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 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 PSK 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 also be 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 been proposed 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 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 the 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], [23].
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 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.

According to 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 ratio and hence subsuming classic PSK as a special case. Alternatively, if the 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 ratio of the 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 \( P \) 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 \( x \) is assumed to satisfy \( E[|x|^2] = 1 \), where \( x \) denotes an \((N_t \times N_r)\)-element identity matrix. Then, the transmitted SM symbol \( y \in \mathbb{C}^{N_r \times 1} \) is given as \( y = s_i^x e_n \) [21], where \( s_i^x \) is the complex-valued symbol of the APM scheme employed at the \( n \)-th TA. For 152 example, \( \text{L-PSK/QAM} \) is associated with \( m_{APM} = \log_2(L) \) input bits, whereas \( e_n \) for \( 1 \leq n \leq N_t \) is selected from the \( N_t \)-dimensional standard basis vectors (i.e., \( e_1 = [1, 0, \ldots, 0]^T \)), 155 according to \( \log_2(N_t) \) input bits. The corresponding received signal is given by

\[
y = Hx + n = h_n s_i^x + n
\]

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

In [11], an improved union bound partitions the ABEP expression of SM-MIMO systems into three terms: the \( P_{\text{spatial}} \) term related to the TA index, the \( P_{\text{signal}} \) term related to the APM 163 signals, and the joint term \( P_{\text{joint}} \), which depends on both the TA 164 index and on the APM signals. This bound is formulated as

\[
P_{\text{SM}}(\rho) \leq P_{\text{spatial}}(\rho) + P_{\text{signal}}(\rho) + P_{\text{joint}}(\rho).
\]

This improved union bound is more accurate than the 166 conventional union-bound-based methods, hence facilitating a 167 deeper understanding of the joint impact of spatial and APM 168 signals, as illustrated in [11]. We focus our attention on the sys- 169 tem’s performance for transmission over i.i.d. Rayleigh fading 170 channels, which may be readily extended to the Nakagami-m 171 fading model of [11]. Let us assume that \( \rho \) is the average SNR, whereas \( x_t \) and \( x_l \) represent two different APM constellation 172 points, with their modulus values being given as \( \beta_x \) and \( \beta_l \), 173 respectively. Then, we have

\[
P_{\text{signal}}(\rho) = \frac{\log_2(L)}{\log_2(N_r \cdot L)} P_{\text{APM}}(\rho)
\]

\[
P_{\text{spatial}}(\rho) = \frac{\log_2(N_t) N_t}{2L \log_2(N_r \cdot L)} \sum_{l=1}^{L} \mathcal{F} \left( \rho \beta_l^2 \right)
\]

\[
P_{\text{joint}}(\rho) = A \sum_{l=1}^{L} \sum_{l \neq l'} \left[ B + C \mathcal{D}_H (x_t \rightarrow x_l) \right] \times \mathcal{F} \left( \rho \beta_l^2 + \beta_l^2 \right)
\]

Here, \( P_{\text{APM}}(\rho) \) represents the error probability of conventional 176 L-APM, which depends on the ED of the constellation points 177 of APM, whereas \( D_H (x_t \rightarrow x_l) \) is the Hamming distance 178 between signals \( x_t \) and \( x_l \). Here, \( A = 1/L \log_2(N_r \cdot L) \), \( B = 179 \frac{N_t \log(N_t)}{2} \), and \( C = (N_t - 1) \) are constants for a fixed 180
1. **TABLE I**

<table>
<thead>
<tr>
<th>Modulation order</th>
<th>$2$</th>
<th>$4$ (MMD)</th>
<th>$8$ (MMD)</th>
<th>$16$ (MMD)</th>
<th>$32$ (MMD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSK</td>
<td>$2$</td>
<td>$\sqrt{2}$</td>
<td>$0.7654$</td>
<td>$0.3902$</td>
<td>$0.1960$</td>
</tr>
<tr>
<td>QAM</td>
<td>-</td>
<td>$\sqrt{2}$</td>
<td>$0.8165$</td>
<td>$0.6325$</td>
<td>$0.4082$</td>
</tr>
<tr>
<td>Proposed star-QAM</td>
<td>$2$</td>
<td>$\sqrt{2}$</td>
<td>$0.9134$</td>
<td>$0.5737$</td>
<td>$0.3952$</td>
</tr>
</tbody>
</table>

