Performance Analysis of a Novel Multiple Access Spatial Modulation Architecture based on STBC-OFDM and CDMA over Nakagami-m fading Channel.

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Abstract—One of the schemes which are likely to be adopted in the forthcoming wireless communication standards is the so-called spatial modulation (SM). However, the wireless channels pertaining to such standards will mostly be frequency selective because of the involved high data rates, and SM technique alone can not overcome the resulting signal distorsion. In this context, orthogonal frequency division multiplexing (OFDM) has been used as an efficient solution to combat this impediment, and space-time block coding (STBC)-OFDM has followed as an innovative approach merging the viable features of OFDM and the reliability enhancement capabilities of STBC. Obviously, SM solutions in the presence of multiple users communicating in frequency selective channels should be targeted. To fulfill such a need, a new SM-based architecture incorporating STBC-OFDM and CDMA is proposed in this work and is shown to exhibit a performance which is superior to state-of-the-art alternatives. Furthermore, its sensitivity to the aforementioned adverse parameters is studied in Nagakami channel.

***Keywords*—SM, STBC, OFDM, CDMA, Nakagami.**

Nomenclature

SM	Spatial Modulation.
OFDM	Orthogonal Frequency Division Multiplexing.
STBC	Space-time Block Coding.
CDMA	Code Division Multiple Access.
MIMO	Multiple Input Multiple Output.

I. Introduction

It has long been believed that equipping the wireless communication systems with multiple input and output (MIMO) antennas was sufficient to ensure the communication requirements for a long period. However, because of the important revolutions wireless industry has gone through and the ever-increasing number of subscribers, along with the need for very high data rates, new challenging concepts and solutions have to be designed, such as massive MIMO [1]. Massive MIMO systems involve the use of a very high number of antennas, more particularly at the transmit side, each with its associated radio-frequency (RF) chain, thereby implying a non-practical hardware complexity. Spatial modulation (SM) is a recently proposed scheme which promises a low complexity transmitter and receiver design, without decreasing the performance of massive MIMO block transceiver. This complexity reduction is achieved by adopting a simple mapping paradigm. SM exploits the spatial information as an additional source to convey the information. In order to increase the data reliability at the reception side, STBC techniques are by now well-established among the research community [2]. The improvement of the quality of the reception has been envisaged by combining STBC and SM schemes. The two STBC-coded words and the two antenna indices are used to identify the source information. Motivated by this principles, the performance of SM-STBC architectures has been investigated in the literature only in quasi-static Rayleigh channel. Indeed, no system has been used to support SM-STBC-OFDM paradgigm in multi-user system [3]. OFDM and its variants have been widely adopted. It is also worthy to recall that Nakagami model is one of the most adopted to reflect different channel conditions, since it encompasses a wide range of models, from the pure Rayleigh to the one approaching deterministic behavior. We propose a novel architecture which supports 5G and beyond communications standard, by incorporating STBC-OFDM structure in SM-CDMA design. The performance of the resulting SM-STBC-OFDM-CDMA system is investigated in Nagakami channel fading, more particularly in the presence of imperfect channel estimates.

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II. SM-STBC Scheme with OFDM and CDMA multiple access

A single-cell multiuser uplink MIMO model is considered in this work, where K users are served by the N_t antennas of the base station (BS).

At the transmitter side, the input data sequence corre-

Table. I
MAPPING TABLE OF SM-OFDM-STBC.

