Constellation Randomization Achieves Transmit Diversity for Single-RF Spatial Modulation

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Abstract—The performance of spatial modulation (SM) is known to be dominated by the minimum Euclidean distance (MED) in the received SM constellation. In this paper, a symbol-scaling technique is proposed for SM in the multiple-input–multiple-output (MIMO) channel that enhances the MED to improve the performance of SM. This is achieved by forming fixed sets of candidate precoding factors for the transmit antennas (TAs), which are randomly generated and are known at both the transmitter and the receiver. For a given channel realization, the receiver independently chooses the specific set of factors that maximizes the MED. Given the channel state information (CSI) readily available at the receiver for detection, the receiver independently chooses the same set of precoding factors and uses them for the detection of both the antenna index (AI) and the symbol of interest. We analytically calculate the attainable gains of the proposed technique, in terms of its transmit diversity order, based on both the distribution of the MED and on the theory of classical order statistics. Furthermore, we show that the proposed scheme offers a scalable performance–complexity tradeoff for SM by varying the number of candidate sets of precoding factors, with significant performance improvements, compared to conventional SM.

Index Terms—Constellation shaping, multiple-input–multiple-output, prescaling, spatial modulation (SM).

I. INTRODUCTION

Traditional spatial multiplexing has been shown to improve the capacity of the wireless channel by exploiting multiantenna transmitters [1]. More recently, spatial modulation (SM) has been explored as a means of implicitly encoding information in the index of the specific antenna activated for the transmission of the modulated symbols, offering a low-complexity alternative [2]. Its central benefits include the absence of interantenna interference (IAI) and the fact that it only requires a subset (down to one) of radio-frequency (RF) chains compared to spatial multiplexing. Accordingly, the interantenna synchronization is also relaxed. Early work has focused on the design of receiver algorithms for minimizing the bit error rate (BER) of SM at a low complexity [2]–[6]. Matched filtering is shown to be a low-complexity technique for detecting the 42 antenna index (AI) used for SM [2]. A maximum-likelihood (ML) detector is introduced in [4] for reducing the complexity of classic spatial multiplexing ML detectors. Compressive sensing and reduced-space sphere detection have been discussed for 46 SM in [5] and [6] for further complexity reduction.

In addition to receive processing, recent work has also proposed constellation shaping for SM [7]–[15]. Specifically, in [7], the transmit diversity of coded SM is analyzed for different spatial constellations, which represent the legitimate sets of activated transmit antennas (TAs). Furthermore, Yang [8] 52 discusses symbol constellation optimization for minimizing the BER. Indeed, spatial- and symbol-constellation shaping are 54 discussed separately, as aforementioned. By contrast, the design 55 of the received SM constellation that combines the choice of 56 the TA, as well as the transmit symbol constellation, is the 57 focus of this paper. Precoding-aided approaches that combine 58 SM with spatial multiplexing are studied in [11] and [12]. A 59 number of constellation-shaping schemes [9]–[15] have also 60 been proposed for the special case of SM, which is referred to 61 as space shift keying, where the information is only carried in 62 the spatial domain, by the activated AI. Their application to the 63 SM transmission, where the transmit waveform is modulated, 64 is nontrivial.

Closely related work has focused on shaping the receive SM 66 constellation by means of symbol prescaling at the transmitter, aiming at maximizing the minimum Euclidean distance (MED) 68 in the received SM constellation [17]–[19]. The constellation-shaping approach in [17] and [18] aims at fitting the receive 70 SM constellation to one of the existing optimal constellation 71 formats in terms of minimum distance, such as, e.g., quadrature 72 amplitude modulation (QAM). Due to the strict constellation 73 fitting requirement imposed on both the amplitude and the 74 phase, this prescaling relies on the inversion of the channel 75 coefficients. In the case of ill-conditioned channels, this sub- 76 stantially increases the power associated to the transmit constel- 77 lation and therefore requires scaling factors for normalizing the 78 transmit power, which, however, reduces the received signal-to-noise ratio (SNR). This problem has been alleviated in [19], 80 where a constellation-shaping scheme based on phase-only 81 scaling is proposed. Nevertheless, the constellation shaping 82 used in the aforementioned schemes is limited in the sense that it 83 only applies to multiple-input–single-output (MISO) systems 84 where a single symbol is received for each transmission, and 85 thus, the characterization and shaping of the receive SM con- 86 stellation is simple. The application of constellation shaping in 87 the multiple-input–multiple-output (MIMO) systems is still an 88 open problem.
In line with the aforementioned challenges, in this paper, we introduce a new transmit prescaling (TPS) scheme, where the received constellation fitting problem is relaxed. As opposed to the aforementioned strict constellation fitting approaches, here, the received SM constellation is randomized by TPS for maximizing the MED between its points for a given channel. In more detail, a number of randomly generated candidate sets of TPS factors are formed offline, which are known to both the transmitter and the receiver. Each of these sets is normalized, so that the average transmit power remains unchanged, and yields a different receive constellation for a certain channel realization. For a given channel, the transmitter then selects that particular set of TPS factors that yields the SM constellation having the maximum MED. By doing so, the TPS alleviates the cases where different TAs yield similar received symbols and thus improves the reliability of symbol detection. At the receiver, by exploiting the channel state information (CSI) readily available for detection, the detector selects the same set of TPS factors to form the received constellation and applies an ML test to estimate the data. The explicit benefit of the aforementioned methodology is that it extends the idea of re-activated TA (the index of the nonzero element in $s^k_m$, conversing log$_2$(M) bits, and $k$ represents the index of the activated TA (the index of the nonzero element in $s^k_m$), conveying log$_2$(N$_t$) bits in the spatial domain. Clearly, since $s$ is an all-zero vector apart from $s^k_m$, there is no IAI.

The per-antenna TPS approach, which is the focus of this 162 paper, is shown in Fig. 1. The signal fed to each TA is scaled by 163 a complex-valued coefficient $\alpha_k$, $k \in \{1, \ldots, N_t\}$, for which 164 we have $E|\alpha_k| = 1$, where $|x|$ denotes the amplitude of a 165 complex number $x$, and $E\{\cdot\}$ denotes the expectation operator. 166 Defining the MIMO channel vector as $H$, with elements $h_{i,j}$ representing the complex channel coefficient between the $i$th 168 TA to the $j$th receive antenna (RA), the received symbol vector 169 can be written as

$$y = HAs^k_m + w$$  

(1)

**II. SYSTEM MODEL AND SPATIAL MODULATION**

**A. System Model**

Consider a MIMO system where the transmitter and receiver are equipped with $N_t$ and $N_r$ antennas, respectively. For simplicity, unless stated otherwise, in this paper, we assume that 149 the transmit power budget is limited to unity, i.e., $P = 1$. See 150 [20]–[22] for extensive reviews and tutorials on the basics and 151 state-of-the-art on SM. Here, we focus on the single-RF-chain 152 SM approach, where the transmit vector is in the all-but-one 153 zero form $s^k_m = [0, \ldots, s^k_m, \ldots, 0]^T$, where the notation $[\cdot]^T$ 154 denotes the transpose operator. Here, $s^k_m, m \in \{1, \ldots, M\}$ is 155 a symbol taken from an $M$-order modulation alphabet that 156 represents the transmitted waveform in the baseband domain 157 conveying log$_2$(M) bits, and $k$ represents the index of the 158 activated TA (the index of the nonzero element in $s^k_m$), conveying 159 log$_2$(N$_r$) bits in the spatial domain. Clearly, since $s$ is an all-zero 160 vector apart from $s^k_m$, there is no IAI.

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171 where \( w \sim \mathcal{CN}(0, \sigma^2 \mathbf{I}) \) is the additive white Gaussian noise component at the receiver, with \( \mathcal{CN}(\mu, \sigma^2) \) denoting the circularly symmetric complex Gaussian distribution with mean \( \mu \) and variance \( \sigma^2 \). Furthermore, \( \mathbf{A} = \text{diag}(\mathbf{a}) \in \mathbb{C}^{N_a \times N_t} \) is the TPS matrix with \( \mathbf{a} = [\alpha_1, \alpha_2, \ldots, \alpha_{N_t}] \), and \( \text{diag}(\mathbf{x}) \) represents the diagonal matrix with its diagonal elements taken from the vector \( \mathbf{x} \). Note that the diagonal structure of \( \mathbf{A} \) guarantees having a transmit vector \( \mathbf{t} = \mathbf{A}s \) with a single nonzero element, so that the single-RF-chain aspect of SM is preserved.

180 At the receiver, a joint ML detection of both the TA index and the transmit symbol is obtained by the minimization

\[
[s_{\hat{m}}, \hat{k}] = \arg \min_{m,k} \| y - \mathbf{y}_s \| = \arg \min_{m,k} \| y - \mathbf{H} \mathbf{A} \mathbf{s}_m \| \tag{2}
\]

where \( \| x \| \) denotes the norm of vector \( x \), and \( \mathbf{y}_s \) is the 1th constellation point in the received SM constellation. By exploiting the specific structure of the transmit vector, this can be further simplified to

\[
[s_{\hat{m}}, \hat{k}] = \arg \min_{m,k} \| y - \mathbf{h}_k \alpha_m s_m \| \tag{3}
\]

where \( \mathbf{h}_k \) denotes the \( k \)th column of matrix \( \mathbf{H} \), and \( \alpha_m \) is the TPS coefficient of the \( k \)th TA. It is widely recognized that the performance of the detection, as explained earlier, is dominated by the MED between adjacent constellation points \( \mathbf{y}_i, \mathbf{y}_j \) in the receive SM constellation, i.e.,

\[
d_{\min} = \min_{i,j} \| y_i - y_j \|^2, i \neq j \tag{4}
\]

190 Accordingly, to improve the likelihood of correct detection, constellation-shaping TPS schemes for SM aim at maximizing this MED. The optimum TPS matrix \( \mathbf{A}^* \) can be found by solving the optimization

\[
\mathbf{A}^* = \arg \max_{\mathbf{A}} \min_{i \neq j} \| y_i - y_j \|^2, \text{s.t. } \text{trace}(\mathbf{A}^H \mathbf{A}^*) \leq P \tag{5}
\]

195 and, additionally, for single-RF-chain SM, subject to \( \mathbf{A}^* \) having a diagonal structure. As aforementioned, \( \mathbf{A}^H \) and \( \text{trace}(\mathbf{A}) \) represent the Hermitian transpose and trace of matrix \( \mathbf{A} \), respectively. The aforementioned optimization, however, is an NP-hard problem, which makes finding the TPS factors prohibitively complex and motivates the conception of lower-complexity suboptimal techniques.

