Star-QAM Signaling Constellations for Spatial Modulation

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***Abstract*—The performance of spatial modulation (SM)-assisted multiple-input–multiple-output (MIMO) communication systems is highly dependent on the specific amplitude/phase modulation (APM) signal constellation adopted. In this paper, we conceive new star-quadrature amplitude modulation (star-QAM)-aided SM schemes. Our goal is to minimize the system's average bit error probability (ABEP). More specifically, a new class of star-QAM constellations is introduced for SM, which is capable of flexibly adapting ring ratios of the amplitude levels. Then, under a specific MIMO configuration and a predetermined transmission rate, a simple and efficient ring-ratio optimization algorithm is proposed to minimize the ABEP. Moreover, to improve further the performance of our star-QAM-aided SM scheme, a diagonal precoding technique is proposed, and a low-complexity minimum-distance-based approach is conceived for extracting the precoding parameters. Our numerical results show that the proposed star-QAM-aided SM arrangement provides beneficial system performance improvements compared with the identical-throughput maximum–minimum distance (MMD) QAM and phase-shift keying (PSK) benchmarkers. Moreover, our precoding scheme is capable of further improving the attainable system performance at a modest feedback requirement.**

***Index Terms*—Constellation optimization, multiple-input–multiple-output (MIMO), spatial modulation (SM), star-quadrature amplitude modulation (star-QAM).**

I. Introduction

Spatial MODULATION (SM), which maps the information bits to two information-carrying entities, namely the antenna indexes and the combined amplitude/phase modulation (APM) constellation, constitutes a promising low-complexity multiple-input–multiple-output (MIMO) transmission technique [1]–[8]. In a conventional single-input–single-output (SISO) system, the Gray-coded maximum–minimum distance (MMD) quadrature amplitude modulation (QAM) constellation minimizes the bit error rate (BER) [9], [10]. However, the advantage of MMD-QAM may be eroded in SM-MIMO systems [11]. This is due to the fact that the BER performance of SM-MIMO systems is jointly determined by the spatial signal (i.e., antenna indexes), by the classic APM constellation, and by their interaction [11]–[18].

Recently, the effects of APM schemes on the performance of SM have been investigated in [11], [14], and [18]. More specifically, in [11], the performance of SM systems relying both on conventional QAM and PSK modulation was studied, demonstrating that, in some MIMO setups, the PSK-modulated SM scheme may outperform the identical-throughput MMD-QAM-aided SM scheme. In [18], the dispersion matrices and the signal constellations were jointly optimized for a near-capacity irregular precoded space–time shift keying (STSK) system, which includes SM as a special case and strikes a flexible rate–diversity tradeoff. It was also shown in [14] that the star-QAM-aided STSK scheme outperforms its MMD-based square-QAM-aided counterpart. This observation may be also valid for SM systems [11]. The aforementioned results indicated that the performance of SM is highly dependent on the specific APM adopted; hence, a suitable APM scheme has to be designed for this hybrid modulation scheme.

On the other hand, star-QAM constitutes a special case of circular amplitude- and phase-shift keying, which is capable of outperforming the classic square-QAM constellation in peak-power-limited systems [19]. Hence, it has been adopted in most of the recent satellite communication standards, such as in the Digital Video Broadcast System (DVB) S2, DVB-SH, and the Internet Protocol over Satellite and Advanced Broadcasting System via Satellite [19]. The star-QAM constellation is composed of multiple concentric circles, and it was shown to be beneficial in the context of STSK systems. Hence, star-QAM may be an attractive APM candidate for SM-MIMO. However, the constellations' optimization has not been carried out for star-QAM-aided SM.

Moreover, to increase the robustness of the SM-MIMO system, limited-feedback-aided link adaptation schemes have been proposed in [20]–[26]. For example, in [20], an opportunistic power-allocation (PA) scheme was conceived for achieving a beneficial transmit diversity gain in SM-MIMO systems. In [21], a beamforming codebook was designed for optimizing the coding gain of SM-MIMO based on the knowledge of the channel envelope's spatial correlation. Recently, an adaptive closed-loop-aided method was invoked for providing both diversity and coding gains in the context of space-shift keying (SSK)[22],

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which is a special case of SM. However, the scheme proposed for SSK may not be directly applicable to the conventional SM scheme. Moreover, ASM-MIMO architectures relying on different combinations of modulation schemes were proposed in [24], which aimed for maximizing the channel capacity at a predefined target BER, rather than for minimizing the BER. In contrast, in [25] and [26], a transmit precoding (TPC) technique was used for improving the modulated signal design for SM. However, this technique may only be suitable for a new class of SM relying on a single-receiver antenna. For the conventional SM, we proposed a near-instantaneously adaptive-modulation-aided scheme for minimizing the BER [7], which was termed adaptive SM (ASM). Then, we further generalized this paper in [12] and [15], where the implementation complexity of ASM was considerably reduced. However, ASM typically transmits a different number of bits in the different-quality time slots, which may be inconvenient in fixed-rate applications and potentially leads to error propagation in the case of ASM-mode signaling errors.

Against this background, the novel contributions of this paper are threefold.

- We introduced the class of star-QAM constellations [27], which is capable of flexibly adapting the ring ratios, hence subsuming classic PSK as a special case. Alternatively, if the ring ratio is appropriately selected, the proposed star-QAM is capable of achieving almost the same Euclidean distance (ED) as the MMD-based QAM.
- Given a specific MIMO configuration and a predetermined transmission rate, a low-complexity yet efficient optimization algorithm *is proposed* to minimize the average bit error probability (ABEP) of SM-MIMO systems, where the effects of both the antenna index, as well as of the APM signal and their interaction, are jointly considered. Only the optimal ring ratios of star-QAM constellation have to be found by the optimization algorithm.
- We introduce a new TPC scheme for star-QAM-aided SM-MIMO systems, which further improves the performance. To retain the benefits of SM, such as its low-complexity single-stream detector and its single RF chain, we design its TPC matrix $\mathbf{P}$ to be diagonal. We demonstrate that this precoded scheme and the ASM schemes of [12] and [15] are capable of exploiting the same degrees of freedom as that offered by the classic SM-MIMO for maximizing the free distance (FD). However, our TPC scheme assigns the same number of bits to each time slot; hence, it is capable of avoiding the potential error propagation effects of ASM encountered in the case of ASM-mode signaling errors. Our simulation results show that the proposed TPC scheme considerably improves the system's performance compared with the conventional star-QAM-aided SM, the PA-aided SM, and ASM arrangements.

The remainder of this paper is organized as follows. In Section II, we conceive a signaling constellation optimization method for star-QAM-aided SM and elaborate both on the choice of our optimization criterion and on the corresponding optimization algorithm. In Section III, we propose a new TPC scheme for enhancing the performance of the star-QAM-aided SM. Our numerical analysis is carried out in Section IV. Finally, our conclusions are presented in Section V.

II. Signaling Constellation Optimization

A. *Performance Metric and Star-QAM Constellation*

Consider a flat-fading MIMO channel associated with N_t transmit antennas (TAs) and N_r receive antennas. The $(N_t \times 1)$-element transmit symbol vector $\mathbf{x}$ is assumed to satisfy $E[\mathbf{x}\mathbf{x}^H] = \mathbf{I}_{N_t}$, where $\mathbf{I}_{N_t}$ denotes an $(N_t \times N_t)$-element identity matrix. Then, the transmitted SM symbol $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is given as $\mathbf{x} = s_l^n \mathbf{e}_n$ [21], where s_l^n is the complex-valued symbol of the APM scheme employed at the nth TA. For example, L-PSK/QAM is associated with $m_{\mathrm{APM}} = log_2(L)$ input bits, whereas $\mathbf{e}_n (1 \le n \le N_t)$ is selected from the N_t-dimensional standard basis vectors (i.e., $\mathbf{e}_1 = [1, 0, \ldots, 0]^T$), according to $\log_2(N_t)$ input bits. The corresponding received signal is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{h}_n s_l^n + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is an $(N_r \times N_t)$-element channel matrix, $\mathbf{h}_n$ is the nth column of $\mathbf{H}$, and the elements of the N_r-dimensional noise vector $\mathbf{n}$ are Gaussian random variables obeying $\mathcal{CN}(0,\, N_0)$.

In [11], an improved union bound partitions the ABEP expression of SM-MIMO systems into three terms: the P_{spatial} term related to the TA index, the P_{signal} term related to the APM signals, and the joint term P_{joint}, which depends on both the TA index and on the APM signals. This bound is formulated as

$$P_{\mathrm{SM}}(\rho) \le P_{\mathrm{spatial}}(\rho) + P_{\mathrm{signal}}(\rho) + P_{\mathrm{joint}}(\rho). \tag{2}$$

This improved union bound is more accurate than the conventional union-bound-based methods, hence facilitating a deeper understanding of the joint impact of spatial and APM signals, as illustrated in [11]. We focus our attention on the system's performance for transmission over i.i.d. Rayleigh fading channels, which may be readily extended to the Nakagami-m fading model of [11]. Let us assume that ρ is the average SNR, whereas x_l and $x_{\hat{l}}$ represent two different APM constellation points, with their modulus values being given as β_l and $\beta_{\hat{l}}$, respectively. Then, we have

$$P_{\mathrm{signal}}(\rho) = \frac{\log_2(L)}{\log_2(N_t \cdot L)} P_{\mathrm{APM}}(\rho) \tag{3}$$

$$P_{\mathrm{spatial}}(\rho) = \frac{\log_2(N_t) N_t}{2L \log_2(N_t \cdot L)} \sum_{l=1}^{L} \mathcal{F}\left(\rho \beta_l^2\right) \tag{4}$$

$$P_{\mathrm{joint}}(\rho) = A \sum_{l=1}^{L} \sum_{\hat{l} \ne l = 1}^{L} \Big[B + C D_H\left(x_l \to x_{\hat{l}}\right)\Big) \times \mathcal{F}\left(\frac{\rho}{2}\left(\beta_l^2 + \beta_{\hat{l}}^2\right)\right)\Big]. \tag{5}$$

Here, $P_{\mathrm{APM}}(\rho)$ represents the error probability of conventional L-APM, which depends on the ED of the constellation points of APM, whereas $D_H(x_l \to x_{\hat{l}})$ is the Hamming distance between signals x_l and $x_{\hat{l}}$. Here, $A = 1/L \log(N_t \cdot L)$, $B = N_t \log(N_t)/2$, and $C = (N_t - 1)$ are constants for a fixed

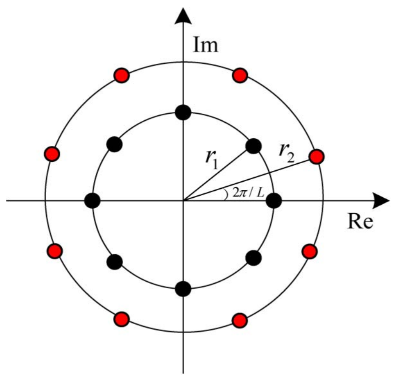

Fig. 1. Complex signal constellation of 16-star-QAM. The symbols are evenly distributed on two rings and the phase differences between the neighboring symbols on the same ring are equal.