j	I/bits	Matrix	j	I/bits	Matrix
1	0000	$\begin{pmatrix} 1 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 \end{pmatrix}^T$	3	1000	$\begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & -1 & 1 & 0 \end{pmatrix}^T$
	0001	$\begin{pmatrix} 1 & -1 & 0 & 0 \\ 1 & 1 & 0 & 0 \end{pmatrix}^T$		1001	$\begin{pmatrix} 0 & 1 & -1 & 0 \\ 0 & 1 & 1 & 0 \end{pmatrix}^T$
	0010	$\begin{pmatrix} -1 & 1 & 0 & 0 \\ -1 & -1 & 0 & 0 \end{pmatrix}^T$		1010	$\begin{pmatrix} 0 & -1 & 1 & 0 \\ 0 & -1 & -1 & 0 \end{pmatrix}^T$
	0011	$\begin{pmatrix} -1 & -1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}^T$		1011	$\begin{pmatrix} 0 & -1 & -1 & 0 \\ 0 & 1 & -1 & 0 \end{pmatrix}^T$
2	0100	$\begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & -1 & 1 \end{pmatrix}^T$	4	1100	$\begin{pmatrix} 1 & 0 & 0 & 1 \\ -1 & 0 & 0 & 1 \end{pmatrix}^T$
	0101	$\begin{pmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & 1 \end{pmatrix}^T$		1101	$\begin{pmatrix} 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \end{pmatrix}^T$
	0110	$\begin{pmatrix} 0 & 0 & -1 & 1 \\ 0 & 0 & -1 & -1 \end{pmatrix}^T$		1110	$\begin{pmatrix} -1 & 0 & 0 & 1 \\ -1 & 0 & 0 & -1 \end{pmatrix}^T$
	0111	$\begin{pmatrix} 0 & 0 & -1 & -1 \\ 0 & 0 & 1 & -1 \end{pmatrix}^T$		1111	$\begin{pmatrix} -1 & 0 & 0 & -1 \\ 1 & 0 & 0 & -1 \end{pmatrix}^T$

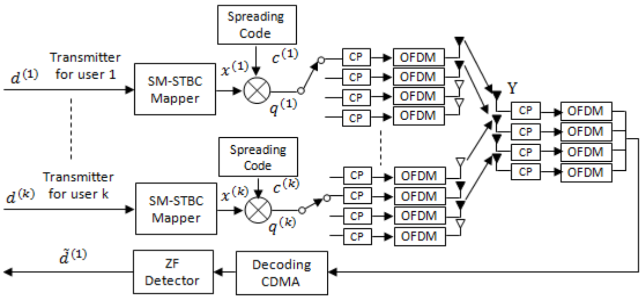

Fig. 1: SM-STBC Scheme with OFDM and CDMA transceiver block

sponding to the k^{th} user, is first encoded by a convolutional encoder, which consists of a concatenation of error correction, preceding an interleaving $\pi^{(k)}$ module. Afterwards, data are divided into blocks of b_{SM} bits, where b_{SM} is given as:

$$b_{SM} = log_2 N_t + 2 \times log_2 M \tag{1}$$

where M is the signal modulation order. The first $log_2 N_t$ bits will select a pair of the transmit antennas to emit the modulated symbols over the two STBC consecutive time slots, while the last $2 \times log_2 M$ bits are consecutively fed to the modulator to generate two modulated symbols x_1 and x_2.

In the SM-STBC architecture, the information is carried by the indices of the transmit antennas. We assume that $N_t = N_r = 4$, where N_t and N_r are the number of transmit and receive antennas. Let us consider the k^{th} user's encoding procedure. By using SM-STBC mapping, two complex information symbols (x_1, x_2), are conveyed from two transmit antennas, in two symbol intervals, in an orthogonal way by the codeword $\mathbf{X}_j^k$, which identifies one component of the mapping matrix represented by the codeword $\mathbf{X} = \{\mathbf{X}_1^k, \mathbf{X}_2^k, \mathbf{X}_3^k, \mathbf{X}_4^k\}$:

$$\{\mathbf{X}_1^k, \mathbf{X}_2^k\} = \left\{ \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \\ 0 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix} \right\} \tag{2}$$

$$\{\mathbf{X}_3^k, \mathbf{X}_4^k\} = \left\{ \begin{pmatrix} 0 & 0 \\ x_1 & -x_2^* \\ x_2 & x_1^* \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} x_1 & -x_2^* \\ 0 & 0 \\ 0 & 0 \\ x_2 & x_1^* \end{pmatrix} \right\} \tag{3}$$

The subscript j represents the TX-antennas index that identifies the pair of activated antennas, and rows and columns of the mapping matrix in Table.I, correspond to the transmit antennas and the two time slots of the STBC coding, respectively.