202 B. Prescaling for the MISO Channel

203 In line with the aforementioned discussions, in [17], a prescaling scheme is proposed for the MISO channel. Assuming a channel vector \( \mathbf{h} \), the receive SM constellation is fitted to a Q-QAM constellation with \( Q = N_t M \) by choosing

\[
\alpha_m^k = \frac{q_{m-k}(m-k)!}{h_k s_m \sqrt{N_t}} \tag{6}
\]

207 where \( q_{i} \) is the \( i \)th constellation point in the Q-QAM constellation, and the factor \( \| \mathbf{h} \| / \sqrt{N_t} \) is used for normalizing the receive constellation so that \( E[|q|] = 1 \).

We note that, while the scaling in (6) normalizes the receive constellation, it does not normalize the transmit power. Therefore, power-normalized scaling coefficients should be used in the form

\[
\alpha_m^k = \frac{\tilde{\alpha}_m^k}{\| \tilde{\alpha}_m^k \|} \tag{7}
\]

Nevertheless, it can be seen that for ill-conditioned channel coefficients, even for just one of the TAs, this leads to low power-scaling factors \( f = 1/\| \tilde{\alpha}_m^k \| \), which limits the obtainable performance. Finally, note that \( \alpha_m^k \) are data dependent for this 217 approach, as evidenced by the index \( m \), which does not allow for a fixed per-antenna scaling coefficient, as shown in Fig. 1.

220 Most importantly, the aforementioned strict constellation fitting cannot be extended to systems having multiple RAs, since the inversion of the full channel matrix \( \mathbf{H} \) would result in nonzero elements in the transmit vector \( \mathbf{t} \), which means that all TAs are used. Therefore, the important benefit of single-RF transmission of SM is lost.

225 An alternative is shown in [19], again for the MISO channel, where the scaling factors are in the form

\[
\alpha_m^k = e^{j\varphi_k} \tag{8}
\]

\[
\varphi_k = \theta_i - \theta_k \tag{9}
\]

where \( \varphi_k \) is the phase of the \( k \)th channel, and \( \theta_i \) is the \( i \)th angle taken from an equally spaced angle arrangement within \( [0, 2\pi] \), in the form

\[
\theta_i = \frac{2\pi}{N_t}(i - 1), i \in \{1, \ldots, N_t\} \tag{10}
\]

In this way, the phases of the points in the receive SM constellation become equispaced, hence maintaining a minimum for the Euclidean distances in the constellation.

230 Aside from their individual limitations and the fact that they are suboptimal, the aforementioned prescaling methods are limited by the fact that they apply solely to MISO systems relying on a single RA and cannot be readily extended to the case of MIMO SM transmission, hence lacking receive diversity.

235 III. PROPOSED CONSTELLATION RANDOMIZATION

236 We propose an adaptive TPS technique that randomizes the received SM constellation. The proposed constellation randomization (CR) simply selects the “best” from a number of randomly generated sets of per-antenna TPS factors, with the aim of improving the resulting MED. By allowing the randomization of the amplitude and phase of the effective channel that combines the TPS factor and the channel gains of the TA, the proposed scheme relaxes the constellation optimization problem and facilitates a better solution for the maximization of \( d_{\min} \). In addition, through the aforementioned randomization and selection of the appropriate TPS factors, the proposed scheme critically improves the transmit diversity of the SM system, as will be shown analytically in the following section. The proposed scheme involves the steps as analyzed in the following.
and the receiver applies the ML detector according to

\[ y \Rightarrow \text{ML detector} \]

A. Formation of Candidate Prescaling Sets

First, a number of \( D \) candidate TPS vectors are generated randomly in the form \( \alpha_d \), where \( d \in [1, D] \) denotes the index of the candidate set, and \( \alpha_d \) is formed by the elements \( \alpha_m^{(d)} \sim \mathcal{CN}(0, 1) \). These are made available to both the transmitter and receiver once, in an offline fashion before transmission. These assist in randomizing the received constellation, which is most useful in the cases where two points in the constellation happen to be very close. To ensure that the average transmit power remains unchanged, the scaling factors are normalized as in (7). It is important to reiterate that, in this work, we focus on power-normalized scaling factors, while the resulting diversity gains would not change.

As mentioned earlier, since the channel coefficients are estimated at the receiver for detection [2]–[6], (12) can be used to derive the aforementioned factors independently at the receiver. Therefore, no feedback forwarding of \( \alpha_m^{(d)} \) or the index \( d \) is required. Indeed, for equal channel coefficients available at the transmitter and receiver, they both select the same TPS vector \( \alpha_o \) independently, as per (12). Alternatively, to dispose of the need for CSI at the transmitter (CSIT), the receiver can indeed select the best scaling factors using (12) and feed the index of the selected scaling vector \( \alpha_o \), out of the \( D \) candidates back to the transmitter, using \( \lceil \log_2 D \rceil \) bits. In comparison to the closely related works in [17]–[19], this provides the proposed scheme with the advantage of a reduced transmit complexity that, instead of CSIT acquisition and prescaling optimization, involves the detection of \( \lceil \log_2 D \rceil \) bits at the end of every 300 channel coherence period, and a single complex multiplication of the classically modulated symbol \( s_m \) with the prescaling factor \( \alpha_m \) in the form shown in (3).

The intuitive benefits of the proposed scheme in the MED of the received SM constellation are shown in Fig. 2 for a (4 × 1)-305 element MISO system employing 4QAM modulation at high 306 SNR, where the original receive SM constellation without TPS 307 is shown in the left-hand side, and the constellation after the 308 selection in (12) is illustrated on the right-hand side. A clear 309 improvement in the MED can be observed, without increasing the 310 average transmit power. In fact, for the example in Fig. 2, a slight reduction of the power in the symbols denoted by “×” 312 can be observed, which, nevertheless, increases the MED in the 313 constellation.

Observe in Fig. 2 that while suboptimal in the constellation design sense, the proposed TPS enhances the MED in the 316 constellation with respect to conventional SM, while imposing 317 a conveniently scalable complexity as per the size of candidate 318 sets \( D \). It is evident that the gains in the MED for the proposed 319 scheme are dependent on the set size \( D \) of the candidate 320 TSP vector sets \( \alpha_d \) to choose from. An indicative result of 321 this dependence is shown in Fig. 3, where the average gains 322 in the MED are shown, with increasing numbers of \( D \) for 323 different transmission scenarios. Theoretically derived upper 324 bounds for these gains for \( N_r = 1, N_r = 2, \) and \( N_r = 4 \), based 325
The pairwise error probability (PEP) for $\gamma$ with $\delta$ which to choose. The system is said to have a diversity order introduces an amplitude–phase diversity in the transmission, single-RF SM is known to be one [7], the proposed TPS diversity gains. That is, while the transmit diversity of the performance targets.

In the search in (12). In the results that follow, we explore the values of $D$ for low values of $D$, significant MED benefits are obtained by increasing the number of candidates, while the gains saturate in the region of higher values of $D$. This justifies the choice of low values of $D$ to constrain the computational complexity involved in the search in (12). In the results that follow, we explore the error rates and complexity and their tradeoff in terms of power efficiency as a means of optimizing the value of $D$ for different performance targets.

**IV. DIVERSITY ANALYSIS**

336 **A. Transmit Diversity**

338 The proposed CR scheme leads to an increase in the transmit diversity gains. That is, while the transmit diversity of the single-RF SM is known to be one [7], the proposed TPS introduces an amplitude–phase diversity in the transmission, due to the existence of $D$ candidate sets of TPS factors from which to choose. The system is said to have a diversity order of $\delta$, if the BER decays with $\gamma^{-\delta}$ in the high-SNR region, with $\gamma$ being the SNR (see Fig. 4). To analyze the attainable diversity order, we note the pairwise error probability (PEP) for $\gamma_i, \gamma_j$ points as [7]

$$\text{PEP} (\gamma_i, \gamma_j) = Q\left(\sqrt{\frac{||\gamma_i - \gamma_j||^2}{2\sigma^2}}\right)$$  \hspace{1cm} (14)$$

where $Q(x)$ denotes the Gaussian Q-function [25], and

$$||\gamma_i - \gamma_j|| = \sqrt{||\gamma_i||^2 + ||\gamma_j||^2 - 2\gamma_i \cdot \gamma_j}$$

$$= \sqrt{||\gamma_i||^2 + ||\gamma_j||^2 - 2||\gamma_i||||\gamma_j||\cos(\Delta \phi)}$$ \hspace{1cm} (15)$$

where $\mathbf{a} \cdot \mathbf{b}$ denotes the dot product of vectors, and $\Delta \phi$ denotes 350 the phase difference between the two constellation points. Accordingly, for the purposes of characterizing the diversity order, we define the gain in the MED for the proposed SM-CR as

$$G(D) = \frac{E\{\max_{d} d_{\min}^D\}}{E\{d_{\min}\}} = \frac{E\{\max_{m,k} \|HA_d s_k^n - HA_d s_k^n\|^2\}}{E\{\min_{m,k} \|HS_m^n - HS_m^n\|^2\}}$$ \hspace{1cm} (16)$$

where we have used the notation $G(D)$ to suggest that the gain is a function of the size of candidate sets $D$. It will be shown in the results section that this gain also represents the transmit diversity gain attained. The following theorem describes an upper bound of this diversity gain.

