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***Abstract*— In this paper, we introduce TOSD–SM (Time–Orthogonal Signal Design assisted Spatial Modulation), which is a novel space modulation scheme based on the principle of the recently proposed Spatial Modulation (SM) wireless transmission technique for Multiple–Input–Multiple–Output (MIMO) systems. We show that, unlike other SM–based methods available in the literature, the proposed approach can offer transmit–diversity gains by properly designing the transmitted signal to have a peaky time auto–correlation function. By considering the basic 2×1 MISO (Multiple–Input–Single–Output) system setup, the optimal Maximum–Likelihood (ML) detector with full Channel State Information (CSI) at the receiver will be developed, and its performance evaluated in closed–form. Performance comparison with other proposed SM schemes over fading channels will evidence two main benefits of TOSD–SM: i) transmit–diversity gains, and ii) intrinsic robustness to spatial correlation of channel fading. Analytical frameworks and findings will also be substantiated via Monte Carlo simulations.**

I. INTRODUCTION

Spatial Modulation (SM) is a novel and recently proposed wireless transmission technique for Multiple–Input–Multiple–Output (MIMO) wireless systems [1], [2]. Along the history, the SM concept has been termed in different ways: i) in [1], it has been called Space Shift Keying (SSK) modulation, ii) in [2], due to its similarity to Orthogonal Frequency–Division Multiplexing (OFDM), it has been named Orthogonal Spatial–Division Multiplexing (OSDM), iii) in [3], the term SM has been coined for the first time, and iv) in [4], the authors have come back and retained the original name SSK. In particular, SSK is a special instance of SM, which can reduce further the receiver complexity owing to the absence of conventional modulation schemes for data transmission [4].

Recent research efforts have pointed out via simulations that SM can be a very promising candidate to the design of low–complexity modulation schemes and transceiver architectures for MIMO systems over fading channels (see, *e.g.*, [3]–[5] and references therein). In particular, it has been shown that SM can offer better performance than well–known MIMO communication systems such as V–BLAST (Vertical Bell Laboratories Layered Space–Time) and Alamouti architectures, as well as generic Amplitude Phase Modulation (APM) schemes [3], [4]. Furthermore, these performance gains are obtained with a significant reduction in receiver complexity and system design: SM methods can efficiently avoid Inter–Channel Interference (ICI) and Inter–Antennas Synchronization (IAS) issues of MIMO systems, as well as reduce the number of computations required by the detection unit [3], [4]. Moreover, only one RF front–end chain is required at the transmitter–side [4], which significantly reduces the overall complexity of the system.

The fundamental and distinguishable feature that makes SM methods different from other MIMO techniques is the exploitation, as a source of information, of the spatial constellation pattern of the transmit–antennas: each index of the transmit–antennas is encoded with a unique sequence of bits emitted by the transmit encoder, and data transmission is based on the following fundamental principles: i) activate the transmit–antenna which is linked to the sequence of bits to be transmitted, and ii) switch off the rest of the transmit–antennas. This way, the estimation, at the receiver–side, of which antenna is not idle results, implicity, in the estimation of the unique sequence of bits emitted by the encoder at the transmitter–side. At the receiver–side, the detection mechanism of the antenna index is based upon the distinct multipath fading characteristics associated to each pair (transmit, receive) antenna [1]. In summary, the underlying principle of SM is twofold: i) at the transmitter, a one–to–one mapping of information bits to transmit–antennas, thus allowing the transmit–antenna index to convey information, and ii) at the receiver, the exploitation, due to the properties of wireless fading channels, of distinct multipath profiles received from different transmit–antennas.

A. Recent Results and Limitations

Moving from the original proposals in [3]–[5], novel SM schemes have been recently introduced. Relevant examples to be mentioned are: i) [6], where the authors have proposed an optimization framework to allow more than one transmit–antenna at a time to convey information and shown some performance improvements due to an optimal constellation design, and ii) [7], where a SM scheme based on Trellis Coded Modulation (TCM) has been introduced and shown to provide better performance over wireless fading channels. However, despite the upsurge of research interest on SM during the last five years, SM is still a young–born research field with several fundamental design issues that need to be explained and fully understood to allow an efficient exploitation of this novel transmission technology. For instance, i) all SM proposals available in the literature to date are unavailable to exploit the multiple antennas at the transmitter–side to get transmit–diversity gains, but only receive–diversity is achieved when the receiver is equipped with multiple antennas [4], [5], ii) there is not a clear comparison among the different SM proposals (*e.g.*, [1] has never been compared to other SM methods in, *e.g.*, [3]–[5]) over correlated fading channels, and it is known that channel correlation is the main aspect to be considered to enable SM capabilities[1], iii) the few studies related to the analysis of the effect of fading spatial correlation have been obtained by using Monte Carlo simulations, and no analytical frameworks exist, to the best of our knowledge, to quantify the performance degradation when channel correlation is considered [3]–[5].