Example: Consider $N_t = 4$, $M = 2$ (binary phase shift keying) and Alamouti scheme for STBC. The transmitted block from a user should includes 4 bits according to (1). The possible transmission matrices are listed in Table I, where j refers to the pair of activated antennas, and rows and columns of each component of the mapping matrix correspond to the transmit antennas and the two time slots of the STBC coding, respectively. Assume that the bit block to be transmitted from a user is $[0, 1, 1, 1]$. The first two bits 01 indicates the second codeword $\mathbf{X}_2$, and 11 being the transmited symbol pair $\{x_1, x_2\} = \{1, 1\}$

that are transmitted from the third and fourth antennas respectively. Mapping this to SM-STBC symbol results in:

$$\mathbf{X}_2 = \begin{pmatrix} 0 & 0 & -1 & -1 \\ 0 & 0 & 1 & -1 \end{pmatrix}^T \tag{4}$$

The signal $\mathbf{q}^{(k)}$ results from the Hadamard product between the transmitted signal array $\mathbf{x}_j^k$, generated from the original signal repeated P times, and the P-length spreading code $\mathbf{c}^{(k)} \in \mathbf{C}^{N_t \times P}$. Therefore, the spread signal has the following equation:

$$\mathbf{q}^{(k)} = \mathbf{x}_j^{(k)}. \quad \mathbf{c}^{(k)} \tag{5}$$

Afterwards, in each k^{th} transmitter side, the resulted signal is transformed to the time domain by applying the inverse fast Fourier transform (IFFT). Hence, a cyclic prefix (CP) is added to eliminate the ISI between the OFDM symbols, to be conveyed over the channel [4]. The multipath signal received at the ϱ^{th} antenna element from the ν^{th} transmit antenna could be written as:

$$\mathbf{y}_\varrho(t) = \sum_{i=0}^{K} \mathbf{h}_{\varrho\nu}^k(t) \otimes \mathbf{x}_\nu^k(t) + \mathbf{w}(t) \tag{6}$$

where $\mathbf{x}_\nu^k(t)$ is the signal emanating from the ν_{th} activated antenna of the k^{th} user, $\mathbf{w}(t)$ is the additive white Gaussian noise vector with $CN(0, \sigma^2)$ elements, $\otimes$ denotes the time convolution operator and $\mathbf{h}_{\varrho\nu}^k(t) = \left[h_{\varrho\nu}(t)^1 \quad h_{\varrho\nu}(t)^2 \cdots h_{\varrho\nu}(t)^L)\right]$ stands for the $L \times 1$ channel vector between each pair of transmit-receive antennas encompassing the L significant multipath channel components.

$\mathbf{H}(t)$ is a block matrix containing a set of $N_r \times N_t$ vectors each of length L, $\mathbf{H}(t)$ sets to:

$$\mathbf{H}(t) = \begin{pmatrix} \mathbf{h}_{1,1}(t) & \mathbf{h}_{1,2}(t) & \dots & \mathbf{h}_{1,N_t}(t) \\ \mathbf{h}_{2,1}(t) & \mathbf{h}_{2,2}(t) & \dots & \mathbf{h}_{2,N_t}(t) \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{h}_{N_r,1}(t) & \mathbf{h}_{N_r,2}(t) & \dots & \mathbf{h}_{N_r,N_t}(t) \end{pmatrix} \tag{7}$$

Each vector of $\mathbf{H}(t)$ corresponds to the L^{th} multipath channel gains.