MIMO setup. Moreover, the function $\mathcal{F}(\varepsilon)$ in (4) and (5) is the pairwise error probability function [11], which is given by

$$\mathcal{F}(\varepsilon) = \gamma(\varepsilon)^{N_r} \sum_{n=0}^{N_r-1} \binom{N_r - 1 + n}{n} [1 - \gamma(\varepsilon)]^n \qquad (6)$$

where we have $\gamma(\varepsilon) \triangleq (1/2)(1 - \sqrt{(\varepsilon/2 + \varepsilon)})$. Note that the ABEP bound of (2) was proposed for the general family of APM schemes, which contains not only the conventional PSK but also the generic rectangular nonsquare-QAM schemes and the square-QAM schemes. Moreover, since P_{signal} is available in closed form for conventional APM modulation schemes, the bound of (2) is more accurate than the conventional results of [21].

As indicated in (3)–(5), P_{signal} mainly depends on the minimum ED $d_{\min}$ of the APM constellation points, whereas P_{joint} and P_{spatial} mainly depend on the modulus values β_l $(l = 1, \ldots, L)$ of the APM constellation points.

Note that the modulus values β_l are represented by the Frobenius norms of the APM constellation points. These results suggested that, for jointly minimizing P_{signal}, P_{joint}, and P_{spatial}, we can focus our attention on the design of $d_{\min}$ and on the β_l parameters of APM.

To make the choice of the APM parameters $d_{\min}$ and β_l as flexible as possible, we consider a class of star-QAM constellations, which subsumes the classic PSK as a special case but may also be configured for maximizing the minimum ED of the constellation by appropriately adjusting the ring ratios of the amplitude levels. For simplicity, we consider the example of a twin-ring 16-star-QAM constellation having a ring ratio of $\alpha = r_2/r_1$, as shown in Fig. 1. The symbols are evenly distributed on the two rings, and the phase differences between the neighboring symbols on the same ring are equal. Unlike the conventional twin-ring star-QAM constellation [19], [28], the constellation points on the outer circle of our proposed star-QAM constellation are rotated by $2\pi/L$ degrees compared with the corresponding constellation points on the inner circle [27]. Hence, again, the conventional PSK constitutes an integral part of our star-QAM scheme, which is associated with $\alpha = 1$. Table I summarizes the minimum EDs $d_{\min}$ between the constellation points for different APM schemes. It is found that this star-QAM scheme is capable of achieving almost the same

TABLE I
MINIMUM ED BETWEEN THE CONSTELLATION POINTS FOR DIFFERENT APM SCHEMES

Modulation order	2	4 (MMD)	8 ([9])	16 (MMD)	32 ([9])
PSK	2	$\sqrt{2}$	0.7654	0.3902	0.1960
QAM	- -	$\sqrt{2}$	0.8165	0.6325	0.4082
Proposed star-QAM	2	$\sqrt{2}$	0.9134	0.5737	0.3952

minimum ED as the MMD-based QAM. Note that, although this twin-ring star-QAM constellation has been indeed applied for noncoherent detection [27], it has not been considered whether this constellation can be directly applied to SM for achieving performance improvements.

The aforementioned twin-ring philosophy of Fig. 1 may be readily extended to multiple-ring star-QAM. The reasons for considering twin-ring star-QAM in our paper are the following.

- It is an attractive APM modulation candidate for SM, exhibiting a high performance at low detection complexity compared with conventional QAM schemes, as detailed in [13]–[15].
- It can be flexibly designed for different $d_{\min}$ and $\beta_l (l = 1, \ldots, L)$ combinations, which is achieved by simply adjusting a single parameter α, whereas β_l can assume two values because only two rings are considered.
- The ABEP of star-QAM, which is related to the P_{spatial} term of (3), has been documented in [28] and [29].

B. Optimization Criteria and Optimization Algorithm

Observe in Fig. 1 that there are numerous options for the parameter α of the star-QAM constellation, for a given MIMO setup, specified by the total number of bits per symbol m_{all}, the $(N_r \times N_t)$ configuration of transceiver, and the number of modulation level L . The goal of star-QAM-aided signaling AQ2 constellation optimization is to find the specific ring ratio α, which minimizes the ABEP of the SM-MIMO of (2). Note that, although the term $P_{\text{SM}}(\rho)$ in (2) cannot be directly represented by parameter α, it varies as a function of α, which may be formulated as $P_{\text{SM}}(\rho, \alpha)$. Following the aforementioned approach, we formulated this optimization problem as

$$\begin{cases} \alpha^* = \min\limits_{\alpha} P_{\text{SM}}(\rho, \alpha) \\ \text{s.t.} \quad \alpha \geq 1 \end{cases} \qquad (7)$$

which may be a convex one for a fixed SNR value ρ, as indicated in Fig. 4. However, deriving the closed-form solution of (7) remains an open challenge since the expression of $P_{\text{SM}}(\rho, \alpha)$ depends both on the specific APM constellation and on the particular MIMO setup [19], and since the expressions of P_{signal}, P_{joint} and P_{spatial} in (3)–(5) are complex. Hence, a numerical search is adopted.

Our optimization algorithm conceived for finding the ring ratio is summarized as follows.

Step 1: Initialize the values of N_r, N_t, m_{all}, L, and the SNR value ρ. Set the iteration step size to $\Delta\alpha = 0.1$ and the number of iterations to $n = 1$. The choice of $\Delta\alpha$ is flexible, and a lower value of $\Delta\alpha$ may lead to a better performance. We then set the search area of α to $1 \leq \alpha \leq U_\alpha$ and the performance metric to $P_{\text{iter}}(n) = 0$.

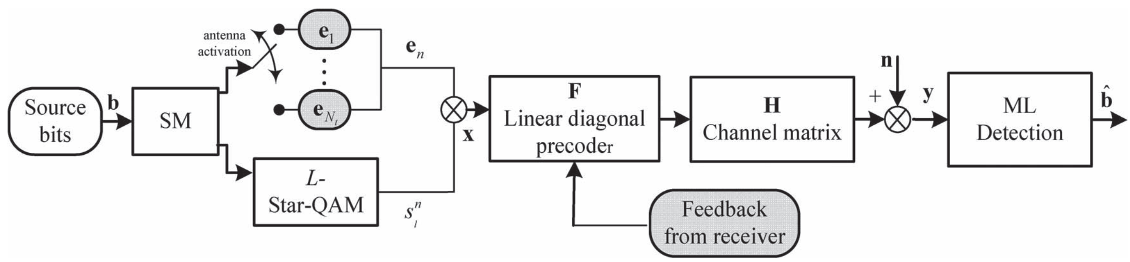

Fig. 2. System model of the diagonal-precoding-assisted star-QAM-aided SM scheme.

Step 2: While $\alpha \leq U_\alpha$, let $\Delta\hat{\alpha} = \min\{\Delta\hat{\alpha}, U_\alpha - \alpha\}$, and calculate the probabilities of P_{signal}, P_{joint}, and P_{spatial} by using (3)–(5) associated with α. Then, let $P_{\text{iter}}(n) = P_{\text{SM}}(\rho)$ using (2), and set $\alpha = \alpha + \Delta\hat{\alpha}$ and $n = n + 1$.

Step 3 : Find the index $n^* = \min_n\{P_{\text{iter}}(n)\}$ to achieve the optimal ring ratio of $\alpha^* = 1 + (n^* - 1)\Delta\hat{\alpha}$.

In the aforementioned optimization algorithm, we have to choose an appropriate U_α to promptly find the optimal α^*. More explicitly, an excessively low value of U_α may lead to missing the optimal solution, whereas an excessively high value of U_α imposes excessive computational complexity on the optimization process. Hence, we will show in Section III that $U_\alpha = 3$ is a beneficial choice for promptly approaching the optimal results. Moreover, the optimum ring ratio α^* is a function of the SNR. However, we will show that the optimum ratio approaches its asymptotic optimum as the SNR increases.

III. Proposed Diagonal Precoding for Star-Quadrature Amplitude Modulation-Aided Spatial Modualtion

Since the performance of the optimum maximum-likelihood (ML) receiver depends on the FD of the received signal constellation [30], we propose a new TPC based on maximizing the FD for the family of star-QAM-aided SM-MIMO systems, when limited channel state information is available at the transmitter. Since the FD is increased by the TPC algorithm, the proposed scheme is expected to provide a beneficial system performance improvement. To retain all the single-RF-related benefits of SM, we design the TPC matrix $\mathbf{P}$ to be diagonal. The system model of the diagonal-TPC-assisted star-QAM-aided SM scheme is shown in Fig. 2. To identify the specific TPC parameters, which are capable of maximizing the FD, we propose a low-complexity TPC design algorithm. We will demonstrate that as few as two elements of the diagonal TPC matrix have to be fed back to the transmitter, regardless of N_t.

A. TPC Design Criterion

To construct a TPC for star-QAM-aided SM-MIMO systems, we can rewrite the system model of (1) as

$$\mathbf{y} = \mathbf{HPx} + \mathbf{n} \tag{8}$$

where $\mathbf{P}$ denotes the diagonal TPC matrix, which can be represented as

$$\mathbf{P} = \text{diag}\{p_1, \ldots, p_n, \ldots, p_{N_t}\} \tag{9}$$

where p_n controls the channel gain associated with x_n. Here, we let $\sum_{n=1}^{N_t} |p_n|^2 = N_t$ for normalizing the transmit power. Note that the introduction of TPC in SM does not affect the advantages of SM, such as the avoidance of the interantenna interference and the reliance on a single RF chain, because the precoded transmit vector $\mathbf{Px}$ includes only a single nonzero component; hence, only a single TA is activated in each time slot, as indicated in (8).