**Theorem 1:** For a frequency-flat Rayleigh fading channel $H \sim C\mathcal{N}(0, (1/2)I_N, \llap{\boxplus} I_N)$, the gain in the MED of the 360 proposed SM-CR is upper bounded as

$$G(D) \le \sum_{k=1}^{D} \left(\alpha^{k+1} - \alpha^k\right) n_{k}\left(\frac{1}{\alpha} - \frac{1}{\alpha^2}\right)$$ \hspace{1cm} (17)$$

where $n = \binom{N^R}{2}$, with $(p\choose q) = p!/(q!(p-q)!)$ denoting the binomial coefficient, with $x!$ being the factorial function and $E(-n, k)$ denoting the generalized exponential integral function [25].

**Proof:** To simplify the analysis, we shall assume that 365 the distances in the receive constellation are statistically in- dependent. It is shown in Fig. 2 that, strictly speaking, this is not true since the constellation points created by each channel are indeed interdependent through the transmit symbol constellation. Nevertheless, we will demonstrate in Fig. 3 that this 370 affordable assumption yields a tight upper bound for the gain. 371 First, regarding the product $HA_d$, it has been shown in [26] that 372 the product of uncorrelated zero-mean Gaussian variables with 373 variances $\sigma_1^2, \sigma_2^2$ is also zero-mean Gaussian with a variance 374 equal to $\sigma_1^2 + \sigma_2^2$. It is therefore clear that, for a normalized transmit constellation, the receive vectors are distributed 376 as $y_i \sim C\mathcal{N}(0, 1/2I_N)$. Accordingly, $y_i - y_j \sim C\mathcal{N}(0, I_N)$, 377 and therefore, $z = ||y_i - y_j||^2 \sim \chi^2_{2N}$, where $\chi^2_k$ denotes the chi-square distribution with $k$ degrees of freedom [25]. The 379 probability density function (PDF) and cumulative distribution function (CDF) of $z$, are therefore, given by

$$f_z(x) = \frac{1}{2^{N} \Gamma(N)} x^{N/2 - 1} e^{-x/2}$$ \hspace{1cm} (18)$$

$$F_z(x) = \frac{1}{\Gamma(N)} \gamma\left(\frac{N}{2}, \frac{x}{2}\right)$$ \hspace{1cm} (19)$$

SM scales with the Euclidean distance between constellation points as [7]
where \( \Gamma(.) \) and \( \gamma(.,.) \) denote the Gamma and lower incomplete Gamma functions, respectively [25]. Based on the theory of order statistics [27], from the \( n=(N_r \frac{M}{2}) \) distances in the receive SM constellation (see Fig. 2), the minimum distance is distributed as

\[
D_{\text{min}}(x) = nF_{\tau}(x)[1 - F_{\tau}(x)]^{n-1} = \frac{n}{2^{n-1} \Gamma(N_r)^n} x^{N_r - 1} e^{-x/2} \left[ \Gamma\left( N_r, \frac{x}{2} \right) \right]^{n-1}
\]

(20)

\[
F_{\text{min}}(x) = 1 - \left( 1 - F_{\tau}(x) \right)^n = 1 - \left[ \frac{1}{\Gamma(N_r)} \Gamma\left( N_r, \frac{x}{2} \right) \right]^n
\]

(21)

where \( \Gamma(.,.) \) denotes the upper incomplete Gamma function and, as mentioned earlier, it is assumed that all distances in the receive SM constellation are independent. Since \( d_{\text{min}} \) is nonnegative, its mean is found as

\[
E\{d_{\text{min}}\} = \int_{0}^{\infty} [1 - F_{\text{min}}(x)] \, dx = \int_{0}^{\infty} (1 - F_{\tau}(x)) \, dx.
\]

(22)

\[
\text{Let us now derive the mean of the maximum minimum distance in the receive SM constellation as per the proposed technique. We note that, for the normalized TPS factors in (7), the distribution of } y_i \text{ remains unchanged. Therefore, the PDF of } \tau = \max_{A_d} d_{\text{min}}, \text{ when selecting the maximum from } D, \text{ candidates are given as}
\]

\[
f_{\tau}(x) = Df_{d_{\text{min}}}(x)F_{d_{\text{min}}}(x)^{D-1} \]

(23)

\[
F_{\tau}(x) = F_{d_{\text{min}}}(x)^D.
\]

(24)

Similarly to the aforementioned calculation, for the mean of \( \tau = \max_{A_d} d_{\text{min}} \), we have

\[
E\{\tau\} = \int_{0}^{\infty} \{1 - F_{\tau}(x)\} \, dx = \int_{0}^{\infty} \{1 - (1 - F_{\tau}(x))^D\} \, dx
\]

\[
= \int_{0}^{\infty} \{1 - (1 - (1 - F_{\tau}(x))^{n})^D\} \, dx
\]

\[
= \int_{0}^{\infty} \left\{ \frac{1}{D} \sum_{k=0}^{D} \binom{D}{k} (-1)^k (1 - F_{\tau}(x))^{nk} \right\} \, dx
\]

\[
= \sum_{k=1}^{D} \binom{D}{k} (-1)^{k+1} \int_{0}^{\infty} (1 - F_{\tau}(x))^{nk} \, dx.
\]

(25)

As stated previously, we have used the binomial expansion \( (1 - x)^m = \sum_{k=0}^{m} \binom{m}{k} (-1)^k x^k \). By substituting (22) and (25) into (16), we arrive at the upper bound for the gain in the MED as

\[
G_u(N_r) = \sum_{k=1}^{D} \binom{D}{k} (-1)^{k+1} \int_{0}^{\infty} (1 - F_{\tau}(x))^{nk} \, dx \int_{0}^{\infty} (1 - F_{\tau}(x))^{n} \, dx
\]

(26)

where we have used the notation \( G_u(N_r) \) to clarify that the upper bound here is a function of \( N_r \). Finally, it can be shown that \( (dG_u(N_r)/dN_r) \leq 0 \), and therefore, the gain is a monotonically decreasing function of the number of RAs. Hence, the gain for the case \( N_r = 1 \) provides a global upper bound for all \( N_r \) cases. Indeed, as it is shown in Fig. 3 and is intuitive, the highest gains can be observed for the single-antenna receiver 408 case, which experiences a diversity of one for conventional SM. For this case, from (18), (19), and (26), we get (17).

B. Error Probability Trends

Based on the aforementioned diversity calculations, we can derive the BER performance of the proposed scheme in the high-SNR region. Indeed, SM systems with \( N_r \) uncorrelated RAs have been shown to experience a unit transmit diversity order and receive diversity order of \( N_r \). Accordingly, since the proposed scheme attains a transmit diversity order of \( G(D) \), the total diversity becomes \( \delta = N_r G(D) \). The resulting probability of error \( P_e \) follows the trend

\[
P_e = \alpha \gamma^{-N_r G(D)}
\]

(27)

where \( \gamma \) is the transmit SNR, \( \delta = N_r G(D) \) is the diversity 420 order based on the calculations of \( G(D) \) in Section IV-A, and \( \alpha \) is an arbitrary coefficient. The diversity order \( \delta = N_r G(D) \) accounts for the inherent receive diversity \( N_r \) in the system and 423 the transmit diversity \( G(D) \) induced by the proposed scheme. 424 Clearly, as per the upper bound of Theorem 1 in (17) and the 425 BER trend in (27), a lower bound in the resulting probability of 426 error can be obtained. In the following results, we show that 427 the aforementioned performance trend matches the simulated 428 performance in the high-SNR region.

V. COMPUTATIONAL COMPLEXITY

It is clear from the aforementioned discussion that the proposed SM-CR leads to an increase in the computational complexity, with respect to conventional SM, due to the need 433 to compute the MED for all the \( D \) candidate scaling factor 434 sets. Here, we analyze the increase in computational complexity 435 at the receiver. We later use this analysis to model the power 436 consumption associated with the required signal processing and 437 compare the proposed SM-CR with conventional SM, in terms 438 of the overall power efficiency of transmission. For reference, 439 we have assumed an LTE Type 2 TDD frame structure [28]. 440 This has a 10-ms duration, which consists of 10 subframes, out 441 of which five subframes, containing 14 symbol time slots each, 442 are used for downlink transmission yielding a block size of 443 \( B = 70 \) for the downlink, while the rest are used for both uplink 444 and control information transmission. A slow-fading channel is 445 assumed, where the channel remains constant for the duration 446 of the frame. In Table I, we summarize the computationally 447 dominant operations involved at the receiver for both SM and 448 SM-CR. In these calculations, we have used the fact that the 449 calculation of the norm of a vector with \( n \) elements involves 450 \( 2n \) elementary operations. In addition, it can be seen that 451 the product \( A_d S_m \) is a scalar that involves a single complex 452 valued multiplication, and its multiplication with the channel 453 matrix involves an additional \( 2N_r \) elementary operations per 454
455 constellation point. This has to be done for each of the $N_t M$
456 points in the receive constellation. Accordingly, there are a
457 number of $\binom{N_t M}{2}$ distances in the constellation, and therefore,
458 there are $\binom{N_t M}{2}$ norms in the form of (12) that need to be
459 calculated for each candidate scaling factor set. The first three
460 operations in the constellation optimization in Table I need to
461 be done for each candidate set: hence, $D$ times in total. For the
462 ML detection, a number of $N_t M$ norms in the form of (13)
463 need to be calculated before the minimum is chosen, and this
464 has to be calculated $B$ times in the frame. Finally, we have
465 used the fact that finding the maximum and the minimum in an
466 $n$-element vector requires $n$ operations.

467 Based on the aforementioned calculations, we have the
468 complexities of the SM receiver and of the SM-CR receiver,
469 respectively, in the form of

$$C_{\text{SM}}(D) = (2 N_r + 1) N_t (M + 1)$$

(28)

$$C_{\text{SM-CR}}(D) = (2 N_r + 1) \left[ \binom{N_t M}{2} + N_t M \right] D + D$$

(29)

where it can be seen that the complexity of SM-CR is in the form

$$C_{\text{SM-CR}}(D) = \chi D + \psi$$

(30)

with

$$\chi = (2 N_r + 1) \left[ \binom{N_t M}{2} + N_t M \right] + 1$$

(31)

$$\psi = (2 N_r + 1) N_t M B.$$  

(32)

In the following section, we use these expressions to calculate
473 the resulting power consumption related to signal process-
474 ing at the receiver for the evaluation of the power efficiency of
475 transmission.