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 $\beta_l$ ($l = 1, \ldots, L$), which is achieved by simply adjusting a single parameter $\alpha$, whereas $\beta_l$ can assume two values because only two rings are considered.
- The ABEP of star-QAM, which is related to the $P_{\text{spatial}}$ 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 $\alpha$ of the star-QAM constellation, for a given MIMO setup, specified by the total number of bits per symbol $m_{\text{all}}$, the $(N_r \times N_t)$ configuration of transceiver, and the number of modulation level $L$. The goal of star-QAM-aided signaling constellation optimization is to find the specific ring ratio $\alpha$, which minimizes the ABEP of the SM-MIMO of (2). Note that, although the term $P_{\text{SM}}(\rho | \alpha)$ in (2) cannot be directly represented by parameter $\alpha$, it varies as a function of $\alpha$, which may be formulated as $P_{\text{SM}}(\rho | \alpha)$. Following the aforementioned approach, we formulated this optimization problem as

\[
\begin{align*}
\{ \alpha^* = \min_{\alpha} & \ P_{\text{SM}}(\rho | \alpha) \\
\text{s.t. } & \alpha \geq 1
\end{align*}
\]

which may be a convex one for a fixed SNR value $\rho$, 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 $P_{\text{signal}}, P_{\text{joint}}$, and $P_{\text{spatial}}$ 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 $N_r, N_t, m_{\text{all}}, L$, and the SNR value $\rho$. 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.

**Step 2:** We then set the search area of $\alpha$ to $1 \leq \alpha \leq U_\alpha$ and the performance metric to $P_{\text{iter}}(n) = 0$. 

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*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.*
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 new 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.

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 305 advantages of SM, such as the avoidance of the interantenna interference and the reliance on a single RF chain, because the 307 precoded transmit vector $Px$ includes only a single nonzero 308 component; hence, only a single TA is activated in each time 309 slot, as indicated in (8).

Numerous techniques may be invoked for constructing the 311 TPC $\mathbf{P}$ [21], [25]. In this paper, similar to the preceding 312 methods conceived for the orthogonalized spatial multiplexing 313 of [31], we decompose $\mathbf{P}$ as

$$\mathbf{P} = \mathbf{P}_\Theta = \text{diag}\{\hat{p}_1e^{j\theta_1}, \ldots, \hat{p}_ne^{j\theta_n}, \ldots, \hat{p}_{N_t}e^{j\theta_{N_t}}\}$$

where $\mathbf{P} = \{\hat{p}_1, \ldots, \hat{p}_n, \ldots, \hat{p}_{N_t}\}$ is the PA matrix, whereas $\Theta = \{e^{j\theta_1}, \ldots, e^{j\theta_n}, \ldots, e^{j\theta_{N_t}}\}$ is the phase 316 rotation matrix. The FD between the constellation points at the 317 receiver is defined as

$$d_{\min}(H, \mathbf{P}) = \min_{x_i, x_j} \|H \mathbf{P}(x_i - x_j)\|_F$$

$$= \min_{e_{ij} \in \mathbb{E}} \|H \mathbf{P}_E e_{ij}\|_F$$

where $\mathbb{E}$ is the set of all legitimate transmit symbols, $e_{ij} = 319 x_i - x_j$, $i \neq j$ denotes the error vector, and $\mathbb{E}$ is a set of error 320 vectors. Then, we design the TPC $\mathbf{P}$ by maximizing the FD 321 with the aid of the following criterion:

$$\mathbf{P}_{\text{opt}} = \arg \max_{\mathbf{P}} d_{\min}(H, \mathbf{P})$$

$$\text{s.t. } \sum_{n=1}^{N_t} |p_n|^2 = N_t; \quad p_n \in C; \quad \theta_n \in [0, 2\pi]; \quad n = 1, \ldots, N_t.$$  