Numerous techniques may be invoked for constructing the TPC $\mathbf{P}$ [21], [25]. In this paper, similar to the precoding methods conceived for the orthogonalized spatial multiplexing of [31], we decompose $\mathbf{P}$ as

$$\mathbf{P} = \bar{\mathbf{P}}\boldsymbol{\Theta} = \text{diag}\left\{\bar{p}_1 e^{j\theta_1}, \ldots, \bar{p}_n e^{j\theta_n}, \ldots, \bar{p}_{N_t} e^{j\theta_{N_t}}\right\} \tag{10}$$

where $\bar{\mathbf{P}} = \text{diag}\{\bar{p}_1, \ldots, \bar{p}_n, \ldots, \bar{p}_{N_t}\}$ represents the PA matrix, whereas $\boldsymbol{\Theta} = \text{diag}\{e^{j\theta_1}, \ldots, e^{j\theta_n}, \ldots, e^{j\theta_{N_t}}\}$ is the phase rotation matrix. The FD between the constellation points at the receiver is defined as

$$\begin{aligned} d_{\min}(\mathbf{H}, \mathbf{P}) &= \min_{\substack{\mathbf{x}_i, \mathbf{x}_j \in \mathbb{X}, \\ \mathbf{x}_i \neq \mathbf{x}_j}} \|\mathbf{HP}(\mathbf{x}_i - \mathbf{x}_j)\|_F \\ &= \min_{\mathbf{e}_{ij} \in \mathbb{E}} \left\|\mathbf{H}\bar{\mathbf{P}}\boldsymbol{\Theta}\mathbf{e}_{ij}\right\|_F \end{aligned} \tag{11}$$

where $\mathbb{X}$ is the set of all legitimate transmit symbols, $\mathbf{e}_{ij} = \mathbf{x}_i - \mathbf{x}_j$, $i \neq j$ denotes the error vector, and $\mathbb{E}$ is a set of error vectors. Then, we design the TPC $\mathbf{P}$ by maximizing the FD with the aid of the following criterion:

$$\begin{cases} \mathbf{P}_{\text{opt}} = \arg\max\limits_{\mathbf{P}} d_{\min}(\mathbf{H}, \mathbf{P}) \\ \text{s.t.} \quad \sum_{n=1}^{N_t} |p_n|^2 = N_t; \quad p_n \in C; \\ \qquad \theta_n \in (0, 2\pi]; \quad n = 1, \ldots, N_t. \end{cases} \tag{12}$$

Note that, since the attainable performance of the optimum single-stream ML receiver depends on the FD of the received signal constellation [30], the maximization of the FD directly reduces the probability of error.[1] Let $\mathbf{x}_i = s_l^i \mathbf{e}_i$ and $\mathbf{x}_j = s_k^j \mathbf{e}_j$ denote two different transmit symbols, whereas s_l^i and s_k^j denote the constellation points l and k represented by the ith and jth antennas, respectively. Then, the FD of (11) can be represented as (13), where $\phi = \angle((s_l^i)^* s_k^j) = -(s_l^i (s_k^j)^*)$. In

[1]Because the conventional PSK-and-QAM-aided SM scheme's performance is worse than that of the proposed star-QAM-aided SM, we only invoked the TPC algorithm for the star-QAM-aided SM for the sake of achieving further performance improvements. However, it is worth noting that the proposed TPC algorithm is also suitable for SM in conjunction with both conventional PSK and QAM schemes.

the ASM scheme of [7], only the APM modulation orders to be used by the transmitter are adapted, i.e., only the elements $|s_l^i|$, $|s_k^j|$, and ϕ of (13), shown at the bottom of the page, are dynamically adapted to the channel conditions, and the legitimate values of these elements are selected from the discrete set depending on the modulation order set utilized. By contrast, our proposed scheme adjusts all the TPC elements $|p_i|$, $|p_j|$, θ_i, and θ_j of (13) for maximizing the FD $d_{\min}(\mathbf{H}, \mathbf{P})$, whose legitimate values are drawn from the real-valued number field. Based on these observations and on (13), the proposed scheme and the ASM scheme may exploit the same degrees of freedom as that offered by the SM-MIMO in terms of maximizing the FD. However, unlike the ASM scheme of [7] and [15], our proposed scheme assigns the same number of bits to each time slot; hence, the potential error propagation effects experienced in ASM are avoided.

B. Low-Complexity TPC Design Algorithm

To identify the specific TPC matrix $\mathbf{P}$, which is capable of maximizing the FD, we have to determine all the N_t parameters $p_n (n = 1, \ldots, N_t)$. Since it may become excessively complex to jointly optimize these N_t parameters in the complex-valued field, we propose a low-complexity precoder design algorithm. Similar to the one-bit reallocation algorithm designed for ASM in [15], only the specific TA pair associated with the FD is considered, and the TPC parameters are selected for appropriately weighting the SM symbols because the FD of this particular TA pair predominantly determines the achievable performance. The calculation of the TPC matrix is summarized in Fig. 3.

To be specific, given the channel matrix $\mathbf{H}$, the indexes of the TA pair (g, k) associated with the FD $d_{\min}(\mathbf{H})$ can be found with the aid of the flowchart shown in Fig. 3. To offer an increased FD, the precoding parameters of this TA pair can be dynamically adapted. Note that, if the value of g is the same as k, it is plausible that the TA g has the smallest channel gain. In this case, the phase rotation elements of (10) do not have to be considered because this would not increase the FD of (13). To increase the FD, we only consider the PA matrix of (10) and may deduct some power from the TA u having the highest channel gain, which may hence be reassigned it to the TA g. As a result, p_u and p_g have to be optimized. On the other hand, if the value of g and k is not the same, parameters p_g and p_k have to be calculated. Overall, there are only two parameters, namely, p_g and p_k, (p_u for $g = k$) that have to be searched for. Finding the optimal values of p_g and p_k as a function of both $\mathbf{H}$ and of the optimal transmit parameters involves an exhaustive search over the vast design space of $\bar{p}_g$, $\bar{p}_k$, θ_g, and θ_k of (10), which is overly complex. To reduce the complexity, according to (12), the power of the TA pair (g, k) satisfies the constraint $\bar{p}_k^2 + \bar{p}_g^2 = 2$; hence, only the element $\bar{p}_k$ has to be searched for in the power matrix $\bar{\mathbf{P}}$ of (10). Moreover, since the phase rotation of the symbol is only carried by two TAs and their phase difference is correlated, we can simplify the computations by fixing $\theta_k = 1$ and then finding the optimal

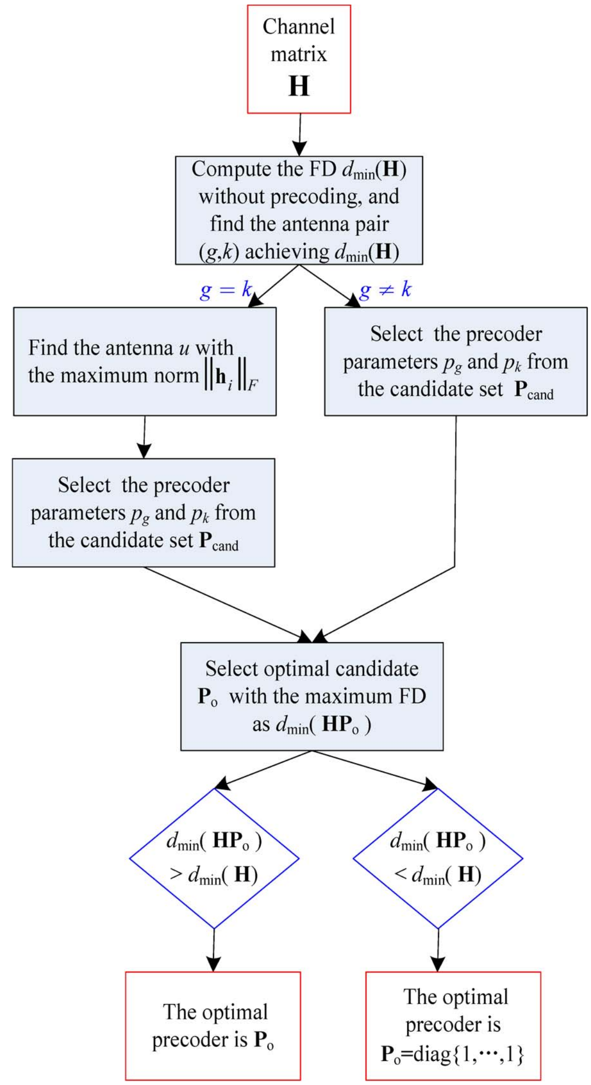

Fig. 3. Calculation of the diagonal precoding matrix for star-QAM-aided SM-MIMO.

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\begin{aligned}
d_{\min}(\mathbf{H}, \mathbf{P}) &= \min_{s_l^j, s_k^j \in S} \left\| \mathbf{HP} \left(s_l^i \mathbf{e}_i - s_k^j \mathbf{e}_j \right) \right\|_F \\
&= \min_{s_l^j, s_k^j \in S} \left\| \left(\mathbf{h}_i p_i s_l^i - \mathbf{h}_j p_j s_k^j \right) \right\|_F \\
&= \min_{s_l^j, s_k^j \in S} \sqrt{ \left| s_l^i \right|^2 |p_i|^2 \mathbf{h}_i^{\mathrm{H}} \mathbf{h}_i + \left| s_k^j \right|^2 |p_j|^2 \mathbf{h}_j^{\mathrm{H}} \mathbf{h}_j - 2 |p_i| |p_j| \left| s_l^i \right| \left| s_k^j \right| \operatorname{Re}\left\{ \mathbf{h}_i^{\mathrm{H}} \mathbf{h}_j e^{j(\phi - \theta_i + \theta_j)} \right\} }
\end{aligned}
\tag{13}
$$

θ_g. This implies that only the phase parameter θ_g has to be optimized for the phase matrix $\mathbf{\Theta}$. In Fig. 3, a numerical search is used for varying $\bar{p}_g$ and θ_g in small steps. Note that we have $0 \le \bar{p}_g \le \sqrt{2}$ and $0 \le \theta_g \le 2\pi$ according to (12). For our numerical search, we have assumed

$$\begin{cases} \bar{p}_g = \sqrt{2}/V_1 * v_1, & v_1 = 0, \ldots, V_1 \\ \theta_g = 2\pi/V_2 * v_2, & v_2 = 0, \ldots, V_2 \end{cases} \quad (14)$$

where V_1 and V_2 represent the number of quantization steps and can be flexibly selected according to the prevalent performance requirements. As a result, the corresponding diagonal TPC matrix candidates are

$$\mathbf{P}_{\text{cand}} = \text{diag}\left\{1, \ldots, \bar{p}_g e^{j\theta_g}, \ldots, \sqrt{2 - \bar{p}_g^2}, \ldots, 1\right\}$$
$$\uparrow g\text{th} \qquad \uparrow k\text{th}. \quad (15)$$

Upon denoting the quantized TPC matrix $\mathbf{P}$ as $\mathbf{P}_{\text{cand}}$, the optimization problem of (12) is reformulated as

$$\mathbf{P}_{\text{opt}} = \arg\max_{\{\mathbf{P} \in \mathbf{P}_{\text{cand}}, \mathbf{P}_{\text{I}}\}} d_{\min}(\mathbf{H}, \mathbf{P}). \quad (16)$$

where we have $\mathbf{P}_{\text{I}} = \mathbf{I}_{N_t}$. In (16), the FD of the TPC matrices $\mathbf{P}_{\text{cand}}$ generated will be compared with that of the conventional scheme associated with $\mathbf{P}_{\text{I}}$, and then we select the one having the largest FD as our final result. The receiver determines the optimal diagonal TPC matrix based on (16) and feeds back the TA indexes and their TPC parameters to the transmitter. Since only the specific TA pair, which predominantly determines the achievable performance, is considered, the proposed low-complexity algorithm can be readily extended to a high number of TAs.