VI. POWER EFFICIENCY

476 As the ultimate metric for evaluating the performance–
477 complexity tradeoff and the overall usefulness of the proposed
478 technique, and toward an energy-efficient communication sys-
479 tem, we consider the power efficiency of SM-CR compared
480 to SM, as well as its dependence on the number of candidate
481 scaling factor sets $D$. We note that prior studies explore the en-
482 ergy efficiency of SM for the purposes of optimizing the num-
483 ber of antennas employed [30], [31]. Following the modeling in 484
29] and [32]–[35], we define the transmit power efficiency of 485
the communication link as the bit rate per total transmit power 486
dissipated, i.e., the ratio of the throughput achieved over the 487
consumed power as

$$P = \frac{T}{P_{\text{PA}} + (1 + N_r) \cdot P_{\text{RF}} + p_c \cdot C}$$

(33)

where $P_{\text{PA}} = (\xi/\eta) - 1) P$ in watts is the power consumed 489
at the power amplifier to produce the total transmit signal 490
power $P$, with $\eta$ being the power amplifier efficiency and 491
$\xi$ being the modulation-dependent peak-to-average power ratio. 492
Furthermore, $P_{\text{RF}} = P_{\text{mix}} + P_{\text{filt}} + P_{\text{DAC}}$ is the power related 493
to the mixers, to the transmit filters, and to the digital-to-analog 494
converter (DAC), which is assumed constant for the purposes 495
of this work. We use practical values of these from [32] as 496
30% and $P_{\text{mix}} = 30.3$ mW, $P_{\text{filt}} = 2.5$ mW, and $P_{\text{DAC}} = 497$
1.6 mW, yielding $P_{\text{RF}} = 34.4$ mW. In (33), $p_c$ in watts/Kops is 498
the power per $10^3$ elementary operations (KOps) of the digital 499
signal processor (DSP), and $C$ is the number of operations 500
involved. This term is used to introduce complexity as a factor 501
of the transmitter power consumption in the power efficiency 502
metric. Typical values of $p_c$ include $p_c = 22.88$ mW/KOps for 503
the Virtex-4 and $p_c = 5.76$ mW/KOps for the Virtex-5 field-
programmable gate array family from Xilinx [36]. Finally

$$T = E B(1 - P_B) = E B(1 - P_c)^B$$

(34)

represents the achieved throughput, where $P_B$ is the block error 506
rate, and

$$E = \log_2(N_t M)$$

(35)

is the spectral efficiency of SM in bits per channel use. For a 508
given transmit power and numbers of TAs and RAs, combining 509
(33) with (27), the power efficiency expression for SM-CR 510
takes the form

$$P = \frac{E B(1 - \alpha \gamma^{-N_c}G(D))}{B}$$

(36)
where both $G(D)$ and $C(D)$ are functions of the number of candidate sets $D$ through (26) and (29), while $\alpha, c$ are constants. This expression can therefore be used to characterize the scalable performance–complexity tradeoff for the proposed scheme and for optimizing the value of $D$ for maximizing power efficiency.

The expression in (33) provides an amalgamated metric that combines throughput, complexity, and transmit signal power, all in a unified metric. By varying the number of candidate scaling factor sets $D$, both the resulting complexity and transmission rates are influenced, as shown earlier. Therefore, a scalable tradeoff between performance and complexity can be achieved accordingly. High values of $P$ indicate that high bit rates are achievable for a given power consumption, and thus denote a high energy efficiency. The following results show that SM-CR provides an increased energy efficiency compared to SM in numerous scenarios using different transmit powers $P$.

**VII. Simulation Results**

To evaluate the benefits of the proposed technique, this section presents numerical results based on Monte Carlo simulations of conventional SM without scaling (termed as SM in the figures) and the proposed SM-CR. Our focus is on systems where the receiver employs more than one antenna, where the prescaling schemes in [17]–[19] are inapplicable. The channel impulse response is assumed to be perfectly known at the transmitter. Without loss of generality, unless stated otherwise, we assume that the transmit power is restricted to $P = 1$. MIMO systems with up to eight TAs employing 4QAM and 16QAM modulation are explored, albeit it is plausible that the benefits of the proposed technique extend to larger scale systems and higher order modulation.

First, for reasons of reference, the BER performance of the proposed scheme is compared with the performance of the most relevant techniques in [17] and [19] for the MISO channel, where the latter techniques are applicable. First, we note the performance loss when applying power scaling to the scheme in [17]. Second, while the true strength of the proposed lies in the fact that it applies to MIMO links where the schemes in [17] and [19] are inapplicable, the results here show that the proposed scheme outperforms the conventional techniques in the MISO channel as well.

Next, we show the BER performance with increasing transmit SNR for a $(4 \times 2)$-element MIMO employing 4QAM, for various numbers of candidate scaling factor sets $D$, in Fig. 5. The graph includes the performance of SM for the $(4 \times 4)$-element MIMO for reference. It can be seen that the slope of the BER curves increases with increasing $D$, which indicates an increase in transmit diversity order. Indeed, for high values of $D$, the $(4 \times 2)$-element system with SM-CR exhibits the same transmit diversity order as the $(4 \times 4)$-element system with conventional SM. Moreover, as also observed in Fig. 3, when increasing $D$, the gains saturate for higher values, which can also be seen here, where the BER for $D = 20$ closely approximates the one for $D = 100$.

In Fig. 6 the BER versus SNR performance is shown for the $(4 \times 2), (8 \times 2)$, and $(8 \times 4)$ systems for both SM and SM-CR.

Theoretical diversity trends observed in the form of $P_e = \frac{568}{\alpha\gamma^{-\delta}}$ are also shown, where $P_e$ denotes the probability of error 569 for high SNR; $\gamma$ is the SNR; and $\delta = N_r G$ is the diversity order, 570 where $G$ is taken from the respective points in Fig. 3, which is 571 upper bounded, as calculated in Section IV. The performance 572 trends for both the exact diversity gains $G(D)$ based on simu- 573 lation in Fig. 3 and the upper bounds $G_{ua}(N_r)$ of Theorem 1 in 574 Section IV-A are shown for comparison. A close match between 575 the analytical and simulated diversity can be observed. With 576 regard to the performance observed, it can be seen that there is a 577 indeed a performance penalty when increasing the number 578 of TAs from four to eight for SM with fixed RA number, due 579 to the growth of the spatial constellation, which harms the 580 detection of the TA index [see (4 \times 2) to (8 \times 2)]. The improved 581 received diversity in the detection of TA index when increasing 582 the number of RA brings the performance benefits observed in 583 Fig. 6 between (8 \times 2) and (8 \times 4). The same comparison is shown in Fig. 7 for the case of 16QAM, and it can be seen
Fig. 7. BER versus SNR for a (8 × 2) and (8 × 4) MIMO with SM and SM-CR with $D = 20$ for 16QAM.

Fig. 8. BER versus $D$ for a (4 × 2), (8 × 2), and (8 × 4) MIMO with SM-CR for 4QAM and 16QAM.

Fig. 9. BER versus SNR for a (4 × 2) MIMO with CSI errors for SM and SM-CR with $D = 20$, for 4QAM.

a study of the performance attainable in the presence of CSI errors and, in particular, in the case where the CSI estimated at the transmitter (CSIT) and the receiver (CSIR) are different. For this reason, in Fig. 9, we explore the situation where both the transmitter (TPS selection) and the receiver (TPS selection and ML detection) rely on erroneous CSI. We model CSIT and CSIR in the form

$$\hat{H} = H + E$$

(37)

where $\hat{H}$ and $E \sim \mathcal{CN}(0, \omega)$ are the estimated channel and the complex Gaussian CSI error having a variance $\omega$, respectively. Independent CSI error matrices are generated at the transmitter and receiver. Fig. 9 illustrates the BER performance upon increasing the CSIT and CSIR errors for SM and SM-CR, with $\omega$ at 15 dB and 20 dB below the signal power. Both techniques are affected by the CSIR errors at the ML detection stage. In addition, for SM-CR, the errors may lead to the selection of different TPS factors at the transmitter and receiver. Nonetheless, it can be seen that both SM and SM-CR experience the same performance degradation trend with increasing the CSI errors and that the performance gains observed for SM-CR persist.

The computational complexity of the proposed technique is examined in Fig. 10, as a function of both $N_t$ and $D$, for 4QAM and 16QAM. The complexity count is based on the operations calculated in Table I, and it can be seen that, for both 4QAM and 16QAM, the performance benefits of SM-CR are achieved at an increased complexity compared to SM, which scales with the selection of the parameter $D$. The overall tradeoff between performance and complexity is shown to be favorable for SM-CR in Fig. 11, where the power efficiency is shown with varying transit power for the (4 × 2) and (8 × 2) systems with $D = 20$. Ranges between 30 dBm (1 W) and 36 dBm (4 W) are depicted, which correspond to the power budgets of small-cell base stations [37]. It can be seen that the improved throughput for SM-CR compensates for the increased complexity in the overall system’s power efficiency, thus providing an improved tradeoff compared to SM.
Finally, Fig. 12 shows the power efficiency for increasing $D$ for the $(4 \times 2)$ MIMO with transmit SNR $\gamma = 15$ dB and the $(8 \times 2)$ MIMO with $\gamma = 20$ dB using 4QAM modulation. The different curves in the figure represent different transmit power budgets ranging from $P = 30$ dBm to $P = 43$ dBm. For ease of illustration, power efficiency is shown as a percentage of its maximum, as the different scenarios in the figure have different maximum power efficiencies. It can be seen in both subfigures that, as the transmit power is increased, higher values of $D$ offer the best power efficiency. This is due to the fact that, with the increase in the transmit power, the power consumption of the DSP becomes less important and the increase in throughput greatly improves the overall power efficiency. In all cases, the maximum power efficiency achieved with SM-CR is better than the one for conventional SM, which corresponds to the points in the figure with $D = 1$, indicating that the proposed scheme offers the required transmission rates at a lower power consumption.

Fig. 11. Power efficiency versus $P$ for a $(4 \times 2)$ and $(8 \times 2)$ MIMO with SM and SM-CR with $D = 20$ and $\gamma = 18$ dB for 4QAM.