Note that, since the attainable performance of the optimum 323 single-stream ML receiver depends on the FD of the received 324 signal constellation [30], the maximization of the FD directly 325 reduces the probability of error. Let $x_i = s_i^k e_j$ and $x_j = s_j^k e_j$ denote two different transmit symbols, whereas $s_i^k$ and $s_j^k$ denote the constellation points $l$ and $k$ represented by the $i$th 328 and $j$th antennas, respectively. Then, the FD of (11) can be 329 represented as (13), where $\phi = \angle(s_i^k) - \angle(s_j^k)$. In 330

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
$|s_k^j|$, $|s_i^j|$, and $\phi$ of (13), shown at the bottom of the page, are
dynamically adapted to the channel conditions, and the legiti-
mate 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 $|p_i|$, $|p_j|$, $\theta_i$, and $\theta_j$ of (13) for maximizing the FD $d_{\text{min}}(H, P)$, 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 $P$, 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
375 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 con-
sidered, 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. 3.367
To be specific, given the channel matrix $H$, the indexes of
the TA pair $(g, k)$ associated with the FD $d_{\text{min}}(H)$ 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
366 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 $H$ and of the optimal transmit parameters involves an
exhaustive search over the vast design space of $\tilde{p}_g$, $\tilde{p}_k$, $\theta_g$, and $\theta_k$ of (10), which is overly complex. To reduce the complexity, according to (12), the power of the TA pair $(g, k)$ satisfies the constraint $\tilde{p}_g^2 + \tilde{p}_k^2 = 2$; hence, only the element $\tilde{p}_k$ has to be searched for in the power matrix $P$ of (10). Moreover, since $\tilde{p}_g$ 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 $\tilde{p}_k$.

![Fig. 3. Calculation of the diagonal precoding matrix for star-QAM-aided SM-MIMO.](534x722)
420 \theta_g$. This implies that only the phase parameter $\theta_g$ has to be 421 optimized for the phase matrix $\Theta$. In Fig. 3, a numerical search 422 is used for varying $\bar{p}_g$ and $\theta_g$ in small steps. Note that we 423 have $0 \leq \bar{p}_g \leq \sqrt{2}$ and $0 \leq \theta_g \leq 2\pi$ according to (12). For our 424 numerical search, we have assumed

\begin{align}
\bar{p}_g &= \sqrt{2}/V_1 \ast v_1, \quad v_1 = 0, \ldots, V_1 \\
\theta_g &= 2\pi/V_2 \ast v_2, \quad v_2 = 0, \ldots, V_2
\end{align}

(14)

where $V_1$ and $V_2$ represent the number of quantization steps and 428 can be flexibly selected according to the prevalent performance 429 requirements. As a result, the corresponding diagonal TPC 430 matrix candidates are

$$P_{\text{cand}} = \text{diag} \left\{ 1, \ldots, \bar{p}_g e^{j\theta_g}, \ldots, \sqrt{2} - \bar{p}_g^2, \ldots, 1 \right\}$$

(15)

Upon denoting the quantized TPC matrix $P$ as $P_{\text{cand}}$, the 435 optimization problem of (12) is reformulated as

$$P_{\text{opt}} = \arg \max_{\{P \in P_{\text{cand}} : \Pi_1\}} d_{\text{min}}(H, P).$$

(16)

where we have $P_1 = I_{N_t}$. In (16), the FD of the TPC matrices 438 $P_{\text{cand}}$ generated will be compared with that of the conventional 439 scheme associated with $P_1$, and then we select the one having 440 the largest FD as our final result. The receiver determines the 441 optimal diagonal TPC matrix based on (16) and feeds back the 442 TA indexes and their TPC parameters to the transmitter. Since 443 only the specific TA pair, which predominantly determines 444 the achievable performance, is considered, the proposed low- 445 complexity algorithm can be readily extended to a high number 446 of TAs.