IV. Simulation Results

Here, we characterize the performance of both the proposed star-QAM-aided SM scheme and of the corresponding TPC scheme, and compare it with that of the conventional QAM-modulated SM schemes, with the PSK-modulated SM schemes and with the ASM schemes [15] for transmission over independent Rayleigh block-flat MIMO channels. It is assumed that the receiver is capable of perfect phase and gain tracking, i.e., of perfect channel estimation. In practice, pilot symbols are used for estimating the MIMO channel; hence, the estimated channel matrix will inevitably be imperfect. To alleviate the effects of channel estimation errors, the joint channel estimation and data detection algorithm of [32] may be considered in the proposed schemes, where the channel estimator and the data detector iteratively exchange their information. We consider two practical MIMO systems here, namely, (2 × 2) and (4 × 4) MIMO systems. Moreover, in the TPC design algorithm, we select $V_1 = V_2 = 5$ for simplicity.[2]

Fig. 4 shows the optimal ring ratios of star-QAM-aided SM relying on (4 × 4) elements for a different number of modulation levels L, where the optimal ring ratio α^* is seen to be a function of the SNR. The bound of (2) is well suited

[2]Note that the values of V_1 and V_2 can be different. Moreover, the selection of V_1 and V_2 is flexible, and higher values of V_1 and V_2 may lead to better performance at the cost of a higher TPC design complexity.

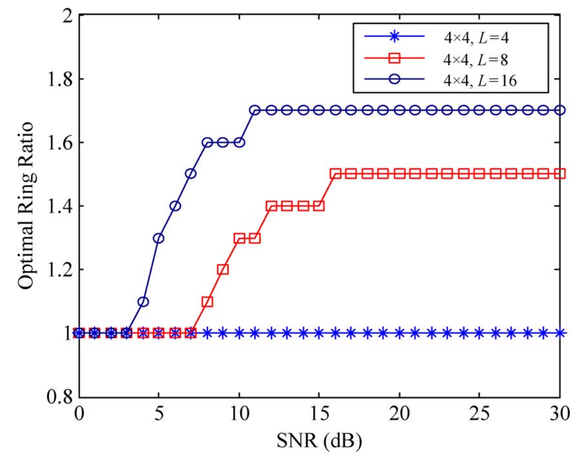

Fig. 4. Optimal ring ratios of star-QAM-aided SM with (4 × 4) MIMO for different numbers of modulation levels L.

for numerically optimizing the ring ratio, particularly in the high-SNR region. Observe in Fig. 4 that the optimal ratios approach their asymptotic values, as the SNR increases. This is expected since the bound of (2) is also asymptotically tight and the probability of an error event in slow fading associated with ML detection is dominated by the minimum-distance error event at high values of the SNR. Moreover, the optimal ring ratios are different for different MIMO parameters.

Since the transmitter operates at a fixed ring ratio, we have opted for the asymptotic ring-ratio value for the evaluation of the BER. For example, we have chosen the optimal ring ratio $\alpha^* = 1.7$ for the 16-star-QAM-aided (4 × 4) SM-MIMO, according to the results in Fig. 4. This result may be readily extended to other star-QAM-aided SM scenarios, such as the (4 × 4)-element star-QAM-aided SM schemes using $L = 4$, 8 in Fig. 4.

In Figs. 5 and 6, we compare various SM-MIMO systems relying on diverse MIMO parameters and modulation orders. First, in Figs. 5 and 6, we depict the BER performance of the conventional QAM-modulated SM schemes, of the PSK-modulated SM arrangements, and of the proposed star-QAM-aided SM scheme. Note that the optimized star-QAM constellation is designed offline for different SM-MIMO systems. Hence, the resultant system does not need any feedback. To be specific, we may create a parameter lookup table for the star-QAM SM schemes associated with the MIMO setups considered; hence, the complexity of the optimal ring-ratio search process detailed in Section II is negligible. For completeness, we also included the theoretical upper bound [30] for the family of conventional SM schemes. We found that the conventional QAM-modulated SM scheme outperforms its identical-throughput PSK counterpart for a (4 × 4)-element MIMO channel in Fig. 5, whereas the PSK scheme is preferred for a (2 × 2)-element MIMO channel in Fig. 6. This indicates that the best choice of the APM scheme depends on the specific SM parameters, such as the MIMO setup and throughput. Moreover, as shown in Fig. 5, the optimized star-QAM-aided SM scheme provides an SNR gain of about 3 dB at BER = 10^{-5} over the conventional 16-PSK-modulated SM scheme and an SNR gain of about 1.1 dB over the identical-throughput

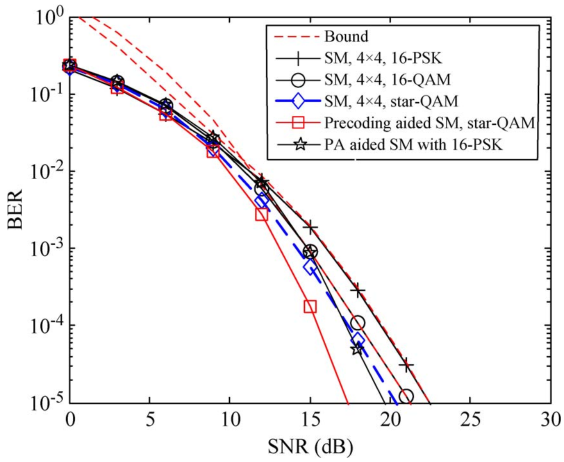

Fig. 5. BER performance of various SM-MIMO schemes operating in a (4 × 4) MIMO channel at a total throughput of 6 b/s. Since the transmitter operates with a fixed ring ratio, we have chosen the asymptotic ring-ratio value for the evaluation of star-QAM-aided schemes. Here, α is chosen as $\alpha = 1.7$.

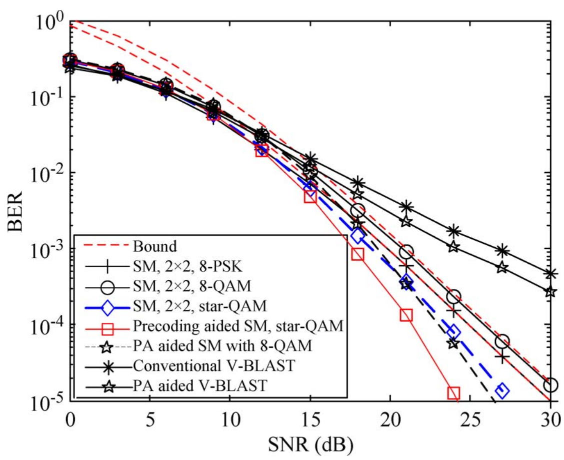

Fig. 6. BER performance of various SM schemes operating in (2 × 2) MIMO channel at a total throughput of 4 b/s. Here, α is chosen as $\alpha = 1.5$.

Gray-coded MMD 16-QAM SM scheme. This advantage of the optimized star-QAM scheme recorded for SM-MIMO is also visible in Fig. 6.

Moreover, in Figs. 5 and 6, we also compare the achievable BER performance of the limited-feedback-aided ASM schemes. To be specific, two diagonal-precoding-aided schemes, namely, the precoding-assisted star-QAM-based SM schemes and the PA-aided SM schemes of [33] are compared. For simplicity, the PA algorithm is only applied to the non-ASM schemes exhibiting an inferior performance in Figs. 5 and 6, namely, to the conventional (4 × 4)-element SM using 16-PSK and (2 × 2)-element SM employing 8-QAM. Note that the (4 × 4)-element SM associated with 16-QAM and (2 × 2)-element SM employing 8-PSK can also use the PA regime to attain a BER improvement. Due to space limitations, these results are not presented here. As shown in Figs. 5 and 6, the proposed TPC schemes provide a gain of 2.5–3 dB at the BER of 10^{-5} over the PA-aided SM schemes. This is because PA-aided SM may be viewed as a special case of the proposed precoding-aided SM created by only considering the PA matrix in (10). To be specific, compared with the PA-aided SM of

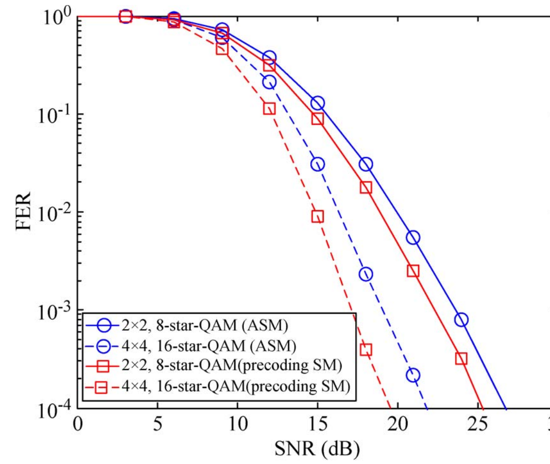

Fig. 7. FER performance of the proposed precoding star-QAM-aided SM and the ASM schemes at total throughputs of 4 and 6 b/s.

[33], our precoding-based SM regime jointly adapts the power and the phases of the transmit signals and hence improves the achievable BER performance.

Furthermore, in Fig. 6, we compare the QPSK-modulated V-BLAST scheme and its PA-aided counterpart associated with a zero-forcing-based successive interference cancelation (ZF-SIC) detector [18] as the benchmarkers because their detection complexity is similar to that of the single-stream ML-based SM schemes. Observe in Fig. 6 for $m_{\mathrm{all}} = 4$ b/s that our TPC-aided SM scheme outperforms the PA-aided VBLAST arrangement relying on a ZF-SIC detector. Indeed, if a powerful ML detector is employed for the VBLAST system, we can achieve a better BER performance. However, designing PA algorithms for ML-based VBLAST systems is a challenge, and their detection complexity is high, as indicated in [34].

Fig. 7 shows the frame error rate (FER) of both the proposed precoded star-QAM-aided SM scheme and of the ASM scheme [15]. The transmission frame size is $L_F = 60$ b.[3] Note that, although the proposed scheme and the ASM scheme exploit the same degrees of freedom offered by the SM-MIMO for improving the performance, our proposed scheme is capable of avoiding the error propagation effects often experienced in ASM, owing to ASM-mode signaling errors. Moreover, the selection of TPC parameters is more flexible than that of ASM because the modulation orders of ASM are selected from a discrete set, whereas the TPC parameters are chosen from the complex-valued field. As expected, the performance gain of the proposed scheme over ASM is seen to be about 2 dB at FER $= 10^{-3}$ in Fig. 7.

V. Conclusion

In this paper, we have investigated the problem of designing APM constellations that minimize the SM system's ABEP. We considered a class of star-QAM constellations, which is

[3]Here, we assume that the channel matrix remains constant within each transmit frame and consider the FER performance of these schemes. Note that the ASM schemes often suffer from error-propagation effects, as indicated in Section I. Hence, using the FER comparison of the ASM and TPC-aided SM schemes may be more suitable than the BER metric.

capable of flexibly adapting the ring ratios. We formulated the constellation design problem as an optimization problem and conceived an efficient iterative constellation-optimization method. Moreover, a diagonal TPC technique was proposed for the optimized star-QAM-aided SM to attain an improved performance. The simulation results confirm that our proposed optimized star-QAM-aided SM scheme outperforms the conventional PSK/QAM schemes. Moreover, our TPC method also exhibits an attractive BER/FER performance. For achieving an improved performance for a high number of bits per symbol, our further work will be focused on the integration of GSM and channel coding into the proposed TPC schemes.

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AUTHOR QUERIES

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AQ1 = There were discrepancies with the current affiliations of S. Li in the first footnote and that in the biography. Please check if the following changes are appropriate. If not, kindly provide the necessary corrections.

AQ2 = The sentence was modified for clarity. Please check if the following changes are appropriate. If not, kindly provide the necessary corrections.