B. Contribution

Motivated by the above considerations, the main aim of this paper is to provide some research advances along three main directions: i) first, we provide a sound performance comparison among the two basic proposals available in the literature for SSK and SM, *i.e.*, [1] and [3]–[5], when fading correlation is taken into account, ii) second, we propose an alternative SM method, which is called TOSD–SM (Time–Orthogonal Signal Design assisted Spatial Modulation), with the main aim to exploit multiple antennas at the transmitter to get transmit–diversity gains, and iii) finally, for all SM methods analyzed in the present contribution we will develop simple closed–form formulas to quantify the error probability performance of the system in the presence of fading correlation.

Without loss of generality and for illustrative purposes, the following assumptions will be retained throughout the manuscript. i) We will restrict the analysis to the basic 2×1 Multiple–Input–Single–Output (MISO) system setting. ii) We will consider the special case of SM called SSK, *i.e.*, it is assumed that transmit–antenna indexes are the only means to convey information. The rationale for these assumptions is as follows. The aim of the paper is to look into the fundamental differences of various SM methods in terms of exploiting the random nature of the wireless channel and to enable data communication capabilities. The conclusions drawn for the 2×1 MISO system can be generalized to general MIMO settings, as well as the analytical frameworks, which can be extended, *e.g.*, via union bound methods [5]. Furthermore, the exploitation of the antenna index to convey information is the most innovative component and distinguishable feature of the SM concept, so there is no restriction in neglecting standard modulation methods to be used after the selection of the antenna index.

C. Summary of Results

The results of the paper can be briefly summarized as follows. i) We will show that distinct SM proposals can lead to different performance in the presence of fading correlation. Our frameworks will show that the method in [1] offers better performance than the solution in [3]–[5] for high channel correlation. ii) The novel proposed TOSD–SM scheme is shown to offer a diversity order equal to two, as well as to be inherently robust to fading correlation. The net result will be a novel SM system whose error performance over correlated fading channels is better than the error performance of other SM schemes over uncorrelated fading channels.

D. Organization

The remainder of the paper is organized as follows. In Section II, system and channel models will be introduced. In Section III, the methods described in [1], [3]–[5] will be revised, and their performance computed in closed–form for correlated Rayleigh fading channels. In Section IV, the novel TOSD–SM scheme will be introduced, and its error performance computed for the optimum detector. In Section V, numerical and simulation results will be shown to substantiate analytical frameworks and findings developed in Section III and Section IV. Finally, Section VI will conclude the paper.

[1]During detection, the receiver needs to exploit the distinct multipath profiles of different wireless links. If correlation exist among them, the detector may be unable to distinguish the different antennas.

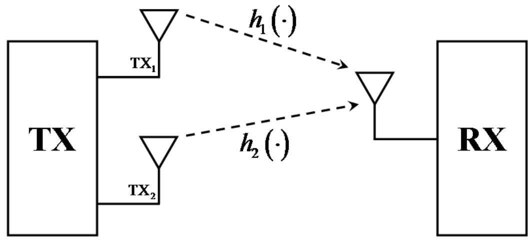

Fig. 1. System model: the 2×1 MISO setting.

II. System Model

Let us consider the 2×1 MISO system depicted in Fig. 1. As mentioned in Section I, SM–based transmission techniques foresee i) at the transmitted–side, to map information data bits to transmit–antenna indexes, and ii) at the receiver–side, to de–map these bits via suitable detection mechanisms for estimating, for each signaling time–interval, the active transmit–antenna. In particular, the detection process at the receiver–side can be cast in terms of a general binary[2] detection problem in Additive White Gaussian Noise (AWGN) [8, Sec. 4.2, pp. 254], when conditioning upon fading channel statistics. In what follows, we will briefly summarize the SM detection problem in a very general setting and develop the Maximum–Likelihood (ML) optimum detector when the receiver has full Channel State Information (CSI). In Section III, the detector will be specialized to analyze and compare the performance of various SM proposals, and in Section IV to introduce and motivate the novel TOSD–SM method.