IV. SIMULATION RESULTS

Here, we characterize the performance of both the proposed 450 star-QAM-aided SM scheme and of the corresponding TPC 451 scheme, and compare it with that of the conventional QAM- 452 modulated SM schemes, with the PSK-modulated SM schemes 453 and with the ASM schemes [15] for transmission over inde- 454 pendent Rayleigh block-flat MIMO channels. It is assumed that 455 the receiver is capable of perfect phase and gain tracking, i.e., 456 of perfect channel estimation. In practice, pilot symbols are 457 used for estimating the MIMO channel; hence, the estimated 458 channel matrix will inevitably be imperfect. To alleviate the 459 effects of channel estimation errors, the joint channel estimation 460 and data detection algorithm of [32] may be considered in the 461 proposed schemes, where the channel estimator and the data 462 detector iteratively exchange their information. We consider 463 two practical MIMO systems here, namely, $(2 \times 2)$ and $(4 \times 4)$ MIMO systems. Moreover, in the TPC design algorithm, we 464 select $V_1 = V_2 = 5$ for simplicity.\footnote{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 shows the optimal ring ratios of star-QAM-aided 465 SM relying on $(4 \times 4)$ elements for a different number of 466 modulation levels $L$, where the optimal ring ratio $\alpha^*$ is seen 467 to be a function of the SNR. The bound of (2) is well suited 468 for numerically optimizing the ring ratio, particularly in the 476 high-SNR region. Observe in Fig. 4 that the optimal ratios 477 approach their asymptotic values, as the SNR increases. This 478 is expected since the bound of (2) is also asymptotically tight 479 and the probability of an error event in slow fading associated 480 with ML detection is dominated by the minimum-distance error 481 event at high values of the SNR. Moreover, the optimal ring 482 ratios are different for different MIMO parameters.

Since the transmitter operates at a fixed ring ratio, we have 483 opted for the asymptotic ring-ratio value for the evaluation 484 of the BER. For example, we have chosen the optimal ring 485 ratio $\alpha^* = 1.7$ for the 16-star-QAM-aided $(4 \times 4)$ SM-MIMO, 486 according to the results in Fig. 4. This result may be readily 487 extended to other star-QAM-aided SM scenarios, such as the $(4 \times 4)$-element star-QAM-aided SM schemes using $L = 4, 8$ in 488 Fig. 4.

In Figs. 5 and 6, we compare various SM-MIMO systems 489 relying on diverse MIMO parameters and modulation orders. 490 First, in Figs. 5 and 6, we depict the BER performance 491 of the conventional QAM-modulated SM schemes, of the 492 PSK-modulated SM arrangements, and of the proposed star- 493 QAM-aided SM scheme. Note that the optimized star-QAM 494 constellation is designed offline for different SM-MIMO sys- 495 tems. Hence, the resultant system does not need any feedback. 496 To be specific, we may create a parameter lookup table for 497 the star-QAM SM schemes associated with the MIMO setups 498 considered; hence, the complexity of the optimal ring-ratio 499 search process detailed in Section II is negligible. For com- 500 pluteness, we also included the theoretical upper bound [30] 501 for the family of conventional SM schemes. We found that 502 the conventional QAM-modulated SM scheme outperforms its 503 identical-throughput PSK counterpart for a $(4 \times 4)$-element 504 star-QAM channel in Fig. 5, whereas the PSK scheme is preferred 505 for a $(2 \times 2)$-element MIMO channel in Fig. 6. This indicates 506 that the best choice of the APM scheme depends on the specific 507 SM parameters, such as the MIMO setup and throughput. 508 Moreover, as shown in Fig. 5, the optimized star-QAM-aided 509 SM scheme provides an SNR gain of about 3 dB at BER $= 10^{-3}$ 510 over the conventional 16-PSK-modulated SM scheme and 465 511 an SNR gain of about 1.1 dB over the identical-throughput 466
Fig. 5. BER performance of various SM-MIMO schemes operating in a \((4 \times 4)\) 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, \(\alpha\) is chosen as \(\alpha = 1.7\).