The few research works addressing the performance of SM-based systems adopt Rayleigh distribution for the channel fading. However, Rayleigh distribution fails to fit the channel behavior over long distances and high frequencies, Nakagami then suggested a parametric gamma distribution-based density function, to describe the experimental data he obtained. Later, it was also shown by different researchers that real-life data was best fitted by the model provided by Nakagami. Basically, Rayleigh distribution is sufficient to model amplitude in urban areas, whereas, Rician distribution suits better sub-urban areas where LOS components exist. By contrast, Nakagami-m distribution is a generalized case which includes different distribution cases. From [5], the envelope of the Nakagami-m fading channel is shown to be distributed according to the law:

$$f_{|\omega_l|}(x) = \frac{2}{\Gamma(m_l)}(\frac{m_l}{\Omega_l})^{m_l} x^{2m_l-1} exp(-\frac{m_l}{\Omega_l}x^2) \quad l = \{1, ..., L\} \tag{8}$$

where L is the number of paths, $\Gamma(\cdot)$ is the gamma function defined as $\Gamma(m) = \int_0^\infty x^{m-1}e^x dx$. The parameter $m \geq \frac{1}{2}$ verifies the relation and indicates the fading severity, while $\Omega_l = \varepsilon\{|\omega_l|^2\}$ designates the mean-square value of the l^{th} path signal and ω_l represents the multipath gain. A variety of fading conditions are generated by varying the fading or Nakagami scale parameter m_l. For critical cases which are represented in Fig. 2, we have:

- ⋆ $m_l = \frac{1}{2}$ represents one sided Gaussian channel with PDF $f_{|\omega_l|}(x) = \sqrt{\frac{2}{\pi\Omega_l}} exp(-\frac{x^2}{2\Omega_l})$.
- ⋆ $m_l = 1$ describes equivalent Rayleigh fading channel with PDF $f_{|\omega_l|}(x) = \frac{2x}{\Omega_l} exp\frac{-x^2}{\Omega_l}$, there is no single line-of-sight path for this distribution, it can cause severe distortion or fading.
- ⋆ $m = 1.5$, in this case, a LOS path exists, the fluctuations of the signal strength are reduced compared to Rayleigh fading; hence, Nakagami tends to Rician distribution.
- ⋆ For $m_l = \infty$, the Nakagami-m fading channel converges to a non fading AWGN with a PDF $f_{|\omega_l|}(x) = \delta(x - \Omega_l)$.

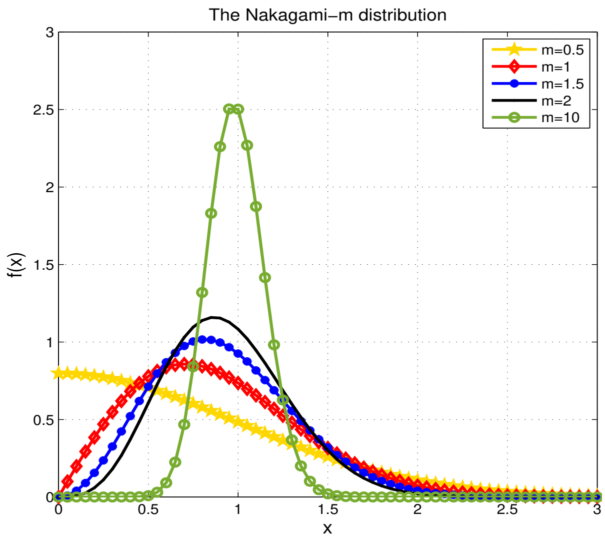

Fig. 2: Nakagami-m distribution.

1— Channel impairments: **Imperfect channel state information (I-CSI)**

Most of research works assume that the channel estimation errors are mitigated, thereby adopting error free (perfect) or erroneous (imperfect) CSI. In practice, this should be considered by formulating the estimated channel matrix as follows [6]:

$$\hat{\mathbf{H}} = \rho\mathbf{H} + (1-\rho)\lambda^{N_r \times N_t} \tag{9}$$

where λ is a normal 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. Perfect CSI estimation is achieved when $\rho = 1$.

where the overall channel model in eq. (9) is obtained by the variation of the parameter ρ.