A. Notation

Let us briefly summarize the main notation used in what follows. i) We adopt a complex–envelope signal representation. ii) $j = \sqrt{-1}$ is the imaginary unit. iii) $\delta(\cdot)$ is the Dirac delta function. iv) $(x \otimes y)(t) = \int_{-\infty}^{+\infty} x(\xi)\, y(t-\xi)\, d\xi$ is the convolution of signals $x(\cdot)$ and $y(\cdot)$. v) $(\cdot)^*$ denotes complex–conjugate. vi) $|\cdot|^2$ denotes square absolute value. vii) $\mathrm{E}\{\cdot\}$ is the expectation operator. viii) $\mathrm{Re}\{\cdot\}$ denotes real part operator. ix) $\Pr\{\cdot\}$ means probability. x) $G \sim N(\mu_G, \sigma_G^2)$ is a Gaussian distributed Random Variable (RV) with mean μ_G and standard deviation σ_G. xi) ρ_{AB} denotes the correlation coefficient of RVs A and B. xii) $Q(x) = \left(1/\sqrt{2\pi}\right)\int_x^{+\infty} \exp\left(-t^2/2\right) dt$ is the Q–function. xiii) m_1 and m_2 denote the two information messages that the transmitter in Fig. 1 can emit with equal probability. xiv) $\hat{m}$ denotes the message estimated at the receiver–side. xv) $E_m = E_{m_1} = E_{m_2}$ is the energy transmitted by each antenna that emits a non–zero signal. xvi) $T_m = T_{m_1} = T_{m_2}$ denotes the signaling interval for both information messages m_1 and m_2. xvii) The noise at the receiver input is denoted by $n(\cdot)$, and it is assumed to be AWG–distributed, with both real and imaginary parts having a double–sided power spectral density

[2]When multiple (*e.g.*, M) antennas are present at the transmitter–side, a M–ary detection problem needs to be considered.

equal to N_0. xviii) For ease of notation, we set $\bar{\gamma}=E_m/(4N_0)$. xix) $\left\{ s_i \left(\cdot | \{m_n\}_{n=1}^2 \right) \right\}_{i=1}^2$ denote the signals emitted by the transmit–antennas $\{\mathrm{TX}_i\}_{i=1}^2$ conditioned upon the transmitted messages $\{m_i\}_{i=1}^2$.

B. Channel Model

We consider a frequency–flat slowly–varying fading channel model, with fading envelopes distributed according to a Rayleigh distribution. This latter assumption is retained only to focus on the main aspects and comparison among various SM methods and to obtain the numerical results in Section V. As a matter of fact, we will see in the next sections that most frameworks developed in the present manuscript can be applied to generalized fading channels [9]. Moreover, we assume the fading gains not to be necessarily identically distributed, and spatial correlation among them will be accounted for in this manuscript. In particular:

- $\{h_i(t)\}_{i=1}^2 = \beta_i \exp(j\varphi_i)\,\delta(t-\tau_i)$ is the channel impulse response from antenna $\{\mathrm{TX}_i\}_{i=1}^2$ in Fig. 1 to the receive antenna, and $\{\beta_i\}_{i=1}^2$, $\{\varphi_i\}_{i=1}^2$, and $\{\tau_i\}_{i=1}^2$ denote gain, phase, and delay of the related wireless link. Moreover, $\{\alpha_i\}_{i=1}^2 = \beta_i \exp(j\varphi_i)$ denotes the channel complex–gain of the related wireless link.
- According to a Rayleigh fading channel model, the channel complex–gains, $\{\alpha_i\}_{i=1}^2$, reduce to $\{\alpha_i\}_{i=1}^2 = \left\{\alpha_i^R\right\}_{i=1}^2 + j\left\{\alpha_i^I\right\}_{i=1}^2$, where $\left\{\alpha_i^R\right\}_{i=1}^2 \sim N\left(0,\sigma_i^2\right)$ and $\left\{\alpha_i^I\right\}_{i=1}^2 \sim N\left(0,\sigma_i^2\right)$, with $\left\{\alpha_i^R\right\}_{i=1}^2$ being independent from $\left\{\alpha_i^I\right\}_{i=1}^2$. Accordingly, $\{\beta_i\}_{i=1}^2$ and $\{\varphi_i\}_{i=1}^2$ will be Rayleigh and uniform distributed RVs, respectively.
- The following spatial correlation model between the two wireless links is assumed: i) $\rho_{\alpha_1^R\alpha_1^I} = \rho_{\alpha_2^R\alpha_2^I} = \rho_{\alpha_1^R\alpha_2^I} = \rho_{\alpha_2^R\alpha_1^I} = 0$, and ii) $\rho_{\alpha_1^R\alpha_2^R} = \rho_{\alpha_1^I\alpha_2^I} = \rho$, with $0 \le \rho \le 1$. Despite this correlation model is not the most general one, it will allow us to get insightful and simple closed–form results for the SM scheme in [3]–[5], while still guaranteeing good adherence to physical reality.
- $\{\tau_i\}_{i=1}^2$ are assumed to be independent and uniformly distributed in $[0,T_m)$, but known at the receiver, *i.e.*, perfect time–synchronization is considered.