Fig. 6. BER performance of various SM schemes operating in \((2 \times 2)\) MIMO channel at a total throughput of 4 b/s. Here, \(\alpha\) 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 \((4 \times 4)\)-element SM using 16-PSK and \((2 \times 2)\)-element SM employing 8-QAM. Note that the \((4 \times 4)\)-element SM associated with 16-QAM and \((2 \times 2)\)-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.

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. 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 510 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 513 complex-valued field. As expected, the performance gain of the proposed scheme over ASM is seen to be about 2 dB at \(\text{FER} = 10^{-3}\) 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.

### References


Available: http://reprints.soton.ac.uk/354175/


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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

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.

END OF ALL QUERIES
Star-QAM Signaling Constellations for Spatial Modulation

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Mohammed El-Hajjar, Member, IEEE, and Lajos Hanzo, Fellow, IEEE

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) 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

S

PATIAL 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 also be 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 62 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)
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 rely 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.

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 $P$ 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 $(N_t \times 147)$-element transmit symbol vector $x$ is assumed to satisfy $E[|x|^2]=1$, where $N_x$ denotes an $(N_t \times N_t)$-element identity matrix. Then, the transmitted SM symbol $x \in \mathbb{C}^{N_t \times 1}$ is given as $x = s^n \epsilon_n$ [21], where $s^n$ is the complex-valued 151 symbol of the APM scheme employed at the $n$th TA. For 152 example, $L$-PSK/QAM is associated with $m_{APM} = \log_2(L)$ 153 input bits, whereas $\epsilon_n (1 \leq n \leq N_t)$ is selected from the $N_t$ 154 dimensional standard basis vectors (i.e., $\epsilon_1 = [1, 0, \ldots, 0]^T$), 155 according to $\log_2(N_t)$ input bits. The corresponding received 156 signal is given by

$$y = Hx + n = h_n s^n + n$$

where $H$ is an $(N_t \times N_t)$-element channel matrix, $h_n$ is the 158 $n$th column of $H$, and the elements of the $N_t$-dimensional noise 159 vector $n$ are Gaussian random variables obeying $CN(0, N_0)$.

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

$$P_{\text{SM}}(\rho) \leq P_{\text{spatial}}(\rho) + P_{\text{signal}}(\rho) + P_{\text{joint}}(\rho).$$

This improved union bound is more accurate than the 166 conventional union-bound-based methods, hence facilitating a 167 deeper understanding of the joint impact of spatial and APM 168 signals, as illustrated in [11]. We focus our attention on the sys- 169 tem’s performance for transmission over i.i.d. Rayleigh fading 170 channels, which may be readily extended to the Nakagami-$m$ 171 fading model of [11]. Let us assume that $\rho$ is the average SNR, 172 whereas $x_l$ and $x_l$ represent two different APM constellation 173 points, with their modulus values being given as $\beta_l$ and $\beta_l$, 174 respectively. Then, we have

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

$$P_{\text{spatial}}(\rho) = \frac{\log_2(N_t) N_t}{2L \log_2(N_t \cdot L)} \sum_{l=1}^{L} f(\rho \beta_l^2)$$

$$P_{\text{joint}}(\rho) = \sum_{l=1}^{L} \sum_{i \neq l}^{L} [B + CD_H (x_l \rightarrow x_i)] \times f\left(\frac{\rho}{2} \left(\beta_l^2 + \beta_i^2\right)\right).$$