AQ3 = Refs. [4] and [13] were the same and so was deleted from the list. Citations were renumbered accordingly. Please check.

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Star-QAM Signaling Constellations for Spatial Modulation

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***Abstract*—The performance of spatial modulation (SM)-assisted multiple-input–multiple-output (MIMO) communication systems is highly dependent on the specific amplitude/phase modulation (APM) signal constellation adopted. In this paper, we conceive new star-quadrature amplitude modulation (star-QAM)-aided SM schemes. Our goal is to minimize the system's average bit error probability (ABEP). More specifically, a new class of star-QAM constellations is introduced for SM, which is capable of flexibly adapting ring ratios of the amplitude levels. Then, under a specific MIMO configuration and a predetermined transmission rate, a simple and efficient ring-ratio optimization algorithm is proposed to minimize the ABEP. Moreover, to improve further the performance of our star-QAM-aided SM scheme, a diagonal precoding technique is proposed, and a low-complexity minimum-distance-based approach is conceived for extracting the precoding parameters. Our numerical results show that the proposed star-QAM-aided SM arrangement provides beneficial system performance improvements compared with the identical-throughput maximum–minimum distance (MMD) QAM and phase-shift keying (PSK) benchmarkers. Moreover, our precoding scheme is capable of further improving the attainable system performance at a modest feedback requirement.**

***Index Terms*—Constellation optimization, multiple-input–multiple-output (MIMO), spatial modulation (SM), star-quadrature amplitude modulation (star-QAM).**

I. Introduction

Spatial modulation (SM), which maps the information bits to two information-carrying entities, namely the antenna indexes and the combined amplitude/phase modulation (APM) constellation, constitutes a promising low-complexity multiple-input–multiple-output (MIMO) transmission technique [1]–[8]. In a conventional single-input–single-output (SISO) system, the Gray-coded maximum–minimum distance (MMD) quadrature amplitude modulation (QAM) constellation minimizes the bit error rate (BER) [9], [10]. However, the advantage of MMD-QAM may be eroded in SM-MIMO systems [11]. This is due to the fact that the BER performance of SM-MIMO systems is jointly determined by the spatial signal (i.e., antenna indexes), by the classic APM constellation, and by their interaction [11]–[18].

Recently, the effects of APM schemes on the performance of SM have been investigated in [11], [14], and [18]. More specifically, in [11], the performance of SM systems relying both on conventional QAM and PSK modulation was studied, demonstrating that, in some MIMO setups, the PSK-modulated SM scheme may outperform the identical-throughput MMD-QAM-aided SM scheme. In [18], the dispersion matrices and the signal constellations were jointly optimized for a near-capacity irregular precoded space–time shift keying (STSK) system, which includes SM as a special case and strikes a flexible rate–diversity tradeoff. It was also shown in [14] that the star-QAM-aided STSK scheme outperforms its MMD-based square-QAM-aided counterpart. This observation may be also valid for SM systems [11]. The aforementioned results indicated that the performance of SM is highly dependent on the specific APM adopted; hence, a suitable APM scheme has to be designed for this hybrid modulation scheme.

On the other hand, star-QAM constitutes a special case of circular amplitude- and phase-shift keying, which is capable of outperforming the classic square-QAM constellation in peak-power-limited systems [19]. Hence, it has been adopted in most of the recent satellite communication standards, such as in the Digital Video Broadcast System (DVB) S2, DVB-SH, and the Internet Protocol over Satellite and Advanced Broadcasting System via Satellite [19]. The star-QAM constellation is composed of multiple concentric circles, and it was shown to be beneficial in the context of STSK systems. Hence, star-QAM may be an attractive APM candidate for SM-MIMO. However, the constellations' optimization has not been carried out for star-QAM-aided SM.

Moreover, to increase the robustness of the SM-MIMO system, limited-feedback-aided link adaptation schemes have been proposed in [20]–[26]. For example, in [20], an opportunistic power-allocation (PA) scheme was conceived for achieving a beneficial transmit diversity gain in SM-MIMO systems. In [21], a beamforming codebook was designed for optimizing the coding gain of SM-MIMO based on the knowledge of the channel envelope's spatial correlation. Recently, an adaptive closed-loop-aided method was invoked for providing both diversity and coding gains in the context of space-shift keying (SSK)[22],

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which is a special case of SM. However, the scheme proposed for SSK may not be directly applicable to the conventional SM scheme. Moreover, ASM-MIMO architectures relying on different combinations of modulation schemes were proposed in [24], which aimed for maximizing the channel capacity at a predefined target BER, rather than for minimizing the BER. In contrast, in [25] and [26], a transmit precoding (TPC) technique was used for improving the modulated signal design for SM. However, this technique may only be suitable for a new class of SM relying on a single-receiver antenna. For the conventional SM, we proposed a near-instantaneously adaptive-modulation-aided scheme for minimizing the BER [7], which was termed adaptive SM (ASM). Then, we further generalized this paper in [12] and [15], where the implementation complexity of ASM was considerably reduced. However, ASM typically transmits a different number of bits in the different-quality time slots, which may be inconvenient in fixed-rate applications and potentially leads to error propagation in the case of ASM-mode signaling errors.

Against this background, the novel contributions of this paper are threefold.

- We introduced the class of star-QAM constellations [27], which is capable of flexibly adapting the ring ratios, hence subsuming classic PSK as a special case. Alternatively, if the ring ratio is appropriately selected, the proposed star-QAM is capable of achieving almost the same Euclidean distance (ED) as the MMD-based QAM.
- Given a specific MIMO configuration and a predetermined transmission rate, a low-complexity yet efficient optimization algorithm *is proposed* to minimize the average bit error probability (ABEP) of SM-MIMO systems, where the effects of both the antenna index, as well as of the APM signal and their interaction, are jointly considered. Only the optimal ring ratios of star-QAM constellation have to be found by the optimization algorithm.
- We introduce a new TPC scheme for star-QAM-aided SM-MIMO systems, which further improves the performance. To retain the benefits of SM, such as its low-complexity single-stream detector and its single RF chain, we design its TPC matrix $\mathbf{P}$ to be diagonal. We demonstrate that this precoded scheme and the ASM schemes of [12] and [15] are capable of exploiting the same degrees of freedom as that offered by the classic SM-MIMO for maximizing the free distance (FD). However, our TPC scheme assigns the same number of bits to each time slot; hence, it is capable of avoiding the potential error propagation effects of ASM encountered in the case of ASM-mode signaling errors. Our simulation results show that the proposed TPC scheme considerably improves the system's performance compared with the conventional star-QAM-aided SM, the PA-aided SM, and ASM arrangements.

The remainder of this paper is organized as follows. In Section II, we conceive a signaling constellation optimization method for star-QAM-aided SM and elaborate both on the choice of our optimization criterion and on the corresponding optimization algorithm. In Section III, we propose a new TPC scheme for enhancing the performance of the star-QAM-aided SM. Our numerical analysis is carried out in Section IV. Finally, our conclusions are presented in Section V.

II. Signaling Constellation Optimization

A. *Performance Metric and Star-QAM Constellation*

Consider a flat-fading MIMO channel associated with N_t transmit antennas (TAs) and N_r receive antennas. The $(N_t \times 1)$-element transmit symbol vector $\mathbf{x}$ is assumed to satisfy $E[\mathbf{x}\mathbf{x}^H] = \mathbf{I}_{N_t}$, where $\mathbf{I}_{N_t}$ denotes an $(N_t \times N_t)$-element identity matrix. Then, the transmitted SM symbol $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$ is given as $\mathbf{x} = s_l^n \mathbf{e}_n$ [21], where s_l^n is the complex-valued symbol of the APM scheme employed at the nth TA. For example, L-PSK/QAM is associated with $m_{\mathrm{APM}} = log_2(L)$ input bits, whereas $\mathbf{e}_n (1 \le n \le N_t)$ is selected from the N_t-dimensional standard basis vectors (i.e., $\mathbf{e}_1 = [1, 0, \ldots, 0]^T$), according to $\log_2(N_t)$ input bits. The corresponding received signal is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} = \mathbf{h}_n s_l^n + \mathbf{n} \tag{1}$$

where $\mathbf{H}$ is an $(N_r \times N_t)$-element channel matrix, $\mathbf{h}_n$ is the nth column of $\mathbf{H}$, and the elements of the N_r-dimensional noise vector $\mathbf{n}$ are Gaussian random variables obeying $\mathcal{CN}(0,\, N_0)$.

In [11], an improved union bound partitions the ABEP expression of SM-MIMO systems into three terms: the P_{spatial} term related to the TA index, the P_{signal} term related to the APM signals, and the joint term P_{joint}, which depends on both the TA index and on the APM signals. This bound is formulated as

$$P_{\mathrm{SM}}(\rho) \le P_{\mathrm{spatial}}(\rho) + P_{\mathrm{signal}}(\rho) + P_{\mathrm{joint}}(\rho). \tag{2}$$

This improved union bound is more accurate than the conventional union-bound-based methods, hence facilitating a deeper understanding of the joint impact of spatial and APM signals, as illustrated in [11]. We focus our attention on the system's performance for transmission over i.i.d. Rayleigh fading channels, which may be readily extended to the Nakagami-m fading model of [11]. Let us assume that ρ is the average SNR, whereas x_l and $x_{\hat{l}}$ represent two different APM constellation points, with their modulus values being given as β_l and $\beta_{\hat{l}}$, respectively. Then, we have

$$P_{\mathrm{signal}}(\rho) = \frac{\log_2(L)}{\log_2(N_t \cdot L)} P_{\mathrm{APM}}(\rho) \tag{3}$$

$$P_{\mathrm{spatial}}(\rho) = \frac{\log_2(N_t) N_t}{2L \log_2(N_t \cdot L)} \sum_{l=1}^{L} \mathcal{F}\left(\rho \beta_l^2\right) \tag{4}$$

$$P_{\mathrm{joint}}(\rho) = A \sum_{l=1}^{L} \sum_{\hat{l} \ne l=1}^{L} \Big[B + C D_H\,(x_l \to x_{\hat{l}})\big) \times \mathcal{F}\left(\frac{\rho}{2}\left(\beta_l^2 + \beta_{\hat{l}}^2\right)\right) \Big]. \tag{5}$$

Here, $P_{\mathrm{APM}}(\rho)$ represents the error probability of conventional L-APM, which depends on the ED of the constellation points of APM, whereas $D_H(x_l \to x_{\hat{l}})$ is the Hamming distance between signals x_l and $x_{\hat{l}}$. Here, $A = 1/L \log(N_t \cdot L)$, $B = N_t \log(N_t)/2$, and $C = (N_t - 1)$ are constants for a fixed

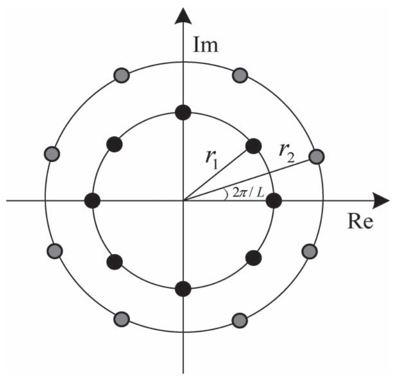

Fig. 1. Complex signal constellation of 16-star-QAM. The symbols are evenly distributed on two rings and the phase differences between the neighboring symbols on the same ring are equal.