C. Binary Detection

Moving from the above system and channel model, the signals after propagation through the wireless fading channel for both wireless links are $\left\{ \tilde{s}_i \left(t | \{m_n\}_{n=1}^2 \right) \right\}_{i=1}^2 = (s_i \otimes h_i)(t) = \beta_i \exp(j\varphi_i)\, s_i(t-\tau_i|\, m_n)$, and the received signal can be written as follows:

$$\begin{cases} r(t|\,m_1) = \tilde{s}_1(t|\,m_1) + \tilde{s}_2(t|\,m_1) + n(t) \\ r(t|\,m_2) = \tilde{s}_1(t|\,m_2) + \tilde{s}_2(t|\,m_2) + n(t) \end{cases} \tag{1}$$

when messages m_1 and m_2 are transmitted, respectively.

Accordingly, for SM the general binary detection problem in (2) can be formulated:

$$\begin{cases} r(t) = \bar{s}_1(t) + n(t) & \text{if } m_1 \text{ is sent} \\ r(t) = \bar{s}_2(t) + n(t) & \text{if } m_2 \text{ is sent} \end{cases} \tag{2}$$

where $\bar{s}_1(t) = \tilde{s}_1(t|\,m_1) + \tilde{s}_2(t|\,m_1)$ and $\bar{s}_2(t) = \tilde{s}_1(t|\,m_2) + \tilde{s}_2(t|\,m_2)$.

Moving from (2), the ML optimum detector with full–CSI and perfect synchronization at the receiver is as follows [8, Sec. 4.2, pp. 254, eq. (31)]:

$$\hat{m} = \begin{cases} m_1 & \text{if } D_1 \ge D_2 \\ m_2 & \text{if } D_2 < D_1 \end{cases} \tag{3}$$

where $\{D_i\}_{i=1}^2$ are the decision metrics defined as follows:

$$\begin{cases} D_1 = \mathrm{Re}\left\{ \int_{T_m} r(t)\,\bar{s}_1^*(t)\,dt \right\} - \frac{1}{2}\int_{T_m} \bar{s}_1(t)\,\bar{s}_1^*(t)\,dt \\ D_2 = \mathrm{Re}\left\{ \int_{T_m} r(t)\,\bar{s}_2^*(t)\,dt \right\} - \frac{1}{2}\int_{T_m} \bar{s}_2(t)\,\bar{s}_2^*(t)\,dt \end{cases} \tag{4}$$

From the decision rule in (3), the probability of error, $\mathrm{P_E}$, of the detection process (*i.e.*, the detection of the index of the transmit–antenna) when conditioning upon the channel impulses responses $\{h_i(\cdot)\}_{i=1}^2$ is as follows:

$$\begin{aligned} \mathrm{P_E}(h_1,h_2) &= \frac{1}{2}\,\mathrm{P_E}(h_1,h_2)|_{m_1} + \frac{1}{2}\,\mathrm{P_E}(h_1,h_2)|_{m_2} \\ &= \frac{1}{2}\Pr\left\{ D_1|_{m_1} < D_2|_{m_1} \right\} + \frac{1}{2}\Pr\left\{ D_2|_{m_2} < D_1|_{m_2} \right\} \end{aligned} \tag{5}$$

where $\left\{ \mathrm{P_E}(\cdot,\cdot)|_{m_i} \right\}_{i=1}^2$ and $\left\{ D_j|_{m_i} \right\}_{i,j=1}^2$ denote the probabilities of error and the decision metrics conditioned upon the transmission of messages $\{m_i\}_{i=1}^2$, respectively.

III. Performance of Known SM Methods over Correlated Rayleigh Fading

In this section, we compute the error probability performance of two SM schemes already presented in the literature ([1], [4]) when correlated fading channels are considered. Although these SM schemes are already available in the literature, the following limitations can be evidenced in current analysis. i) [1] and [4] techniques have never been compared to each other, either over uncorrelated or correlated fading channels. ii) The detector introduced in [1] exploits average channel knowledge only. We will develop the optimum ML detector with instantaneous CSI at the receiver, thus allowing a fair comparison with [4] and our proposed solution in Section IV. iii) Performance analysis of method in [4] will be extended to correlated fading, and the performance drop in the presence of correlation will be quantified analytically.

A. Chau and Yu Method [1]

The SM concept in [1] is based on the rule as follows:

$$\begin{cases} \bar{s}_1(t) = \tilde{s}_1(t|\,m_1) \\ \bar{s}_2(t) = \tilde{s}_1(t|\,m_2) + \tilde{s}_2(t|\,m_2) \end{cases} \tag{6}$$

which means that only one transmit–antenna (*i.e.*, TX_1) is activated when m_1 is sent, while both transmit–antennas (*i.e.*, TX_1 and TX_2) are activated when m_2 is sent.