Here, $P_{\text{APM}}(\rho)$ represents the error probability of conventional 176 $L$-APM, which depends on the ED of the constellation points 177 and the corresponding $D_H (x_l \rightarrow x_i)$ is the Hamming distance 178 between signals $x_l$ and $x_i$. Here, $A = 1/L \log(N_t \cdot L)$, $B = 179 N_t \log(N_t)/2$, and $C = (N_t - 1)$ are constants for a fixed 180
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 \( d_{\text{min}} \) and \( \beta_l = \{ 231, 1, \ldots, L \} \) combinations, which is achieved by simply adjusting a single parameter \( \alpha \), whereas \( \beta_l \) can assume two values because only two rings are considered.
- The ABEP of star-QAM, which is related to the \( P_{\text{spatial}} \) 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 \( \alpha \) of the star-QAM constellation, for a given MIMO setup, specified by the total number of bits per symbol \( m_{\text{all}} \), the \((N_r \times N_t)\) configuration of transceiver, and the number of modulation level \( L \). The goal of star-QAM-aided signaling constellation optimization is to find the specific ring ratio \( \rho, \alpha \) which minimizes the ABEP of the SM-MIMO of (2). Note that, although the term \( P_{\text{SM}}(\rho, \alpha) \) in (2) cannot be directly represented by parameter \( \alpha \), it varies as a function of \( \alpha \), which may be formulated as \( P_{\text{SM}}(\rho, \alpha) \). Following the aforementioned approach, we formulated this optimization problem as

\[
\begin{align*}
\alpha^* &= \min_{\alpha} P_{\text{SM}}(\rho, \alpha) \\
&\text{s.t. } \alpha \geq 1
\end{align*}
\]

which may be a convex one for a fixed SNR value \( \rho \), 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 \( P_{\text{signal}}, P_{\text{joint}} \), and \( P_{\text{spatial}} \) 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 \( N_r, N_t, m_{\text{all}}, L \), and the SNR value \( \rho \). 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 \( \alpha \) to \( 1 \leq \alpha \leq U_\alpha \) and the performance metric to \( P_{\text{iter}}(n) = 0 \).

---

**Table I**

<table>
<thead>
<tr>
<th>Modulation order</th>
<th>2</th>
<th>4 (MMD)</th>
<th>8 (MMD)</th>
<th>16 (MMD)</th>
<th>32 (MMD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSK</td>
<td>2</td>
<td>( \sqrt{2} )</td>
<td>0.7654</td>
<td>0.3902</td>
<td>0.1960</td>
</tr>
<tr>
<td>QAM</td>
<td>-</td>
<td>( \sqrt{2} )</td>
<td>0.8165</td>
<td>0.6325</td>
<td>0.4082</td>
</tr>
<tr>
<td>Proposed star-QAM</td>
<td>2</td>
<td>( \sqrt{2} )</td>
<td>0.9134</td>
<td>0.5737</td>
<td>0.3952</td>
</tr>
</tbody>
</table>

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**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.

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

\[
F(\varepsilon) = \gamma(\varepsilon)^{N_r} \sum_{n=0}^{N_r-1} \left( \frac{N_r - 1 + n}{n} \right) [1 - \gamma(\varepsilon)]^n \tag{6}
\]

where we have \( \gamma(\varepsilon) = (1/2)(1 - \sqrt{\varepsilon/2 + \varepsilon}) \). 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 \( P_{\text{signal}} \) is available in closed form for conventional APM modulation schemes, the bound of (2) is more accurate than the conventional results of [21].

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

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

187 To make the choice of the APM parameters \( d_{\text{min}} \) and \( \beta_l \) 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 \( \alpha = r_2/r_1 \), 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 [24].

189 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 \( d_{\text{min}} \) between the constellation points for different APM schemes. It is found that this star-QAM scheme is capable of achieving almost the same performance as the MMD-based QAM.

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194 - The ABEP of star-QAM, which is related to the \( P_{\text{spatial}} \) term of (3), has been documented in [28] and [29].