III. Simulation results

Fig. 3 compares the achieved BER performance for different values of m, and different CSI conditions, when adopting SM-STBC-OFDM-CDMA scheme over Nakagami-m fading channel. Rayleigh channel scenario, obtained when $m = 1$, is compared against Rician and Gaussian cases, simulated with $m = 1.5$ and $m = 0.5$ respectively. Furthermore, ideally estimated channels are herein taken as a reference and are obtained by setting the value of ρ to 1. *BPSK*

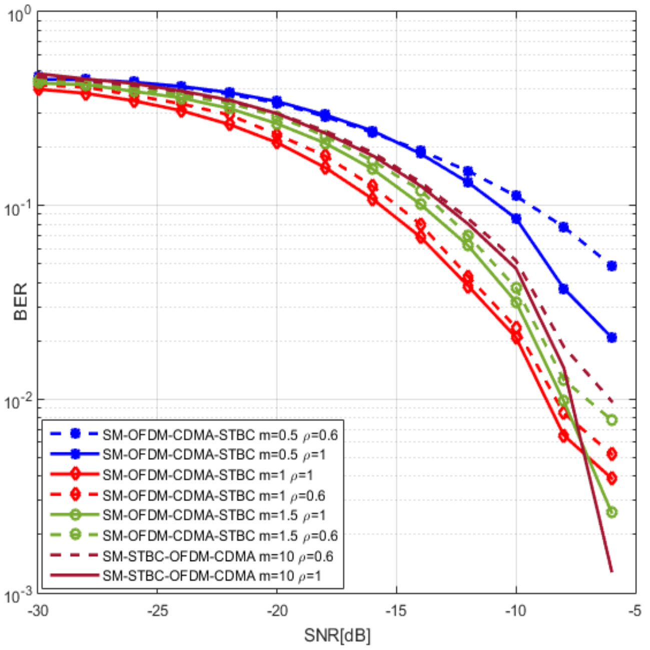

Fig. 3: Comparison of the achieved BER performance of SM-STBC-OFDM-CDMA architecture over Nakagami-m fading channel.

scheme is used. Other simulation parameters are fixed as follows: the number of users $K = 2$, the length of spreading code $P = 128$, the number of paths $L = 3$, and the number of sub-carriers $N_c = 128$. It can be observed from Fig. 3 that, in ideal channel conditions, Rayleigh channel is more favorable to communication than the general Nagakami channel where $m = 10$. Gaussian channel exhibits the lowest performance. The attained data reliability in all channel conditions remains quite interesting since low BER values are provided at low SNR range. However, as shown in this figure, increasing slightly the imperfection levels, has a drastic degradation effect on the data reliability, more particularly in Gaussian channel.

References

[1] K. Ghanem and P. S. Hall, "Power and bit allocation in on-body channels using mimo antenna arrays," *IEEE transactions on vehicular technology*, vol. 62, no. 1, pp. 404–408, 2012.

[2] H. Tayakout, I. Dayoub, K. Ghanem, and H. Bousbia-Salah, "Automatic modulation classification for d-stbc cooperative relaying networks," *IEEE Wireless Communications Letters*, vol. 7, no. 5, pp. 780–783, 2018.

[3] K. Ghanem, P. S. Hall, and R. Langley, "Interference cancellation in body-area networks using linear multiuser receivers," *International Journal of Wireless Information Networks*, vol. 17, no. 3-4, pp. 126–136, 2010.

[4] M. Djeddou, F. Berrahma, and K. Ghanem, "Improved spectral efficiency of sm-ofdm using a set of rotated constellations," *AEU-International Journal of Electronics and Communications*, vol. 93, pp. 317–324, 2018.

[5] M. D. Yacoub, "Nakagami-m phase-envelope joint distribution: An improved model," in *Microwave and Optoelectronics Conference (IMOC), 2009 SBMO/IEEE MTT-S International*. IEEE, 2009, pp. 335–339.

[6] E. Soujeri and G. Kaddoum, "Performance comparison of spatial modulation detectors under channel impairments," in *Ubiquitous Wireless Broadband (ICUWB), 2015 IEEE International Conference on*. IEEE, 2015, pp. 1–5.

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