Moreover, in [1] the authors assume that the transmitted signals are always pure sinusoidal tones, *i.e.*, $s_1(t|\,m_1) = s_1(t|\,m_2) = s_2(t|\,m_2) = \sqrt{E_m}$ and $s_2(t|\,m_1) = 0$. This assumption allows us to embed the propagation delays $\{\tau_i\}_{i=1}^2$ into the channel phases $\{\varphi_i\}_{i=1}^2$. So, (1) simplifies as follows:

$$\begin{cases} r(t|\,m_1) = \beta_1\sqrt{E_m}\exp(j\varphi_1) + n(t) \\ r(t|\,m_2) = \beta_1\sqrt{E_m}\exp(j\varphi_1) + \beta_2\sqrt{E_m}\exp(j\varphi_2) + n(t) \end{cases} \tag{7}$$

After some analytical computations, which are omitted in the present manuscript due to space constraints, $\mathrm{P_E}$ in (5) can be written as follows:

$$\mathrm{P_E}(h_1,h_2)=\mathrm{P_E}(h_2)=Q\left(\sqrt{\frac{E_m}{4N_0}\beta_2^2}\right) \tag{8}$$

which yields different performance with respect to [1], since in our setup the receiver has instantaneous channel knowledge.

From (8), the average error probability ($\bar{\mathrm{P}}_\mathrm{E}$) over Rayleigh fading channels can be written in closed–form as follows [9]:

$$\bar{\mathrm{P}}_\mathrm{E}=\frac{1}{2}-\frac{1}{2}\sqrt{\frac{\sigma_2^2\bar{\gamma}}{1+\sigma_2^2\bar{\gamma}}} \tag{9}$$

By carefully looking into (8) and (9), the advantages and disadvantages of the SSK method in [1] are as follows:

1) Looking at (9), we observe that, even though two transmit–antennas are employed, the SSK scheme offers a diversity order only equal to 1.
2) The probability of error in (9) depends only on the channel power gain of the wireless link related to the antenna that can be either switched on or off during data transmission (*i.e.*, antenna TX_2 for our system setup). So, in an adaptive system and for optimizing the system performance, the antenna with the best (average) channel conditions could be switched on and off.
3) Since the probability of error in (9) is a function of one wireless communication link only, this means that the system is very robust to channel spatial correlation: regardless of channel correlation between the links $\mathrm{TX}_1-\mathrm{RX}$ and $\mathrm{TX}_2-\mathrm{RX}$, the performance of the system is always the same.
4) When message m_2 has to be sent, each antenna at the transmitter–side is required to emit a signal with energy E_m. This leads to doubling the energy consumption cost with respect to when m_1 needs to be sent.

Moreover, although in the present manuscript only a Rayleigh fading channel model is considered for illustrative purposes, (8) can be used for performance analysis over generalized fading channels by exploiting the Moment Generating Function (MGF–) based approach in [9].

B. Mesleh et al. [3] and Jeganathan et al. [5] Methods

The SM concept in [3]–[5] is based on the rule as follows:

$$\begin{cases} \bar{s}_1(t)=\tilde{s}_1(t|\,m_1) \\ \bar{s}_2(t)=\tilde{s}_2(t|\,m_2) \end{cases} \tag{10}$$

which means that only one transmit–antenna is activated when either m_1 or m_2 are sent, *i.e.*, TX_1 or TX_2, respectively.

Similar to [1], also in this case the authors assume that the transmitted signals are always pure sinusoidal tones, *i.e.*, $s_1(t|\,m_1)=s_2(t|\,m_2)=\sqrt{E_m}$ and $s_1(t|\,m_2)=s_2(t|\,m_1)=0$. So, (1) simplifies as follows:

$$\begin{cases} r(t|\,m_1)=\beta_1\sqrt{E_m}\exp(j\varphi_1)+n(t) \\ r(t|\,m_2)=\beta_2\sqrt{E_m}\exp(j\varphi_2)+n(t) \end{cases} \tag{11}$$

After some analytical computations, which are omitted in the present manuscript due to space constraints, $\mathrm{P_E}$ in (5) can be written as follows:

$$\mathrm{P_E}(h_1,h_2)=Q\left(\sqrt{\frac{E_m}{4N_0}|\alpha_2-\alpha_1|^2}\right) \tag{12}$$

which agrees with the result in [5].

From (12), $\bar{\mathrm{P}}_\mathrm{E}$ over Rayleigh fading channels can be written in closed–form as follows:

$$\bar{\mathrm{P}}_\mathrm{E}=\frac{1}{2}-\frac{1}{2}\sqrt{\frac{\bar{\sigma}^2\bar{\gamma}}{1+\bar{\sigma}^2\bar{\gamma}}} \tag{13}$$

where we have defined $\bar{\sigma}^2=\sigma_1^2+\sigma_2^2-2\rho\sigma_1\sigma_2$. When $\rho=0$, (13) reduces to the result developed in [5] for uncorrelated Rayleigh fading and identically distributed wireless links.