MIMO setup. Moreover, the function $\mathcal{F}(\varepsilon)$ in (4) and (5) is the pairwise error probability function [11], which is given by

$$\mathcal{F}(\varepsilon) = \gamma(\varepsilon)^{N_r} \sum_{n=0}^{N_r-1} \binom{N_r - 1 + n}{n} [1 - \gamma(\varepsilon)]^n \qquad (6)$$

where we have $\gamma(\varepsilon) \triangleq (1/2)(1 - \sqrt{(\varepsilon/2 + \varepsilon)})$. Note that the ABEP bound of (2) was proposed for the general family of APM schemes, which contains not only the conventional PSK but also the generic rectangular nonsquare-QAM schemes and the square-QAM schemes. Moreover, since P_{signal} is available in closed form for conventional APM modulation schemes, the bound of (2) is more accurate than the conventional results of [21].

As indicated in (3)–(5), P_{signal} mainly depends on the minimum ED $d_{\min}$ of the APM constellation points, whereas P_{joint} and P_{spatial} mainly depend on the modulus values β_l $(l = 1, \ldots, L)$ of the APM constellation points.

Note that the modulus values β_l are represented by the Frobenius norms of the APM constellation points. These results suggested that, for jointly minimizing P_{signal}, P_{joint}, and P_{spatial}, we can focus our attention on the design of $d_{\min}$ and on the β_l parameters of APM.

To make the choice of the APM parameters $d_{\min}$ and β_l as flexible as possible, we consider a class of star-QAM constellations, which subsumes the classic PSK as a special case but may also be configured for maximizing the minimum ED of the constellation by appropriately adjusting the ring ratios of the amplitude levels. For simplicity, we consider the example of a twin-ring 16-star-QAM constellation having a ring ratio of $\alpha = r_2/r_1$, as shown in Fig. 1. The symbols are evenly distributed on the two rings, and the phase differences between the neighboring symbols on the same ring are equal. Unlike the conventional twin-ring star-QAM constellation [19], [28], the constellation points on the outer circle of our proposed star-QAM constellation are rotated by $2\pi/L$ degrees compared with the corresponding constellation points on the inner circle [27]. Hence, again, the conventional PSK constitutes an integral part of our star-QAM scheme, which is associated with $\alpha = 1$. Table I summarizes the minimum EDs $d_{\min}$ between the constellation points for different APM schemes. It is found that this star-QAM scheme is capable of achieving almost the same minimum ED as the MMD-based QAM. Note that, although this twin-ring star-QAM constellation has been indeed applied for noncoherent detection [27], it has not been considered whether this constellation can be directly applied to SM for achieving performance improvements.

TABLE I
MINIMUM ED BETWEEN THE CONSTELLATION POINTS FOR DIFFERENT APM SCHEMES

Modulation order	2	4 (MMD)	8 ([9])	16 (MMD)	32 ([9])
PSK	2	$\sqrt{2}$	0.7654	0.3902	0.1960
QAM	- -	$\sqrt{2}$	0.8165	0.6325	0.4082
Proposed star-QAM	2	$\sqrt{2}$	0.9134	0.5737	0.3952

The aforementioned twin-ring philosophy of Fig. 1 may be readily extended to multiple-ring star-QAM. The reasons for considering twin-ring star-QAM in our paper are the following.

- It is an attractive APM modulation candidate for SM, exhibiting a high performance at low detection complexity compared with conventional QAM schemes, as detailed in [13]–[15].
- It can be flexibly designed for different $d_{\min}$ and $\beta_l (l = 1, \ldots, L)$ combinations, which is achieved by simply adjusting a single parameter α, whereas β_l can assume two values because only two rings are considered.
- The ABEP of star-QAM, which is related to the P_{spatial} term of (3), has been documented in [28] and [29].

B. *Optimization Criteria and Optimization Algorithm*

Observe in Fig. 1 that there are numerous options for the parameter α of the star-QAM constellation, for a given MIMO setup, specified by the total number of bits per symbol m_{all}, the $(N_r \times N_t)$ configuration of transceiver, and the number of modulation level L . The goal of star-QAM-aided signaling AQ2 constellation optimization is to find the specific ring ratio α, which minimizes the ABEP of the SM-MIMO of (2). Note that, although the term $P_{\text{SM}}(\rho)$ in (2) cannot be directly represented by parameter α, it varies as a function of α, which may be formulated as $P_{\text{SM}}(\rho, \alpha)$. Following the aforementioned approach, we formulated this optimization problem as

$$\begin{cases} \alpha^* = \min\limits_{\alpha} P_{\text{SM}}(\rho, \alpha) \\ \text{s.t.} \quad \alpha \geq 1 \end{cases} \qquad (7)$$

which may be a convex one for a fixed SNR value ρ, as indicated in Fig. 4. However, deriving the closed-form solution of (7) remains an open challenge since the expression of $P_{\text{SM}}(\rho, \alpha)$ depends both on the specific APM constellation and on the particular MIMO setup [19], and since the expressions of P_{signal}, P_{joint} and P_{spatial} in (3)–(5) are complex. Hence, a numerical search is adopted.

Our optimization algorithm conceived for finding the ring ratio is summarized as follows.

Step 1: Initialize the values of N_r, N_t, m_{all}, L, and the SNR value ρ. Set the iteration step size to $\Delta\alpha = 0.1$ and the number of iterations to $n = 1$. The choice of $\Delta\alpha$ is flexible, and a lower value of $\Delta\alpha$ may lead to a better performance. We then set the search area of α to $1 \leq \alpha \leq U_\alpha$ and the performance metric to $P_{\text{iter}}(n) = 0$.

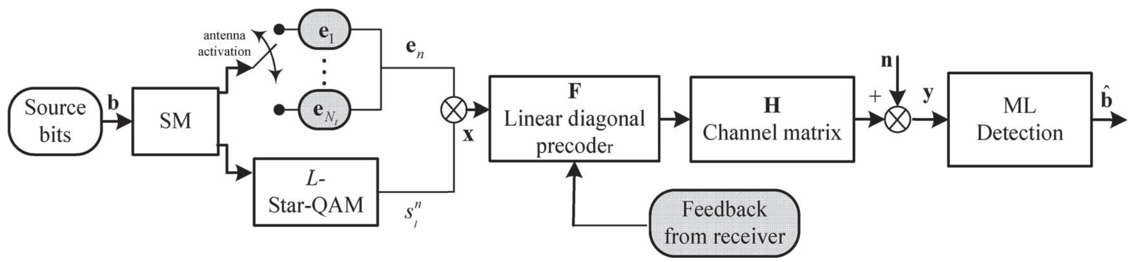

Fig. 2. System model of the diagonal-precoding-assisted star-QAM-aided SM scheme.

Step 2: While $\alpha \le U_\alpha$, let $\Delta\hat{\alpha} = \min\{\Delta\hat{\alpha}, U_\alpha - \alpha\}$, and calculate the probabilities of P_{signal}, P_{joint}, and P_{spatial} by using (3)–(5) associated with α. Then, let $P_{\text{iter}}(n) = P_{\text{SM}}(\rho)$ using (2), and set $\alpha = \alpha + \Delta\hat{\alpha}$ and $n = n + 1$.

Step 3 : Find the index $n^* = \min_n\{P_{\text{iter}}(n)\}$ to achieve the optimal ring ratio of $\alpha^* = 1 + (n^* - 1)\Delta\hat{\alpha}$.

In the aforementioned optimization algorithm, we have to choose an appropriate U_α to promptly find the optimal α^*. More explicitly, an excessively low value of U_α may lead to missing the optimal solution, whereas an excessively high value of U_α imposes excessive computational complexity on the optimization process. Hence, we will show in Section III that $U_\alpha = 3$ is a beneficial choice for promptly approaching the optimal results. Moreover, the optimum ring ratio α^* is a function of the SNR. However, we will show that the optimum ratio approaches its asymptotic optimum as the SNR increases.

III. Proposed Diagonal Precoding for Star-Quadrature Amplitude Modulation-Aided Spatial Modualtion

Since the performance of the optimum maximum-likelihood (ML) receiver depends on the FD of the received signal constellation [30], we propose a new TPC based on maximizing the FD for the family of star-QAM-aided SM-MIMO systems, when limited channel state information is available at the transmitter. Since the FD is increased by the TPC algorithm, the proposed scheme is expected to provide a beneficial system performance improvement. To retain all the single-RF-related benefits of SM, we design the TPC matrix $\mathbf{P}$ to be diagonal. The system model of the diagonal-TPC-assisted star-QAM-aided SM scheme is shown in Fig. 2. To identify the specific TPC parameters, which are capable of maximizing the FD, we propose a low-complexity TPC design algorithm. We will demonstrate that as few as two elements of the diagonal TPC matrix have to be fed back to the transmitter, regardless of N_t.

A. TPC Design Criterion

To construct a TPC for star-QAM-aided SM-MIMO systems, we can rewrite the system model of (1) as

$$\mathbf{y} = \mathbf{HPx} + \mathbf{n} \tag{8}$$

where $\mathbf{P}$ denotes the diagonal TPC matrix, which can be represented as

$$\mathbf{P} = \text{diag}\{p_1, \ldots, p_n, \ldots, p_{N_t}\} \tag{9}$$

where p_n controls the channel gain associated with x_n. Here, we let $\sum_{n=1}^{N_t} |p_n|^2 = N_t$ for normalizing the transmit power. Note that the introduction of TPC in SM does not affect the advantages of SM, such as the avoidance of the interantenna interference and the reliance on a single RF chain, because the precoded transmit vector $\mathbf{Px}$ includes only a single nonzero component; hence, only a single TA is activated in each time slot, as indicated in (8).