VIII. CONCLUSION

A new receive-constellation-shaping approach has been introduced for SM in the MIMO channel. Conventional constellation-shaping techniques offer limited gains for SM, due to the strict fitting to a fixed constellation, and tend to require the inversion of all ill-conditioned channel coefficients. Moreover, existing practical low-complexity constellation-shaping schemes are only applicable to the case where the receiver has a single antenna. We have proposed a CR scheme, where transmit diversity is introduced by appropriately selecting the TPS factors from sets of randomly generated coefficients. The proposed scheme has been shown, both analytically and by simulation, to offer significant performance gains with respect to conventional SM. Our future work will involve the application of the proposed approach to more advanced SM techniques, such as generalized SM, as well as SM with antenna selection and adaptive modulation.

REFERENCES


AUTHOR QUERIES

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Constellation Randomization Achieves Transmit Diversity for Single-RF Spatial Modulation

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Abstract—The performance of spatial modulation (SM) is known to be dominated by the minimum Euclidean distance (MED) in the received SM constellation. In this paper, a symbol-scaling technique is proposed for SM in the multiple-input–multiple-output (MIMO) channel that enhances the MED to improve the performance of SM. This is achieved by forming fixed sets of candidate prescaling factors for the transmit antennas (TAs), which are randomly generated and are known at both the transmitter and the receiver. For a given channel realization, the transmitter chooses the specific set of factors that maximizes the MED. Given the channel state information (CSI) readily available at the receiver for detection, the receiver independently chooses the same set of prescaling factors and uses them for the detection of both the antenna index (AI) and the symbol of interest. We analytically calculate the achievable gains of the proposed technique, in terms of its transmit diversity order, based on both the distribution of the MED and on the theory of classical order statistics.

Index Terms—Constellation shaping, multiple-input–single-output, prescaling, spatial modulation (SM).

I. INTRODUCTION

TRADITIONAL spatial multiplexing has been shown to improve the capacity of the wireless channel by exploiting multiantenna transmitters [1]. More recently, spatial modulation (SM) has been explored as a means of implicitly encoding information in the index of the specific antenna activated for the transmission of the modulated symbols, offering a low-complexity alternative [2]. Its central benefits include the absence of interantenna interference (IAI) and the fact that it only requires a subset (down to one) of radio-frequency (RF) chains compared to spatial multiplexing. Accordingly, the interantenna synchronization is also relaxed. Early work has focused on the design of receiver algorithms for minimizing the bit error rate (BER) of SM at a low complexity [2]–[6]. Matched filtering is shown to be a low-complexity technique for detecting the antenna index (AI) used for SM [2]. A maximum-likelihood (ML) detector is introduced in [4] for reducing the complexity of classic spatial multiplexing ML detectors. Compressive sensing and reduced-space sphere detection have been discussed for SM in [5] and [6] for further complexity reduction.

In addition to receive processing, recent work has also proposed constellation shaping for SM [7]–[15]. Specifically, in [7], the transmit diversity of coded SM is analyzed for different spatial constellations, which represent the legitimate sets of activated transmit antennas (TAs). Furthermore, Yang [8] discusses symbol constellation optimization for minimizing the BER. Indeed, spatial- and symbol-constellation shaping are discussed separately, as aforementioned. By contrast, the design of the received SM constellation that combines the choice of the active TA, as well as the transmit symbol constellation, is the focus of this paper. Precoding-aided approaches that combine SM with spatial multiplexing are studied in [11] and [12]. A number of constellation-shaping schemes [9]–[15] have also been proposed for the special case of SM, which is referred to as space shift keying, where the information is only carried in the spatial domain, by the activated AI. Their application to the SM transmission, where the transmit waveform is modulated, is nontrivial.

Closely related work has focused on shaping the receive SM constellation by means of symbol prescaling at the transmitter, aiming at maximizing the minimum Euclidean distance (MED) in the received SM constellation [17]–[19]. The constellation-shaping approach in [17] and [18] aims at fitting the receive SM constellation to one of the existing optimal constellation formats in terms of minimum distance, such as, e.g., quadrature amplitude modulation (QAM). Due to the strict constellation fitting requirement imposed on both the amplitude and the phase, this prescaling relies on the inversion of the channel coefficients. In the case of ill-conditioned channels, this substantially increases the power associated to the transmit constellation and therefore requires scaling factors for normalizing the transmit power, which, however, reduces the received signal-to-noise ratio (SNR). This problem has been alleviated in [19], where a constellation-shaping scheme based on phase-only scaling is proposed. Nevertheless, the constellation shaping used in the aforementioned schemes is limited in the sense that it only applies to multiple-input–single-output (MISO) systems where a single symbol is received for each transmission, and thus, the characterization and shaping of the receive SM constellation is simple. The application of constellation shaping in the multiple-input–multiple-output (MIMO) systems is still an open problem.

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In line with the aforementioned challenges, in this paper, we introduce a new transmit prescaling (TPS) scheme, where the received constellation fitting problem is relaxed. As opposed to the aforementioned strict constellation fitting approaches, here, the received SM constellation is randomized by TPS for maximizing the MED between its points for a given channel.

In more detail, a number of randomly generated candidate sets of TPS factors are formed offline, which are known to both the transmitter and the receiver. Each of these sets is normalized, so that the average transmit power remains unchanged, and yields a different receive constellation for a certain channel realization. For a given channel, the transmitter then selects that particular set of TPS factors that yields the SM constellation having the maximum MED. By doing so, the TPS alleviates the cases where different TAs yield similar received symbols so that the average transmit power remains unchanged, and thus improves the reliability of symbol detection. At the receiver, by exploiting the channel state information (CSI) readily available for detection, the detector selects the same set of TPS factors to form the received constellation and applies an ML test to estimate the data. The explicit benefit of the aforementioned methodology is that it extends the idea of re-activated TA to the point-to-point MIMO transmission that improves the at-attainable power efficiency. Section VII presents our numerical results, and finally, our conclusions are offered in Section VIII.

II. SYSTEM MODEL AND SPATIAL MODULATION

A. System Model

Consider a MIMO system where the transmitter and receiver are equipped with \( N_t \) and \( N_r \) antennas, respectively. For simplicity, unless stated otherwise, in this paper, we assume that the transmit power budget is limited to unity, i.e., \( P = 1 \). See [20]–[22] for extensive reviews and tutorials on the basics and state-of-the-art on SM. Here, we focus on the single-RF-chain SM approach, where the transmit vector is in the all-but-one zero form \( s_m^k = [0, \ldots, s_{mk}, \ldots, 0]^T \), where the notation \( [.]^T \) denotes the transpose operator. Here, \( s_{m}, m \in \{1, \ldots, M\} \) is a symbol taken from an \( M \)-order modulation alphabet that represents the transmitted waveform in the baseband domain, conveying \( \log_2(M) \) bits, and \( k \) represents the index of the activated TA (the index of the nonzero element in \( s_{m}^k \)) conveying \( \log_2(N_t) \) bits in the spatial domain. Clearly, since \( s \) is an all-zero vector apart from \( s_{m}^k \), there is no IAI.

The per-antenna TPS approach, which is the focus of this 162 paper, is shown in Fig. 1. The signal fed to each TA is scaled by a power efficiency metric that combines the transmit power, the achieved throughput, and the computational complexity imposed to quantify the improved power efficiency offered by the proposed scheme.

The remainder of this paper is organized as follows. Section II presents the MIMO system model and introduces the SM transmission. Section III details the proposed TPS scheme, while in Section IV, we present our analytical study of the obtained transmit diversity gains of the proposed scheme. Sections V–VI detail the complexity calculation and the study of the attainable power efficiency. Section VII presents our numerical results, and finally, our conclusions are offered in Section VIII.

![Block diagram of SM transceiver with constellation randomization (SM-CR).](Image)

\[ y = H A s_m^k + w \]
where $w \sim \mathcal{CN}(0, \sigma^2 \mathbf{I})$ is the additive white Gaussian noise component at the receiver, with $\mathcal{CN}(\mu, \sigma^2)$ denoting the circularly symmetric complex Gaussian distribution with mean $\mu$ and variance $\sigma^2$. Furthermore, $\mathbf{A} = \text{diag}(\mathbf{a}) \in \mathbb{C}^{N_t \times N_t}$ is the TPS matrix with $\mathbf{a} = [\alpha_1, \alpha_2, \ldots, \alpha_{N_t}]$, and $\text{diag}(\mathbf{x})$ represents the diagonal matrix with its diagonal elements taken from vector $\mathbf{x}$. Note that the diagonal structure of $\mathbf{A}$ guarantees having a transmit vector $\mathbf{t} = \mathbf{A}s$ with a single nonzero element, so that the single-RF-chain aspect of SM is preserved.

At the receiver, a joint ML detection of both the TA index and the transmit symbol is obtained by the minimization

$$[\hat{s}_m, \hat{k}] = \arg \min_{m,k} \| \mathbf{y} - \mathbf{y}_i \|$$

$$= \arg \min_{m,k} \| \mathbf{y} - \mathbf{H} \mathbf{A} s_m^k \|$$

where $\| \mathbf{x} \|$ denotes the norm of vector $\mathbf{x}$, and $\mathbf{y}_i$ is the $i$th constellation point in the received SM constellation. By exploiting the specific structure of the transmit vector, this can be further simplified to

$$[\hat{s}_m, \hat{k}] = \arg \min_{m,k} \| \mathbf{y} - \mathbf{h}_k \alpha_m^k s_m \|$$

where $\mathbf{h}_k$ denotes the $k$th column of matrix $\mathbf{H}$, and $\alpha_m^k$ is the TPS coefficient of the $k$th TA. It is widely recognized that the performance of the detection, as explained earlier, is dominated by the MED between adjacent constellation points $\mathbf{y}_i, \mathbf{y}_j$ in the receive SM constellation, i.e.,

$$d_{\text{min}} = \min_{i,j} \| \mathbf{y}_i - \mathbf{y}_j \|^2, i \neq j.$$  

Accordingly, to improve the likelihood of correct detection, constellation-shaping TPS schemes for SM aim at maximizing this MED. The optimum TPS matrix $\mathbf{A}^*$ can be found by solving the optimization

$$\mathbf{A}^* = \arg \max_{\mathbf{A}} \min_{i,j} \| \mathbf{y}_i - \mathbf{y}_j \|^2, i \neq j$$

s.t. $\text{trace}(\mathbf{A}^* \mathbf{H} \mathbf{A}^*) \leq P$  

and, additionally, for single-RF-chain SM, subject to $\mathbf{A}^*$ having a diagonal structure. As aforementioned, $\mathbf{A}^H$ and $\text{trace}(\mathbf{A})$ represent the Hermitian transpose and trace of matrix $\mathbf{A}$, respectively. The aforementioned optimization, however, is an NP-hard problem, which makes finding the TPS factors prohibitively complex and motivates the conception of lower complexity suboptimal techniques.

