly the receive spatial correlation and CSI imperfection levels, has a drastic degradation effect on the data reliability, more particularly in purely Nagakami channel.

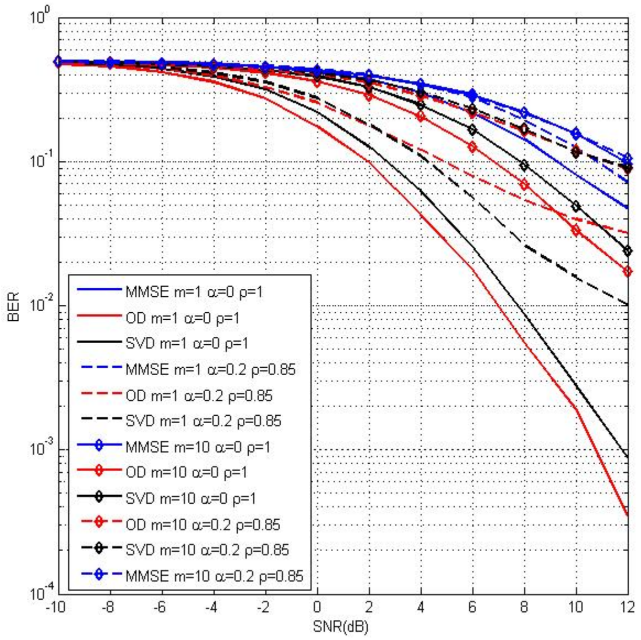


Fig. 6: Comparison of the achieved BER performances of three different SM-OFDM architectures in Nakagami channel with different CSIs and correlations.

IX. CONCLUSION

This paper has presented the recent research progress on SM-OFDM detectors. Moreover, the operating principles of SM and SM-OFDM are provided. The major contribution is the proposed MRC-cosine-based rule detector. Its provided robustness and improved performance have been confirmed. The performance of SM-OFDM scheme has been investigated with different detectors over Nakagami-m fading channel, in the presence of channel impairements. It was found that, in ideal correlation and CSI conditions, and in the presence of Rayleigh fading. SM-OFDM with OD detector outperforms MMSE and SVD alternatives. Nagakami channel offers a more favorable propagation scenario, and the attained BER performance is quite viable. Moreover, SM-OFDM was shown to be quite sensitive to the increase of spatial correlation and CSI imprecisions, regardless of the used detector and the considered channel.

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