Numerous techniques may be invoked for constructing the TPC $\mathbf{P}$ [21], [25]. In this paper, similar to the precoding methods conceived for the orthogonalized spatial multiplexing of [31], we decompose $\mathbf{P}$ as

$$\mathbf{P} = \bar{\mathbf{P}}\boldsymbol{\Theta} = \text{diag}\left\{\bar{p}_1 e^{j\theta_1}, \ldots, \bar{p}_n e^{j\theta_n}, \ldots, \bar{p}_{N_t} e^{j\theta_{N_t}}\right\} \tag{10}$$

where $\bar{\mathbf{P}} = \text{diag}\{\bar{p}_1, \ldots, \bar{p}_n, \ldots, \bar{p}_{N_t}\}$ represents the PA matrix, whereas $\boldsymbol{\Theta} = \text{diag}\{e^{j\theta_1}, \ldots, e^{j\theta_n}, \ldots, e^{j\theta_{N_t}}\}$ is the phase rotation matrix. The FD between the constellation points at the receiver is defined as

$$\begin{aligned} d_{\min}(\mathbf{H}, \mathbf{P}) &= \min_{\substack{\mathbf{x}_i, \mathbf{x}_j \in \mathbb{X}, \\ \mathbf{x}_i \neq \mathbf{x}_j}} \|\mathbf{HP}(\mathbf{x}_i - \mathbf{x}_j)\|_F \\ &= \min_{\mathbf{e}_{ij} \in \mathbb{E}} \left\|\mathbf{H}\bar{\mathbf{P}}\boldsymbol{\Theta}\mathbf{e}_{ij}\right\|_F \end{aligned} \tag{11}$$

where $\mathbb{X}$ is the set of all legitimate transmit symbols, $\mathbf{e}_{ij} = \mathbf{x}_i - \mathbf{x}_j$, $i \neq j$ denotes the error vector, and $\mathbb{E}$ is a set of error vectors. Then, we design the TPC $\mathbf{P}$ by maximizing the FD with the aid of the following criterion:

$$\begin{cases} \mathbf{P}_{\text{opt}} = \arg\max\limits_{\mathbf{P}} d_{\min}(\mathbf{H}, \mathbf{P}) \\ \text{s.t.} \quad \sum_{n=1}^{N_t} |p_n|^2 = N_t; \quad p_n \in C; \\ \qquad \theta_n \in (0, 2\pi]; \quad n = 1, \ldots, N_t. \end{cases} \tag{12}$$

Note that, since the attainable performance of the optimum single-stream ML receiver depends on the FD of the received signal constellation [30], the maximization of the FD directly reduces the probability of error.[1] Let $\mathbf{x}_i = s_l^i \mathbf{e}_i$ and $\mathbf{x}_j = s_k^j \mathbf{e}_j$ denote two different transmit symbols, whereas s_l^i and s_k^j denote the constellation points l and k represented by the ith and jth antennas, respectively. Then, the FD of (11) can be represented as (13), where $\phi = \angle((s_l^i)^* s_k^j) = -(s_l^i (s_k^j)^*)$. In

[1] Because the conventional PSK-and-QAM-aided SM scheme's performance is worse than that of the proposed star-QAM-aided SM, we only invoked the TPC algorithm for the star-QAM-aided SM for the sake of achieving further performance improvements. However, it is worth noting that the proposed TPC algorithm is also suitable for SM in conjunction with both conventional PSK and QAM schemes.

the ASM scheme of [7], only the APM modulation orders to be used by the transmitter are adapted, i.e., only the elements $|s_l^i|$, $|s_k^j|$, and ϕ of (13), shown at the bottom of the page, are dynamically adapted to the channel conditions, and the legitimate values of these elements are selected from the discrete set depending on the modulation order set utilized. By contrast, our proposed scheme adjusts all the TPC elements $|p_i|$, $|p_j|$, θ_i, and θ_j of (13) for maximizing the FD $d_{\min}(\mathbf{H}, \mathbf{P})$, whose legitimate values are drawn from the real-valued number field. Based on these observations and on (13), the proposed scheme and the ASM scheme may exploit the same degrees of freedom as that offered by the SM-MIMO in terms of maximizing the FD. However, unlike the ASM scheme of [7] and [15], our proposed scheme assigns the same number of bits to each time slot; hence, the potential error propagation effects experienced in ASM are avoided.

B. Low-Complexity TPC Design Algorithm

To identify the specific TPC matrix $\mathbf{P}$, which is capable of maximizing the FD, we have to determine all the N_t parameters $p_n (n = 1, \ldots, N_t)$. Since it may become excessively complex to jointly optimize these N_t parameters in the complex-valued field, we propose a low-complexity precoder design algorithm. Similar to the one-bit reallocation algorithm designed for ASM in [15], only the specific TA pair associated with the FD is considered, and the TPC parameters are selected for appropriately weighting the SM symbols because the FD of this particular TA pair predominantly determines the achievable performance. The calculation of the TPC matrix is summarized in Fig. 3.

To be specific, given the channel matrix $\mathbf{H}$, the indexes of the TA pair (g, k) associated with the FD $d_{\min}(\mathbf{H})$ can be found with the aid of the flowchart shown in Fig. 3. To offer an increased FD, the precoding parameters of this TA pair can be dynamically adapted. Note that, if the value of g is the same as k, it is plausible that the TA g has the smallest channel gain. In this case, the phase rotation elements of (10) do not have to be considered because this would not increase the FD of (13). To increase the FD, we only consider the PA matrix of (10) and may deduct some power from the TA u having the highest channel gain, which may hence be reassigned it to the TA g. As a result, p_u and p_g have to be optimized. On the other hand, if the value of g and k is not the same, parameters p_g and p_k have to be calculated. Overall, there are only two parameters, namely, p_g and p_k, (p_u for $g = k$) that have to be searched for. Finding the optimal values of p_g and p_k as a function of

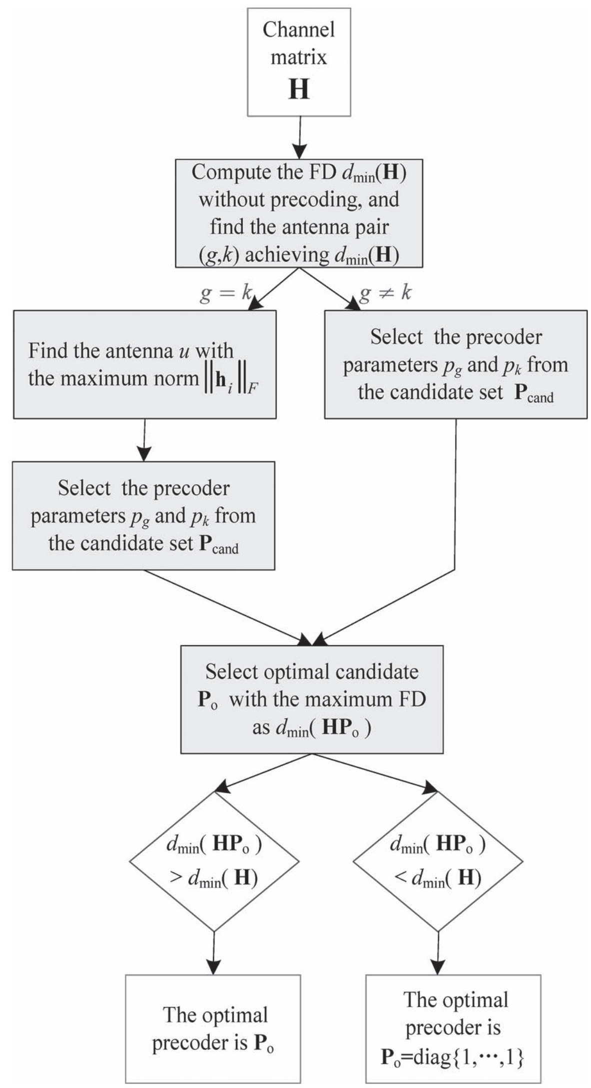

Fig. 3. Calculation of the diagonal precoding matrix for star-QAM-aided SM-MIMO.

both $\mathbf{H}$ and of the optimal transmit parameters involves an exhaustive search over the vast design space of $\bar{p}_g$, $\bar{p}_k$, θ_g, and θ_k of (10), which is overly complex. To reduce the complexity, according to (12), the power of the TA pair (g, k) satisfies the constraint $\bar{p}_k^2 + \bar{p}_g^2 = 2$; hence, only the element $\bar{p}_k$ has to be searched for in the power matrix $\bar{\mathbf{P}}$ of (10). Moreover, since the phase rotation of the symbol is only carried by two TAs and their phase difference is correlated, we can simplify the computations by fixing $\theta_k = 1$ and then finding the optimal

$$
\begin{aligned}
d_{\min}(\mathbf{H}, \mathbf{P}) &= \min_{s_l^j, s_k^j \in S} \left\| \mathbf{HP} \left(s_l^i \mathbf{e}_i - s_k^j \mathbf{e}_j \right) \right\|_F \\
&= \min_{s_l^j, s_k^j \in S} \left\| \left(\mathbf{h}_i p_i s_l^i - \mathbf{h}_j p_j s_k^j \right) \right\|_F \\
&= \min_{s_l^j, s_k^j \in S} \sqrt{ \left| s_l^i \right|^2 |p_i|^2 \mathbf{h}_i^{\mathrm{H}} \mathbf{h}_i + \left| s_k^j \right|^2 |p_j|^2 \mathbf{h}_j^{\mathrm{H}} \mathbf{h}_j - 2 |p_i| |p_j| \left| s_l^i \right| \left| s_k^j \right| \mathrm{Re}\left\{ \mathbf{h}_i^{\mathrm{H}} \mathbf{h}_j e^{j(\phi - \theta_i + \theta_j)} \right\} }
\end{aligned}
\quad (13)
$$

θ_g. This implies that only the phase parameter θ_g has to be optimized for the phase matrix $\mathbf{\Theta}$. In Fig. 3, a numerical search is used for varying $\bar{p}_g$ and θ_g in small steps. Note that we have $0 \le \bar{p}_g \le \sqrt{2}$ and $0 \le \theta_g \le 2\pi$ according to (12). For our numerical search, we have assumed

$$\begin{cases} \bar{p}_g = \sqrt{2}/V_1 * v_1, & v_1 = 0, \ldots, V_1 \\ \theta_g = 2\pi/V_2 * v_2, & v_2 = 0, \ldots, V_2 \end{cases} \tag{14}$$

where V_1 and V_2 represent the number of quantization steps and can be flexibly selected according to the prevalent performance requirements. As a result, the corresponding diagonal TPC matrix candidates are

$$\mathbf{P}_{\text{cand}} = \text{diag}\left\{1, \ldots, \underset{\uparrow\, g\text{th}}{\bar{p}_g e^{j\theta_g}}, \ldots, \underset{\uparrow\, k\text{th.}}{\sqrt{2 - \bar{p}_g^2}}, \ldots, 1\right\} \tag{15}$$

Upon denoting the quantized TPC matrix $\mathbf{P}$ as $\mathbf{P}_{\text{cand}}$, the optimization problem of (12) is reformulated as

$$\mathbf{P}_{\text{opt}} = \underset{\{\mathbf{P} \in \mathbf{P}_{\text{cand}}, \mathbf{P}_{\text{I}}\}}{\arg\max}\, d_{\min}(\mathbf{H}, \mathbf{P}). \tag{16}$$

where we have $\mathbf{P}_{\text{I}} = \mathbf{I}_{N_t}$. In (16), the FD of the TPC matrices $\mathbf{P}_{\text{cand}}$ generated will be compared with that of the conventional scheme associated with $\mathbf{P}_{\text{I}}$, and then we select the one having the largest FD as our final result. The receiver determines the optimal diagonal TPC matrix based on (16) and feeds back the TA indexes and their TPC parameters to the transmitter. Since only the specific TA pair, which predominantly determines the achievable performance, is considered, the proposed low-complexity algorithm can be readily extended to a high number of TAs.