**B. Prescaling for the MISO Channel**

In line with the aforementioned discussions, in [17], a prescaling scheme is proposed for the MISO channel. Assuming a channel vector $\mathbf{h}$, the receive SM constellation is fitted to a Q-QAM constellation with $Q = N_t M$ by choosing

$$\alpha_m^k = \frac{q_{m+k} \| \mathbf{h} \|}{h_k s_m \sqrt{N_t}$$

where $q_i$ is the $i$th constellation point in the Q-QAM constellation, and the factor $\| \mathbf{h} \| / \sqrt{N_t}$ is used for normalizing the receive constellation so that $E\{|q|^2\} = 1$.

We note that, while the scaling in (6) normalizes the receive constellation, it does not normalize the transmit power. Therefore, power-normalized scaling coefficients should be used in the form

$$\alpha_m^k = \frac{\alpha_m^k}{\| \mathbf{a} \|}$$

Nevertheless, it can be seen that for ill-conditioned channel coefficients, even for just one of the TAs, this leads to low power-scaling factors $f = 1 / \| \mathbf{a} \|$, which limits the obtainable performance. Finally, note that $\alpha_m^k$ are data dependent for this approach, as evidenced by the index $m$, which does not allow for a fixed per-antenna scaling coefficient, as shown in Fig. 1.

Most importantly, the aforementioned strict constellation fitting cannot be extended to systems having multiple RAs, since the inversion of the full channel matrix $\mathbf{H}$ would result in nonzero elements in the transmit vector $\mathbf{t}$, which means that all TAs are used. Therefore, the important benefit of single-RF transmission of SM is lost.

An alternative is shown in [19], again for the MISO channel, where the scaling factors are in the form

$$\alpha_k = e^{j\varphi_k}$$

$$\varphi_k = \theta_i - \vartheta_k$$

where $\vartheta_k$ is the phase of the $k$th channel, and $\theta_i$ is the $i$th angle taken from an equally spaced angle arrangement within $[0, 2\pi)$ in the form

$$\theta_i = \frac{2\pi}{N_t}(i - 1), i \in \{1, \ldots, N_t\}.$$  

In this way, the phases of the points in the receive SM constellation become equispaced, hence maintaining a minimum for the Euclidean distances in the constellation.

Aside from their individual limitations and the fact that they are suboptimal, the aforementioned prescaling methods are limited by the fact that they apply solely to MISO systems relying on a single RA and cannot be readily extended to the case of MIMO SM transmission, hence lacking receive diversity.

**III. Proposed Constellation Randomization**

**Prescaling (SM-CR)**

To alleviate the drawbacks of the aforementioned techniques, we propose an adaptive TPS technique that randomizes the received SM constellation. The proposed constellation randomization (CR) simply selects the “best” from a number of randomly generated sets of per-antenna TPS factors, with the aim of improving the resulting MED. By allowing the randomization of the amplitude and phase of the effective channel that combines the TPS factor and the channel gains of the TA, the proposed scheme relaxes the constellation optimization problem and facilitates a better solution for the maximization of $d_{\text{min}}$. In addition, the aforementioned randomization and selection of the appropriate TPS factors, the proposed scheme critically improves the transmit diversity of the SM system, as will be shown analytically in the following section. The proposed scheme involves the steps as analyzed in the following.
256 A. Formation of Candidate Prescaling Sets

First, a number of $D$ candidate TPS vectors are generated randomly in the form $a_d$, where $d \in [1, D]$ denotes the index of the candidate set, and $a_d$ is formed by the elements $\alpha_m^{(d)} \sim C \mathcal{N}(0, 1)$. These are made available to both the transmitter and receiver once, in an offline fashion before transmission. These assist in randomizing the received constellation, which is most useful in the cases where two points in the constellation happen to be very close. To ensure that the average transmit power remains unchanged, the scaling factors are normalized as in (7). It is important to reiterate that, in this work, we focus on power-normalized scaling gains, and hence, the proposed scheme does not constitute a power-allocation scheme. This allows us to isolate the diversity gains from the power and coding gains in our analysis in the following section. In the generalized case, power allocation could be applied on top of the prescaling, by employing a diagonal power-allocation matrix, while the resulting diversity selection in (12) is illustrated on the right-hand side. A clear slight reduction of the power in the symbols denoted by ”$\times$” in Fig. 2 can be observed, which, nevertheless, increases the MED in the 313 constellation.

Observe in Fig. 2 that while suboptimal in the constellation design sense, the proposed TPS enhances the MED in the 316 constellation with respect to conventional SM, while imposing a conveniently scalable complexity as per the size of candidate 318 sets $D$. It is evident that the gains in the MED for the proposed scheme are dependent on the set size $D$ of the candidate 320 TSP vector sets $a_d$ to choose from. An indicative result of 321 this dependence is shown in Fig. 3, where the average gains 322 in the MED are shown, with increasing numbers of $D$ for 323 different transmission scenarios. Theoretically derived upper 324 bounds for these gains for $N_r = 1, N_r = 2$, and $N_r = 4$, based 325

As mentioned earlier, since the channel coefficients are estimated at the receiver for detection [2]–[6], (12) can be used to derive the aforementioned factors independently at the receiver. Therefore, no feed forwarding of $\alpha_m^{(d)}$ or the index $d$ is required. Indeed, for equal channel coefficients available at the transmitter and receiver, they both select the same TPS vector $a_o$ independently, as per (12). Alternatively, to dispose of the 292 need for CSI at the transmitter (CSIT), the receiver can indeed 293 select the best scaling factors using (12) and feed the index of 294 the selected scaling vector $a_o$ out of the $D$ candidates back 295 to the transmitter, using $\lceil \log_2 D \rceil$ bits. In comparison to the 296 closely related works in [17]–[19], this provides the proposed 297 scheme with the advantage of a reduced transmit complexity 298 that, instead of CSIT acquisition and prescaling optimization, 299 involves the detection of $\lceil \log_2 D \rceil$ bits at the end of every 300 channel coherence period, and a single complex multiplication 301 of the classically modulated symbol $s_m$ with the prescaling 302 factor $a_o^{(d)}$ in the form shown in (3).

The intuitive benefits of the proposed scheme in the MED of 304 the received SM constellation are shown in Fig. 2 for a $(4 \times 1)$- 305 element MISO system employing 4QAM modulation at high 306 SNR, where the original receive SM constellation without TPS 307 is shown in the left-hand side, and the constellation after the 308 selection in (12) is illustrated on the right-hand side. A clear 309 increase in the MED can be observed, without increasing the 310 average transmit power. In fact, for the example in Fig. 2, a 311 slight reduction of the power in the symbols denoted by ”$\times$” 312 can be observed, which, nevertheless, increases the MED in the 313 constellation.

Observe in Fig. 2 that while suboptimal in the constellation 315 design sense, the proposed TPS enhances the MED in the 316 constellation with respect to conventional SM, while imposing 317 a conveniently scalable complexity as per the size of candidate 318 sets $D$. It is evident that the gains in the MED for the proposed 319 scheme are dependent on the set size $D$ of the candidate 320 TSP vector sets $a_d$ to choose from. An indicative result of 321 this dependence is shown in Fig. 3, where the average gains 322 in the MED are shown, with increasing numbers of $D$ for 323 different transmission scenarios. Theoretically derived upper 324 bounds for these gains for $N_r = 1, N_r = 2$, and $N_r = 4$, based 325
SM scales with the Euclidean distance between constellation points as [7]

$$\text{PEP}(y_i, y_j) = Q\left(\sqrt{\frac{\|y_i - y_j\|^2}{2\sigma^2}}\right)$$ (14)

where $Q(x)$ denotes the Gaussian Q-function [25], and

$$\|y_i - y_j\| = \sqrt{\|y_i\|^2 + \|y_j\|^2 - 2y_i \cdot y_j}$$

$$= \sqrt{\|y_i\|^2 + \|y_j\|^2 - 2\|y_i\|||y_j||\cos(\Delta \phi)}$$ (15)

where $a \cdot b$ denotes the dot product of vectors, and $\Delta \phi$ denotes the phase difference between the two constellation points. Accordingly, for the purposes of characterizing the diversity order, we define the gain in the MED for the proposed SM-CR as

$$G(D) = E\{\max_{d \in \mathbb{D}} d_{\min}\}$$

$$E\{d_{\min}\} = E\{\max_{m,k} \|HA_{\mathbb{D}}s_{m1} - HA_{\mathbb{D}}s_{m2}\|^2\}$$

$$E\{\min_{m,k} \|H_Hs_{m1} - H_Hs_{m2}\|^2\}$$ (16)

where we have used the notation $G(D)$ to suggest that the gain $354$ is a function of the size of candidate sets $D$. It will be shown in the results section that this gain also represents the transmit 355 diversity gain attained. The following theorem describes an upper bound of this diversity gain.

**Theorem 1:** For a frequency-flat Rayleigh fading channel $H \sim \mathcal{C}\mathcal{N}(0, (1/2)I_N + I_N)$, the gain in the MED of the proposed SM-CR is upper bounded as

$$G(D) \leq G_u = \sum_{k=1}^{D} \left(\frac{D}{k}\right) (-1)^{k+1} e^{(n-1)(k-1)\frac{Ei(-nk, nk)}{Ei(-n, n)}}$$ (17)

where $n \approx \frac{\binom{N^2M}{2}}{N^2}$, with $\binom{p}{q} = p!/(q!)(p-q)!$ denoting the binomial coefficient, with $x!$ being the factorial function and $Ei(-n, n)$ denoting the generalized exponential integral function [25], [36].