After a closer inspection of (12) and (13), the advantages and disadvantages of the SM method in [3]–[5] can be summarized as follows:

1) Similar to [1], also the SM scheme in [3]–[5] offers a diversity order only equal to 1.
2) The probability of error in (12) depends on both channel complex–gains $\{\alpha_i\}_{i=1}^2$, and, in particular, is a function of the difference of them: depending on instantaneous channel conditions, constructive and destructive combinations can take place, thus preventing the exploitation of the two transmit–antennas for diversity purposes.
3) The probability of error in (13) is a function of the spatial correlation coefficient ρ, and, in particular, the more the wireless links are correlated, the worse the error probability is. Via direct inspection of (13), the performance drop in the presence of spatial correlation can be computed as follows:

$$\mathrm{SNR_{penalty}}\,[\mathrm{dB}]=-10\log_{10}\left(1-2\rho\frac{\sigma_1\sigma_2}{\sigma_1^2+\sigma_2^2}\right) \tag{14}$$

which yields the additional SNR (Signal–to–Noise–Ratio) required to have the same average probability of error as in the absence of spatial correlation. In other words, if we have $\bar{\mathrm{P}}_\mathrm{E}=\bar{\mathrm{P}}_\mathrm{E}^\dagger$ for $\bar{\gamma}_\mathrm{dB}=\bar{\gamma}_\mathrm{dB}^\dagger$ when $\rho=0$, then when $\rho\neq0$ we need a SNR equal to $\bar{\gamma}_\mathrm{dB}=\bar{\gamma}_\mathrm{dB}^\dagger+\mathrm{SNR_{penalty}}\,[\mathrm{dB}]$ to get the same $\bar{\mathrm{P}}_\mathrm{E}=\bar{\mathrm{P}}_\mathrm{E}^\dagger$.

IV. TOSD–SM: SM WITH TRANSMIT–DIVERSITY

By carefully analyzing the advantages and disadvantages of the SM methods described above, we can conclude that they have an important limitation in common: both proposals do not take maximum advantage of multiple antennas at the transmitter–side to get transmit–diversity gains. In detail, signal designs and optimal detectors available so far offer a diversity order that depends on the number of receive antennas only. As a consequence, these SM methods might find limited applicability to low–complexity and low–cost downlink settings and operations, where it is more economical to add equipment to base stations rather than to remote mobile units. The novel scheme introduced in this section is specifically tailored to offer a simple way to design a SM–based wireless communication system with transmit–diversity capabilities.

The basic idea behind TOSD–SM is to lift the restriction that the transmitted signals are pure sinusoidal tones, but to properly design the signal waveform in order to exploit, in an efficient way, the different propagation delays $\{\tau_i\}_{i=1}^2$ of the wireless links $\mathrm{TX}_1-\mathrm{RX}$ and $\mathrm{TX}_2-\mathrm{RX}$. In particular, similar to [3]–[5], TOSD–SM retains the main assumption that only one transmit–antenna is activated in each signaling interval T_m. Accordingly, the transmission rule is the same as in (10), and the received signals are the same as in (11). However, unlike the assumptions in [1] and [3]–[5], TOSD–SM relies on the following signal design:

$$\begin{cases} s_1(t|\, m_1) = s_2(t|\, m_2) = \sqrt{E_m}w(t) \\ s_1(t|\, m_2) = s_2(t|\, m_1) = 0 \end{cases} \tag{15}$$

where $w(\cdot)$ is a signal waveform which is chosen to satisfy the following condition:

$$R_w(\tau) = \int_{-\infty}^{+\infty} w(\xi)\, w^*(\xi - \tau)\, d\xi = \delta(\tau) \tag{16}$$

which simply states that $w(\cdot)$ is required to have a very peaky time auto–correlation function $R_w(\cdot)$ (which, under ideal signal design conditions, can be assumed to be a Dirac delta function as shown in (16)).

By exploiting (16) for each pair of delays (τ_1, τ_2) with $\tau_1 \neq \tau_2$[3], and after a few algebraic manipulations, which are omitted in the present manuscript due to space constraints, $\mathrm{P_E}$ in (5) is as follows:

$$\mathrm{P_E}(h_1, h_2) = Q\left(\sqrt{\frac{E_m}{4N_0}\left(\beta_1^2 + \beta_2^2\right)}\right) \tag{17}$$

Finally, $\bar{\mathrm{P}}_\mathrm{E}$ over Rayleigh fading channels can be written in closed–form as follows [10]:

$$\bar{\mathrm{P}}_\mathrm{E} = \frac{1}{\pi}\int_0^{\pi/2} M\left(\frac{\bar{\gamma}}{2\sin^2(\theta)}\right) d\theta \tag{18}$$

where we have defined $M(s) = \left[1 + 2\left(\sigma_1^2 + \sigma_2^2\right)s + 4\left(1 - \rho^2\right)\sigma_1^2\sigma_2^2 s^2\right]^{-1}$, which is the MGF of RV $\beta = \beta_1^2 + \beta_2^2$, *i.e.*, $M(s) = \mathrm{E}\{\exp(-s\beta)\}$.