IV. SIMULATION RESULTS

Here, we characterize the performance of both the proposed star-QAM-aided SM scheme and of the corresponding TPC scheme, and compare it with that of the conventional QAM-modulated SM schemes, with the PSK-modulated SM schemes and with the ASM schemes [15] for transmission over independent Rayleigh block-flat MIMO channels. It is assumed that the receiver is capable of perfect phase and gain tracking, i.e., of perfect channel estimation. In practice, pilot symbols are used for estimating the MIMO channel; hence, the estimated channel matrix will inevitably be imperfect. To alleviate the effects of channel estimation errors, the joint channel estimation and data detection algorithm of [32] may be considered in the proposed schemes, where the channel estimator and the data detector iteratively exchange their information. We consider two practical MIMO systems here, namely, (2×2) and (4×4) MIMO systems. Moreover, in the TPC design algorithm, we select $V_1 = V_2 = 5$ for simplicity.[2]

Fig. 4 shows the optimal ring ratios of star-QAM-aided SM relying on (4×4) elements for a different number of modulation levels L, where the optimal ring ratio α^* is seen to be a function of the SNR. The bound of (2) is well suited

[2]Note that the values of V_1 and V_2 can be different. Moreover, the selection of V_1 and V_2 is flexible, and higher values of V_1 and V_2 may lead to better performance at the cost of a higher TPC design complexity.

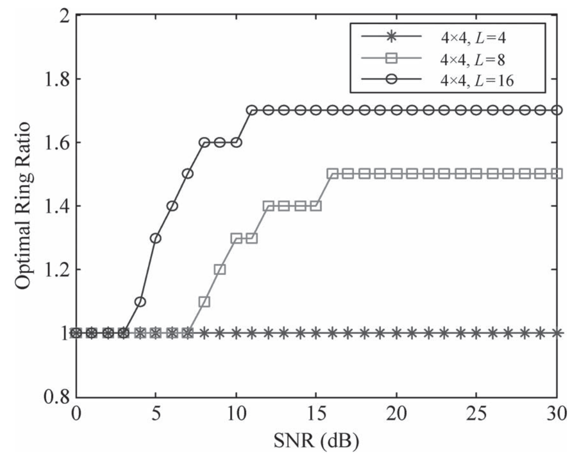

Fig. 4. Optimal ring ratios of star-QAM-aided SM with (4×4) MIMO for different numbers of modulation levels L.

for numerically optimizing the ring ratio, particularly in the high-SNR region. Observe in Fig. 4 that the optimal ratios approach their asymptotic values, as the SNR increases. This is expected since the bound of (2) is also asymptotically tight and the probability of an error event in slow fading associated with ML detection is dominated by the minimum-distance error event at high values of the SNR. Moreover, the optimal ring ratios are different for different MIMO parameters.

Since the transmitter operates at a fixed ring ratio, we have opted for the asymptotic ring-ratio value for the evaluation of the BER. For example, we have chosen the optimal ring ratio $\alpha^* = 1.7$ for the 16-star-QAM-aided (4×4) SM-MIMO, according to the results in Fig. 4. This result may be readily extended to other star-QAM-aided SM scenarios, such as the (4×4)-element star-QAM-aided SM schemes using $L = 4$, 8 in Fig. 4.

In Figs. 5 and 6, we compare various SM-MIMO systems relying on diverse MIMO parameters and modulation orders. First, in Figs. 5 and 6, we depict the BER performance of the conventional QAM-modulated SM schemes, of the PSK-modulated SM arrangements, and of the proposed star-QAM-aided SM scheme. Note that the optimized star-QAM constellation is designed offline for different SM-MIMO systems. Hence, the resultant system does not need any feedback. To be specific, we may create a parameter lookup table for the star-QAM SM schemes associated with the MIMO setups considered; hence, the complexity of the optimal ring-ratio search process detailed in Section II is negligible. For completeness, we also included the theoretical upper bound [30] for the family of conventional SM schemes. We found that the conventional QAM-modulated SM scheme outperforms its identical-throughput PSK counterpart for a (4×4)-element MIMO channel in Fig. 5, whereas the PSK scheme is preferred for a (2×2)-element MIMO channel in Fig. 6. This indicates that the best choice of the APM scheme depends on the specific SM parameters, such as the MIMO setup and throughput. Moreover, as shown in Fig. 5, the optimized star-QAM-aided SM scheme provides an SNR gain of about 3 dB at BER $= 10^{-5}$ over the conventional 16-PSK-modulated SM scheme and an SNR gain of about 1.1 dB over the identical-throughput

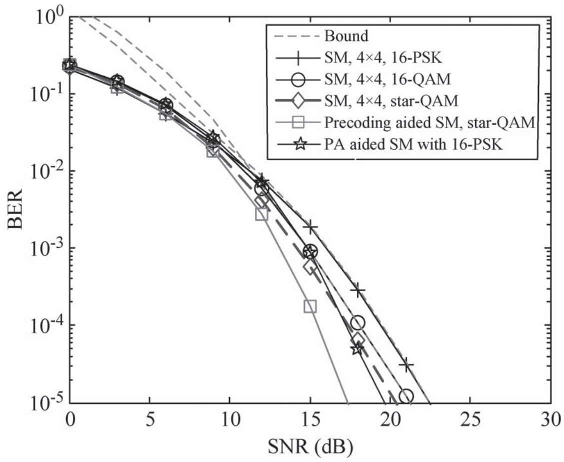

Fig. 5. BER performance of various SM-MIMO schemes operating in a (4 × 4) MIMO channel at a total throughput of 6 b/s. Since the transmitter operates with a fixed ring ratio, we have chosen the asymptotic ring-ratio value for the evaluation of star-QAM-aided schemes. Here, α is chosen as $\alpha = 1.7$.

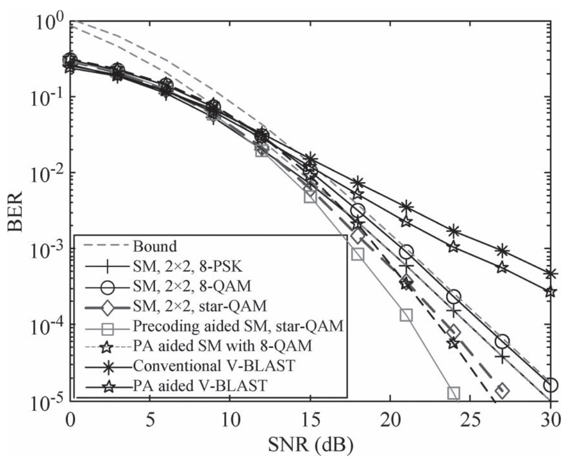

Fig. 6. BER performance of various SM schemes operating in (2 × 2) MIMO channel at a total throughput of 4 b/s. Here, α is chosen as $\alpha = 1.5$.

Gray-coded MMD 16-QAM SM scheme. This advantage of the optimized star-QAM scheme recorded for SM-MIMO is also visible in Fig. 6.

Moreover, in Figs. 5 and 6, we also compare the achievable BER performance of the limited-feedback-aided ASM schemes. To be specific, two diagonal-precoding-aided schemes, namely, the precoding-assisted star-QAM-based SM schemes and the PA-aided SM schemes of [33] are compared. For simplicity, the PA algorithm is only applied to the non-ASM schemes exhibiting an inferior performance in Figs. 5 and 6, namely, to the conventional (4 × 4)-element SM using 16-PSK and (2 × 2)-element SM employing 8-QAM. Note that the (4 × 4)-element SM associated with 16-QAM and (2 × 2)-element SM employing 8-PSK can also use the PA regime to attain a BER improvement. Due to space limitations, these results are not presented here. As shown in Figs. 5 and 6, the proposed TPC schemes provide a gain of 2.5–3 dB at the BER of 10^{-5} over the PA-aided SM schemes. This is because PA-aided SM may be viewed as a special case of the proposed precoding-aided SM created by only considering the PA matrix in (10). To be specific, compared with the PA-aided SM of [33], our precoding-based SM regime jointly adapts the power and the phases of the transmit signals and hence improves the achievable BER performance.

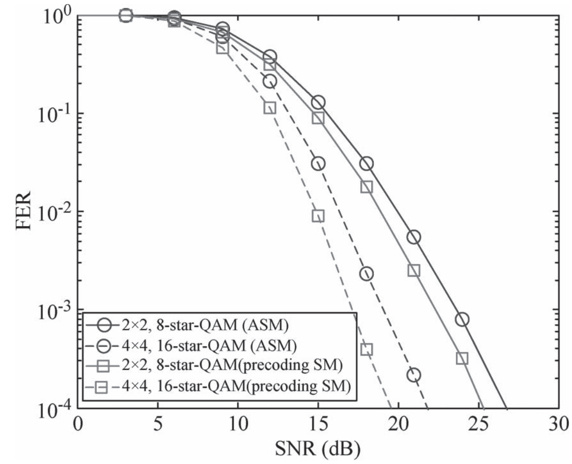

Fig. 7. FER performance of the proposed precoding star-QAM-aided SM and the ASM schemes at total throughputs of 4 and 6 b/s.

Furthermore, in Fig. 6, we compare the QPSK-modulated V-BLAST scheme and its PA-aided counterpart associated with a zero-forcing-based successive interference cancelation (ZF-SIC) detector [18] as the benchmarkers because their detection complexity is similar to that of the single-stream ML-based SM schemes. Observe in Fig. 6 for $m_{\text{all}} = 4$ b/s that our TPC-aided SM scheme outperforms the PA-aided VBLAST arrangement relying on a ZF-SIC detector. Indeed, if a powerful ML detector is employed for the VBLAST system, we can achieve a better BER performance. However, designing PA algorithms for ML-based VBLAST systems is a challenge, and their detection complexity is high, as indicated in [34].

Fig. 7 shows the frame error rate (FER) of both the proposed precoded star-QAM-aided SM scheme and of the ASM scheme [15]. The transmission frame size is $L_F = 60$ b.[3] Note that, although the proposed scheme and the ASM scheme exploit the same degrees of freedom offered by the SM-MIMO for improving the performance, our proposed scheme is capable of avoiding the error propagation effects often experienced in ASM, owing to ASM-mode signaling errors. Moreover, the selection of TPC parameters is more flexible than that of ASM because the modulation orders of ASM are selected from a discrete set, whereas the TPC parameters are chosen from the complex-valued field. As expected, the performance gain of the proposed scheme over ASM is seen to be about 2 dB at FER $= 10^{-3}$ in Fig. 7.

V. Conclusion

In this paper, we have investigated the problem of designing APM constellations that minimize the SM system's ABEP. We considered a class of star-QAM constellations, which is

[3]Here, we assume that the channel matrix remains constant within each transmit frame and consider the FER performance of these schemes. Note that the ASM schemes often suffer from error-propagation effects, as indicated in Section I. Hence, using the FER comparison of the ASM and TPC-aided SM schemes may be more suitable than the BER metric.

capable of flexibly adapting the ring ratios. We formulated the constellation design problem as an optimization problem and conceived an efficient iterative constellation-optimization method. Moreover, a diagonal TPC technique was proposed for the optimized star-QAM-aided SM to attain an improved performance. The simulation results confirm that our proposed optimized star-QAM-aided SM scheme outperforms the conventional PSK/QAM schemes. Moreover, our TPC method also exhibits an attractive BER/FER performance. For achieving an improved performance for a high number of bits per symbol, our further work will be focused on the integration of GSM and channel coding into the proposed TPC schemes.

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