196 In (3)–(5), \( \varepsilon(\varepsilon) \) of the APM constellation points, whereas \( \gamma(\varepsilon) \) mainly depends on the modulus values \( \beta_l \) of APM. (Note that the modulus values \( \beta_l \) are represented by the Frobenius norms of the APM constellation points. These results suggested that, for jointly minimizing \( P_{\text{signal}}, P_{\text{joint}}, \) and \( P_{\text{spatial}} \), we can focus our attention on the design of \( d_{\text{min}} \) and \( \beta_l \) of APM.)

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where $p_n$ controls the channel gain associated with $x_n$. Here, 303 we let $\sum_{n=1}^{N} |p_n|^2 = N_t$ for normalizing the transmit power. 304 Note that the introduction of TPC in SM does not affect the 305 advantages of SM, such as the avoidance of the interantenna 306 interference and the reliance on a single RF chain, because the 307 precoded transmit vector $Px$ includes only a single nonzero 308 component; hence, only a single TA is activated in each time 309 slot, as indicated in (8). 310

Numerous techniques may be invoked for constructing the 311 TPC $P$ [21], [25]. In this paper, similar to the preceding 312 methods conceived for the orthogonalized spatial multiplexing 313 of [31], we decompose $P$ as

$$P = P\Theta = \text{diag}\{p_1e^{j\theta_1}, \ldots, p_ne^{j\theta_n}, \ldots, p_{N_t}e^{j\theta_{N_t}}\}$$

(10)

where $\hat{P} = \text{diag}\{p_1, \ldots, p_n, \ldots, p_{N_t}\}$ represents the PA matrix, whereas $\Theta = \text{diag}\{e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_{N_t}}\}$ is the phase 316 rotation matrix. The FD between the constellation points at the 317 receiver is defined as

$$d_{\min}(H, P) = \min_{x_i, x_j \in \mathbb{X}} \|HP(x_i - x_j)\|_F$$

(11)

where $\mathbb{X}$ is the set of all legitimate transmit symbols, $e_{ij} = 319 x_i - x_j, i \neq j$ denotes the error vector, and $\mathbb{E}$ is a set of error vectors. Then, we design the TPC $P$ by maximizing the FD with the aid of the following criterion:

$$\begin{align}
\begin{cases}
P_{\text{opt}} = \arg \max_P d_{\min}(H, P) \\
s.t. \quad \sum_{n=1}^{N_t} |p_n|^2 = N_t; \quad p_n \in C; \\
\theta_n \in [0, 2\pi]; \quad n = 1, \ldots, N_t.
\end{cases}
\end{align}$$

(12)

Note that, since the attainable performance of the optimum 322 single-stream ML receiver depends on the FD of the received 324 signal constellation [30], the maximization of the FD directly 325 reduces the probability of error.\footnote{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.}

Let $x_i = s_i^k e_i$ and $x_j = s_j^k e_j$ denote two different transmit symbols, whereas $s_i^k$ and $s_j^k$ denote the constellation points $l$ and $k$ represented by the $i$th and $j$th antennas, respectively. Then, the FD of (11) can be represented as (13), where $\phi = \mathcal{L}(s_i^k)^*s_j^k = -(s_i^k)^*(s_j^k)^*$. In 330
the ASM scheme of [7], only the APM modulation orders to be used by the transmitter are adapted, i.e., only the elements $|s_l^g|$, $|s_k^g|$, and $\phi$ 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 $|p_l|$, $|p_j|$, $\theta_i$, and $\theta_j$ of (13) for maximizing the FD $d_{\text{min}}(H, P)$, 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.