**Proof:** To simplify the analysis, we shall assume that the distances in the receive constellation are statistically independent. It is shown in Fig. 2 that, strictly speaking, this is not true since the constellation points created by each channel are indeed independent through the transmit symbol constellation. Nevertheless, we will demonstrate in Fig. 3 that this affordable assumption yields a tight upper bound for the gain. First, regarding the product $HA_{\mathbb{D}}$, it has been shown in [26] that $372$ the product of uncorrelated zero-mean Gaussian variables with variances $\sigma_1^2, \sigma_2^2$ is also zero-mean Gaussian with a variance $\sigma_1^2 + \sigma_2^2$. Thus, it is clear that, for a normalized transmit constellation, the receive vectors are distributed as $y_i \sim \mathcal{C}\mathcal{N}(0, 1/2I_N)$. Accordingly, $y_i - y_j \sim \mathcal{C}\mathcal{N}(0, I_N)$, and therefore, $z = \|y_i - y_j\|^2 \sim \chi^2_{2N}$, where $\chi^2_{2N}$ denotes the chi-square distribution with $k$ degrees of freedom [25]. The probability density function (PDF) and cumulative distribution function (CDF) of $z$ are, therefore, given by

$$f_z(x) = \frac{1}{2^N}\Gamma(N_x)\gamma(N_x, \frac{x}{2})$$ (18)

$$F_z(x) = \frac{1}{\Gamma(N_x)}\gamma(N_x, \frac{x}{2})$$ (19)
382 where $\Gamma(\cdot)$ and $\gamma(\cdot, \cdot)$ denote the Gamma and lower incomplete Gamma functions, respectively [25]. Based on the theory of order statistics [27], from the $n = \binom{N_r M}{n}$ distances in the receive SM constellation (see Fig. 2), the minimum distance is distributed as

$$f_{\text{d}_{\text{min}}}(x) = n f_2(x) \left(1 - F_2(x)\right)^{n-1} = \frac{n}{2^{N_r}} \Gamma(N_r)^{-1} x^{N_r - 1} e^{-x/2} \left[\Gamma \left(N_r, \frac{x}{2} \right)\right]^{n-1}$$

$$F_{\text{d}_{\text{min}}}(x) = 1 - \left(1 - F_2(x)\right)^n = 1 - \left[\frac{1}{\Gamma(N_r)} \Gamma \left(N_r, \frac{x}{2} \right)\right]^n$$

387 where $\Gamma(\cdot, \cdot)$ denotes the upper incomplete Gamma function and, as mentioned earlier, it is assumed that all distances in the receive SM constellation are independent. Since $d_{\text{min}}$ is nonnegative, its mean is found as

$$E\{d_{\text{min}}\} = \int_0^\infty \left[1 - F_{d_{\text{min}}}(x)\right] dx$$

$$= \int_0^\infty \left[1 - F_2(x)\right]^n dx. \quad (22)$$

397 Similarly to the aforementioned calculation, for the mean of $\tau = \max_{A_d} d_{\text{min}}$, we have

$$E\{\tau\} = \int_0^\infty \left\{1 - F_2(x)\right\} dx$$

$$= \int_0^\infty \left\{1 - F_{d_{\text{min}}}(x)\right\} dx$$

$$= \int_0^\infty \left\{1 - \left[1 - (1 - F_2(x))^n\right]^D\right\} dx$$

$$= \sum_{k=1}^D \left(D \binom{k}{D}(-1)^k(1 - F_2(x))^{nk}\right) dx$$

$$= \sum_{k=1}^D \left(D \binom{k}{D}(-1)^{k+1} \int_0^\infty (1 - F_2(x))^{nk} dx\right). \quad (25)$$

399 As stated previously, we have used the binomial expansion $$(1 - x)^n = \sum_{k=0}^n \binom{n}{k} (-1)^k x^k.$$ By substituting (22) and (25) into (16), we arrive at the upper bound for the gain in the MED as

$$G_u(N_r) = \sum_{k=1}^D \binom{D}{k}(-1)^{k+1} \int_0^\infty (1 - F_2(x))^{nk} dx \int_0^\infty (1 - F_2(x))^{nD} dx$$

where we have used the notation $G_u(N_r)$ to clarify that the upper bound here is a function of $N_r$. Finally, it can be shown that $(dG_u(N_r)/dN_r) \leq 0$, and therefore, the gain is a monotonically decreasing function of the number of RAs. Hence, the highest gains can be observed for the single-antenna receiver case, which experiences a diversity of one for conventional SM. For this case, from (18), (19), and (26), we get (17).

B. Error Probability Trends

Based on the aforementioned diversity calculations, we can derive the BER performance of the proposed scheme in the high-SNR region. Indeed, SM systems with $N_r$ uncorrelated RAs have been shown to experience a unit transmit diversity order and receive diversity order of $N_r$. Accordingly, since the proposed scheme attains a transmit diversity order of $G(D)$, the total diversity becomes $\delta = N_r G(D)$. The resulting probability of error $P_e$ follows the trend

$$P_e = \alpha \gamma^{-N_r G(D)}$$

where $\gamma$ is the transmit SNR, $\delta = N_r G(D)$ is the diversity order based on the calculations of $G(D)$ in Section IV-A, and $\alpha$ is an arbitrary coefficient. The diversity order $\delta = N_r G(D)$ accounts for the inherent receive diversity $N_r$ in the system and the transmit diversity $G(D)$ induced by the proposed scheme. Clearly, as per the upper bound of Theorem 1 in (17) and the $425$ $P_e$ trend in (27), a lower bound in the resulting probability of $426$ error can be obtained. In the following results, we show that the aforementioned performance trend matches the simulated performance in the high-SNR region.

V. COMPUTATIONAL COMPLEXITY

It is clear from the aforementioned discussion that the proposed SM-CR leads to an increase in the computational complexity, with respect to conventional SM, due to the need to compute the MED for all the $D$ candidate scaling factor sets. Here, we analyze the increase in computational complexity at the receiver. We later use this analysis to model the power consumption associated with the required signal processing and compare the proposed SM-CR with conventional SM, in terms of the overall power efficiency of transmission. For reference, we have assumed an LTE Type 2 TDD frame structure [28]. This has a 10-ms duration, which consists of 10 subframes, out of which five subframes, containing 14 symbol time slots each, are used for downlink transmission yielding a block size of 443. $B = 70$ for the downlink, while the rest are used for both uplink and control information transmission. A slow-fading channel is assumed, where the channel remains constant for the duration 446 of the frame. In Table I, we summarize the computational complexity dominant operations involved at the receiver for both SM and SM-CR. In these calculations, we have used the fact that the 449 calculation of the norm of a vector with $n$ elements involves 450 $2n$ elementary operations. In addition, it can be seen that the product $A_d s_m^m$ is a scalar that involves a single complex- 452 valued multiplication, and its multiplication with the channel 453 matrix involves an additional $2N_r$ elementary operations per 454
constellation point. This has to be done for each of the $N_t M$ points in the receive constellation. Accordingly, there are a total of $\left( \frac{N_t M}{2} \right)$ distances in the constellation, and therefore, there are $\left( \frac{N_t M}{2} \right)$ norms in the form of (12) that need to be calculated for each candidate scaling factor set. The first three operations in the constellation optimization in Table I need to be done for each candidate set: hence, $D$ times in total. For the ML detection, a number of $2 N_t M$ norms in the form of (13) need to be calculated before the minimum is chosen, and this has to be done $B$ times in the frame. Finally, we have used the fact that finding the maximum and the minimum in an $n$-element vector requires $n$ operations.

Based on the aforementioned calculations, we have the complexities of the SM receiver and of the SM-CR receiver, respectively, in the form of

$$C_{\text{SM}}(D) = (2 N_r + 1) N_t M (B + 1)$$

$$C_{\text{SM-CR}}(D) = (2 N_r + 1) \left( \frac{N_t M}{2} \right) D + D + (2 N_r + 1) N_t M B$$

where it can be seen that the complexity of SM-CR is in the form

$$C_{\text{SM-CR}}(D) = \chi D + \psi$$

with

$$\chi = (2 N_r + 1) \left( \frac{N_t M}{2} \right) N_t M + 1$$

$$\psi = (2 N_r + 1) N_t M B.$$ 

In the following section, we use these expressions to calculate the resulting power consumption related to signal processing at the receiver for the evaluation of the power efficiency of transmission.

### VI. POWER EFFICIENCY

As the ultimate metric for evaluating the performance-complexity tradeoff and the overall usefulness of the proposed technique, and toward an energy-efficient communication system, we consider the power efficiency of SM-CR compared to SM, as well as its dependence on the number of candidate scaling factor sets $D$. We note that prior studies explore the energy efficiency of SM for the purposes of optimizing the number of antennas employed [30], [31]. Following the modeling in [29] and [32]–[35], we define the transmit power efficiency of SM-CR as the bit rate per total transmit power consumption related to signal processing (DSP), and to the mixers, to the transmit filters, and to the digital-to-analog converter (DAC), which is assumed constant for the purposes of this work. We use practical values of these from [32] as $\eta = 0.35$ and $P_{\text{mix}} = 30.3$ mW, $P_{\text{hit}} = 2.5$ mW, and $P_{\text{DAC}} = 497$ mW, yielding $P_{\text{RF}} = 34.4$ mW. In [33], $P_c$ in watts/KOps is 498 the power per 10$^3$ elementary operations (KOps) of the digital 999 signal processor (DSP), and $C$ is the number of operations involved. This term is used to introduce complexity as a factor of the transmitted power consumption in the power efficiency metric. Typical values of $P_c$ include $P_c = 22.88$ mW/KOps for the Virtex-4 and $P_c = 5.76$ mW/KOps for the Virtex-5 field-programmable gate array family from Xilinx [36]. Finally, represents the achieved throughput, where $P_B$ is the block error rate, and