A careful inspection of (17) and (18), reveals the following about the TOSD–SM scheme:

1) The main advantage of the proposed SM method is to provide transmit–diversity. In particular, for a 2×1 MISO system a transmit–diversity order equal to 2 is obtained. This can be proved by following the arguments in [11]. In particular, the diversity order can be computed by analyzing the behavior of $M(\cdot)$ for large values of $|s|$. It can be readily proved that:

$$\lim_{|s| \to +\infty}\{M(s)\} \cong \frac{1}{4\left(1 - \rho^2\right)\sigma_1^2\sigma_2^2}\,|s|^{-2} \tag{19}$$

and from [11, Prop. 3] we know that the diversity order is equal to the negative exponent of $|s|$, *i.e.*, 2 in (19). As a result of the higher diversity order, the probability of error is expected to have a steeper slope for increasing SNRs, which results in substantial improvements in system performance (see Section V).

2) A careful analysis of (18) also reveals that TOSD–SM turns out to be more robust to channel correlation. As a matter of fact, the probability of error in (18) depends on the squared value of the correlation coefficient only. So, since $0 \le \rho \le 1$ the performance drop for increasing ρ is expected to be smaller than in [3]–[5]. The performance of the SSK scheme in [1] is independent of ρ, but no transmit–diversity is achieved.

3) Similar to [3]–[5] (and different from [1]), TOSD–SM does not suffer ICI and does not require IAS. As a matter of fact, when (16) is verified for every time–lag τ the transmit–antennas do not need to meet any synchronization constraints. However, all SM proposals require perfect time–synchronization at the receiver.

4) The main benefits of TOSD–SM stem from (16). The problem of designing signals with a very good time auto–correlation function is well–known in the literature, and several signal waveforms that almost satisfy the ideal condition in (16) can be found [12]. For example, the application of Impulse Radio Ultra Wide Band (IR–UWB) transmission technology [13] might be a good choice to enable the temporal separation of spatially–closed transmit–antennas, as recently proposed in [4].

Moreover, although in this paper only a Rayleigh fading channel model is considered for illustrative purposes, (17) can be used for performance analysis over generalized fading channels by exploiting the MGF–based approach in [9].

V. Numerical and Simulation Results

The aim of this section is to validate the claimed advantages and novelties of the proposed TOSD–SM scheme via some numerical results, which are obtained from the analytical frameworks derived above. Moreover, to make our verifications more sound, claims and conclusions obtained from analysis are substantiated via pure Monte Carlo simulations employing the ML optimum detectors proposed above.

The following setup is used: i) $\sigma_1^2 = \sigma_2^2 = 1$, ii) $\rho = \{0.00, 0.25, 0.50, 0.75, 0.99\}$, and iii) the probability of error from Monte Carlo simulations is obtained by requiring a number of wrong detections equal to 10^4.

Numerical results are shown in Figs. 2–4 for the schemes in [1], in [3]–[5], and the TOSD–SM method, respectively. In particular, the following conclusions can be drawn:

- In Fig. 2, we can observe the error probability of the SSK scheme introduced in [1]. Numerical results confirm that no performance degradation can be observed for increasing values of the correlation coefficient.
- In Fig. 3, the error probability of the SM scheme in [3]–[5] is shown. It is observed that spatial correlation between the wireless links can remarkably increase the error probability. More in detail, the SNR penalty with respect to spatial correlation is 1.25dB, 3dB, and 6dB for $\rho = 0.25$, $\rho = 0.5$, and $\rho = 0.75$, respectively. These SNR penalties are also substantiated by (14).
- In Fig. 4, the error probability for the novel TOSD–SM scheme is depicted. Numerical results confirm that the proposed method shows a higher diversity order than other SM schemes: the probability of error shows a steeper slope than the other two proposals. This yields a substantial performance gain with respect to other solutions. Moreover, we can observe that spatial correlation of wireless links has a significant less impact than the proposal in [3]–[5], which is also confirmed by (18).

Finally, in Fig. 5 it is shown a comparison among the various solutions in order to understand the different behavior of them as a function of the channel spatial correlation coefficient ρ. The following facts can be observed. i) The proposed TOSD–SM yields a significant performance gain with respect to all other SM proposals and, even in the presence of channel correlation, it offers better error probabilities than other SM schemes over independent wireless links: this is a

[3]Propagation through the wireless links $\mathrm{TX}_1 - \mathrm{RX}$ and $\mathrm{TX}_2 - \mathrm{RX}$ is subject to different propagation delays due to the different positions of the antennas at the transmitter.

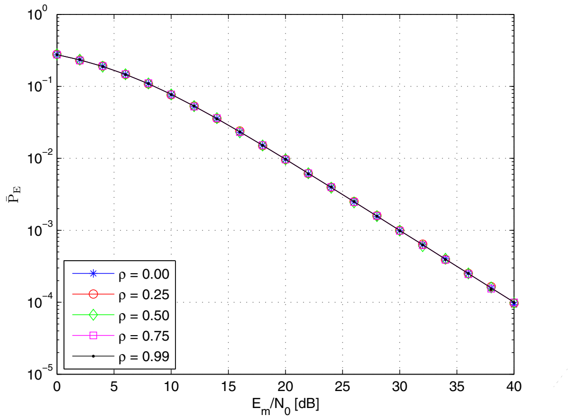

Fig. 2. Average error probability of SM in [1]. Markers show Monte Carlo simulation and solid lines the analytical model.

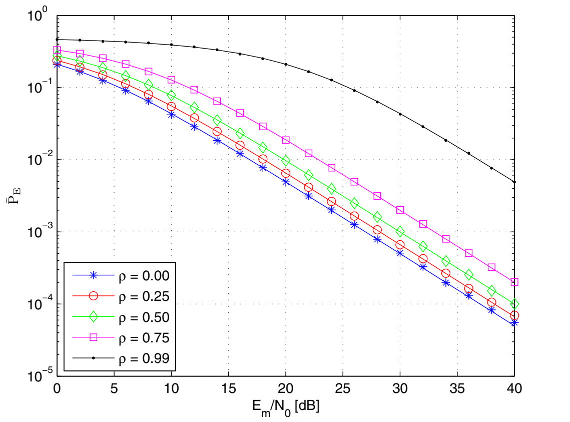

Fig. 3. Average error probability of SM in [3], [5]. Markers show Monte Carlo simulation and solid lines the analytical model.

clear indication of the robustness of the proposed method to spatial correlation of fading. ii) The SSK proposal in [1] offers worse performance than the SM scheme in [3]–[5] when the wireless links are uncorrelated. However, in the presence of channel correlation the situation is reversed: SSK in [1] offers a better error probability than SM in [3]–[5].

VI. Conclusion

In this paper, we have proposed a novel space modulation scheme based on the principle of the recently proposed SM wireless transmission technique. Analytical derivations and Monte Carlo simulations have shown that the proposed method can offer transmit–diversity gains, and, in particular, for a 2×1 MISO system a diversity order equal to two is achieved. It has also been verified that the proposed method yields better performance over correlated fading channels. As a byproduct of the analysis, we have compared various SM proposals available in the literature and have shown that they might offer different performance for various levels of fading correlation.

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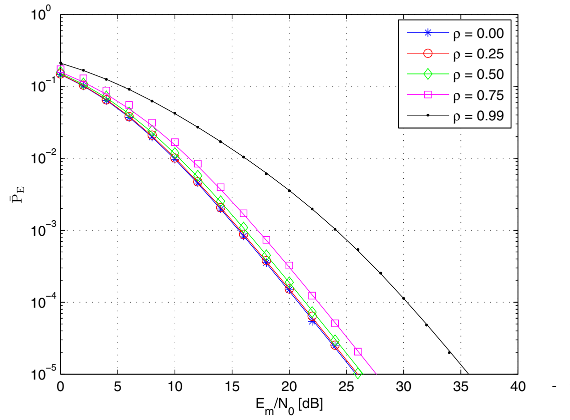

Fig. 4. Average error probability of TOSD–SM. Markers show Monte Carlo simulation and solid lines the analytical model.

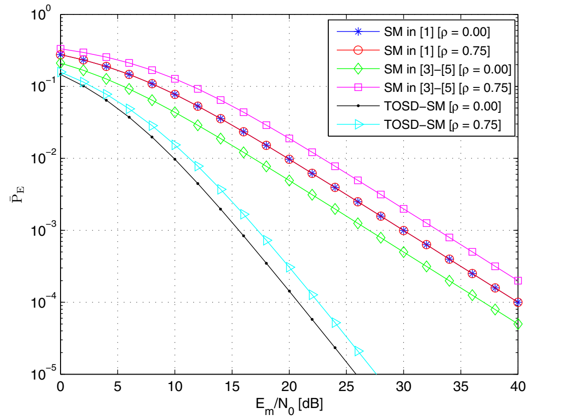

Fig. 5. Comparison of the average error probability for different SM schemes. The results are obtained from the analytical models substantiated in Figs. 2–4.

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