$$\mathcal{P} = \frac{\mathcal{E} B (1 - P_B)}{c + p_c C(D)}$$

is the spectral efficiency of SM in bits per channel use. For a given transmit power and numbers of TAs and RAs, combining (33) with (27), the power efficiency expression for SM-CR takes the form

$$\mathcal{P} = \frac{\mathcal{E} B (1 - \alpha \gamma^{-N_t M} G(D)) B}{c + p_c C(D)}$$

| TABLE I  
<table>
<thead>
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<tbody>
<tr>
<td><strong>SM-CR</strong></td>
<td><strong>Operations</strong></td>
<td><strong>SM</strong></td>
<td><strong>Operations</strong></td>
</tr>
<tr>
<td>Constellation Optimization</td>
<td>Constellation Calculation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H A^k_i s^k_m, \forall m, k \times D (2 N_r + 1) N_t M D$</td>
<td>$H A^k_i s^k_m, \forall m, k$</td>
<td>$(2 N_r + 1) N_t M$</td>
<td></td>
</tr>
<tr>
<td>$d^k_m^{(4)} \min {k^1_1, k^2_2} \times D (N_t M) D$</td>
<td>$d^k_m^{(4)} =</td>
<td></td>
<td>y - H A^k_i s^k_m</td>
</tr>
<tr>
<td>$\arg \max d^k_m^{(4)} \times B N_t M B$</td>
<td>$\arg \max d^k_m^{(4)} \times B N_t M B$</td>
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</tr>
<tr>
<td>Total: $(2 N_r + 1) \left( \left( \frac{N_t M}{2} \right) + N_t M \right) D + D + (2 N_r + 1) N_t M B$</td>
<td>Total: $(2 N_r + 1) N_t M (B + 1)$</td>
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where both \( G(D) \) and \( C(D) \) are functions of the number of candidate sets \( D \) through (26) and (29), while \( \alpha, \epsilon \) are constants. This expression can therefore be used to characterize the scalable performance–complexity tradeoff for the proposed scheme and for optimizing the value of \( D \) for maximizing power efficiency.

The expression in (33) provides an amalgamated metric that combines throughput, complexity, and transmit signal power, all in a unified metric. By varying the number of candidate scaling factor sets \( D \), both the resulting complexity and transmission rates are influenced, as shown earlier. Therefore, a scalable tradeoff between performance and complexity can be achieved accordingly. High values of \( P \) indicate that high bit rates are achievable for a given power consumption, and thus denote a high energy efficiency. The following results show that SM-CR provides an increased energy efficiency compared to SM in numerous scenarios using different transmit powers \( P \).

### VII. Simulation Results

To evaluate the benefits of the proposed technique, this section presents numerical results based on Monte Carlo simulations of conventional SM without scaling (termed as SM in the figures) and the proposed SM-CR. Our focus is on systems where the receiver employs more than one antenna, where the prescaling schemes in [17]–[19] are inapplicable. The channel impulse response is assumed to be perfectly known at the transmitter. Without loss of generality, unless stated otherwise, we assume that the transmit power is restricted to \( P = 1 \). MIMO systems with up to eight TAs employing 4QAM and 16QAM modulation are explored, albeit it is plausible that the benefits of the proposed technique extend to larger scale systems and higher order modulation.

First, for reasons of reference, the BER performance of the proposed scheme is compared with the performance of the most relevant techniques in [17] and [19] for the MISO channel, where the latter techniques are applicable. First, we note the performance loss when applying power scaling to the scheme in [17]. Second, while the true strength of the proposed lies in the fact that it applies to MIMO links where the schemes in [17] and [19] are inapplicable, the results here show that the proposed scheme outperforms the conventional techniques in the MISO channel as well.

Next, we show the BER performance with increasing transmit SNR for a \((4 \times 2)\)-element MIMO employing 4QAM, for various numbers of candidate scaling factor sets \( D \), in Fig. 5. The graph includes the performance of SM for the \((4 \times 4)\)-element MIMO for reference. It can be seen that the slope of the BER curves increases with increasing \( D \), which indicates an increase in transmit diversity order. Indeed, for high values of \( D \), the \((4 \times 2)\)-element system with SM-CR exhibits the same transmit diversity order as the \((4 \times 4)\)-element system with conventional SM. Moreover, as also observed in Fig. 3, when increasing \( D \), the gains saturate for higher values, which can also be seen here, where the BER for \( D = 20 \) closely approximates the one for \( D = 100 \).

In Fig. 6 the BER versus SNR performance is shown for the \((4 \times 2)\), \((8 \times 2)\), and \((8 \times 4)\) systems for both SM and SM-CR.

The theoretical diversity trends observed in the form of \( P_e = 568 \alpha \gamma^{-\delta} \) are also shown, where \( P_e \) denotes the probability of error 569 for high SNR; \( \gamma \) is the SNR; and \( \delta = N_r G \) is the diversity order, 570 where \( G \) is taken from the respective points in Fig. 3, which is 571 upper bounded, as calculated in Section IV. The performance 572 trends for both the exact diversity gains \( G(D) \) based on simu- lation in Fig. 3 and the upper bounds \( G_u(N_r) \) of Theorem 1 in 574 Section IV-A are shown for comparison. A close match between 575 the analytical and simulated diversity can be observed. With 576 regard to the performance observed, it can be seen that there 577 is indeed a performance penalty when increasing the number 578 of TAs from four to eight for SM with fixed RA number, due 579 to the growth of the spatial constellation, which harms the 580 detection of the TA index [see (4 \( \times 2 \)) to (8 \( \times 2 \))]. The improved 581 received diversity in the detection of TA index when increasing 582 the number of RA brings the performance benefits observed in 583 Fig. 6 between (8 \( \times 2 \)) and (8 \( \times 4 \)). The same comparison is 584 shown in Fig. 7 for the case of 16QAM, and it can be seen 585
Fig. 7. BER versus SNR for a (8 × 2) and (8 × 4) MIMO with SM and SM-CR with D = 20 for 16QAM.

Fig. 8. BER versus D for a (4 × 2), (8 × 2), and (8 × 4) MIMO with SM-CR for 4QAM and 16QAM.

Fig. 9. BER versus SNR for a (4 × 2) MIMO with CSI errors for SM and SM-CR with D = 20, for 4QAM.

\[ \hat{H} = H + E \]  

(37)

where \( \hat{H} \) and \( E \sim \mathcal{CN}(0, \omega) \) are the estimated channel and the complex Gaussian CSI error having a variance \( \omega \), respectively. 612 Independent CSI error matrices are generated at the transmitter 613 and receiver. Fig. 9 illustrates the BER performance upon 614 increasing the CSIT and CSIR errors for SM and SM-CR, with 615 \( \omega \) at 15 dB and 20 dB below the signal power. Both techniques 616 are affected by the CSIR errors at the ML detection stage. In 617 addition, for SM-CR, the errors may lead to the selection of dif- 618 ferent TPS factors at the transmitter and receiver. Nonetheless, 619 it can be seen that both SM and SM-CR experience the same 620 performance degradation trend with increasing the CSI errors 621 and that the performance gains observed for SM-CR persist.

The computational complexity of the proposed technique is 623 examined in Fig. 10, as a function of both \( N_t \) and \( D \), for 4QAM 624 and 16QAM. The complexity count is based on the operations 625 calculated in Table I, and it can be seen that, for both 4QAM 626 and 16QAM, the performance benefits of SM-CR are achieved 627 at an increased complexity compared to SM, which scales with 628 the selection of the parameter \( D \). The overall tradeoff between 629 performance and complexity is shown to be favorable for 630 SM-CR in Fig. 11, where the power efficiency is shown with 631 varying transit power for the (4 × 2) and (8 × 2) systems with 632 \( D = 20 \). Ranges between 30 dBm (1 W) and 36 dBm (4 W) are 633 depicted, which correspond to the power budgets of small-cell 634 base stations [37]. It can be seen that the improved throughput 635 for SM-CR compensates for the increased complexity in the 636 overall system’s power efficiency, thus providing an improved 637 tradeoff compared to SM.
Finally, Fig. 12 shows the power efficiency for increasing $D$ for the (4 × 2) MIMO with transmit SNR $\gamma = 15$ dB and the (8 × 2) MIMO with $\gamma = 20$ dB using 4QAM modulation. The different curves in the figure represent different transmit power budgets ranging from $P = 30$ dBm to $P = 43$ dBm. For ease of illustration, power efficiency is shown as a percentage of its maximum, as the different scenarios in the figure have different maximum power efficiencies. It can be seen in both subfigures that, as the transmit power is increased, higher values of $D$ offer the best power efficiency. This is due to the fact that, with the increase in the transmit power, the power consumption of the DSP becomes less important and the increase in throughput greatly improves the overall power efficiency. In all cases, the maximum power efficiency achieved with SM-CR is better than the one for conventional SM, which corresponds to the points in the figure with $D = 1$, indicating that the proposed scheme offers the required transmission rates at a lower power consumption.

Fig. 10. Computational complexity as a function of $N_t$ and $D$ for SM and SM-CR for 4QAM and 16QAM.

Fig. 11. Power efficiency versus $P$ for a (4 × 2) and (8 × 2) MIMO with SM and SM-CR with $D = 20$ and $\gamma = 18$ dB for 4QAM.

Fig. 12. Power efficiency versus $D$ for a (4 × 2), (8 × 2) MIMO with SM and SM-CR for 4QAM.

VIII. CONCLUSION

A new receive-constellation-shaping approach has been introduced for SM in the MIMO channel. Conventional constellation-shaping techniques offer limited gains for SM, due to the strict fitting to a fixed constellation, and tend to require the inversion of ill-conditioned channel coefficients. Moreover, existing practical low-complexity constellation-shaping schemes are only applicable to the case where the receiver has a single antenna. We have proposed a CR scheme, where transmit diversity is introduced by appropriately selecting the TPS factors from sets of randomly generated coefficients. The proposed scheme has been shown, both analytically and by simulation, to offer significant performance gains with respect to conventional SM. Our future work will involve the application of the proposed approach to more advanced SM techniques, such as generalized SM, as well as SM with antenna selection and adaptive modulation.

REFERENCES


AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

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