### 3.4.7 B. Low-Complexity TPC Design Algorithm

To identify the specific TPC matrix $P$, 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 $H$, the indexes of the TA pair $(g, k)$ associated with the FD $d_{\text{min}}(H)$ 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 $H$ and of the optimal transmit parameters involves an exhaustive search over the vast design space of ${\bar{p}_g, \bar{p}_k, \theta_g, \theta_k}$, and $\theta_h$ of (10), which is overly complex. To reduce the complexity, according to (12), the power of the TA pair $(g, k)$ satisfies the constraint $\bar{p}_g^2 + \bar{p}_k^2 = 2$; hence, only the element $\bar{p}_k$ has to be searched for in the power matrix $P$ of (10). Moreover, since $\theta_k$ the phase rotation of the symbol is only carried by two TAs 381 and their phase difference is correlated, we can simplify the computations by fixing $\theta_k = 1$ and then finding the optimal $\theta_g$.

The calculation of the diagonal precoding matrix for star-QAM-aided SM-MIMO.

$$
\begin{align*}
    d_{\text{min}}(H, P) &= \min_{s_l^g, s_k^g \in S} \left\| H P \left( s_l^g e_l - s_k^g e_j \right) \right\|_F \\
    &= \min_{s_l^g, s_k^g \in S} \left\| (h_p s_l^g - h_j s_k^g) \right\|_F \\
    &= \min_{s_l^g, s_k^g \in S} \sqrt{|s_l^g|^2 |p_l|^2 h_l^H n_l + |s_k^g|^2 |p_j|^2 h_j^H n_j - 2 |p_l| |p_j| s_l^g s_k^g \Re \{ h_l^H h_j e^{j(\phi - \theta_l + \theta_j)} \}} \\
    &= d_{\text{min}}(H, P) \\
    &> d_{\text{min}}(H) \\
    &< d_{\text{min}}(H)
\end{align*}
$$

Fig. 3. Calculation of the diagonal precoding matrix for star-QAM-aided SM-MIMO.
This implies that only the phase parameter $\theta_y$ has to be optimized for the phase matrix $\Theta$. In Fig. 3, a numerical search is used for varying $\tilde{p}_y$ and $\theta_y$ in small steps. Note that we have $0 \leq \tilde{p}_y \leq \sqrt{2}$ and $0 \leq \theta_y \leq 2\pi$ according to (12). For our numerical search, we have assumed

$$
\begin{align*}
\tilde{p}_y &= \sqrt{2}/V_1 \ast v_1, \quad v_1 = 0, \ldots, V_1 \\
\theta_y &= 2\pi/V_2 \ast v_2, \quad v_2 = 0, \ldots, V_2
\end{align*}
$$

(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

$$
P_{\text{cand}} = \text{diag}\left\{1, \ldots, \tilde{p}_y e^{j\theta_y}, \ldots, \sqrt{2 - \tilde{p}_y^2}, \ldots, 1\right\}
$$

$\uparrow$ $g$th $\uparrow$ $k$th. (15)

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

$$
P_{\text{opt}} = \arg\max_{\{P \in P_{\text{cand}}: P_1\}} d_{\min}(H, P).$$

(16)

where we have $P_1 = I_{N_t}$. In (16), the FD of the TPC matrices $P_{\text{cand}}$ generated will be compared with that of the conventional scheme associated with $P_1$, 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., 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 iterately exchange their information. We consider two practical MIMO systems here, namely, $(2 \times 2)$ and $(4 \times 4)$ 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 $(4 \times 4)$ elements for a different number of modulation levels $L$, where the optimal ring ratio $\alpha^*$ is seen to be a function of the SNR. The bound of (2) is well suited 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 $(4 \times 4)$ MIMO, according to the results in Fig. 4. This result may be readily extended to other star-QAM-aided SM scenarios, such as the $(4 \times 4)$-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. 444 First, in Figs. 5 and 6, we depict the BER performance of the conventional QAM-modulated SM schemes, of the conventional QAM-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 $(4 \times 4)$-element MIMO channel in Fig. 5, whereas the PSK scheme is preferred for a $(2 \times 2)$-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 466...
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, $\alpha$ 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, $\alpha$ 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.

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 benchmarks 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 510 selection of TPC parameters is more flexible than that of ASM 511 because the modulation orders of ASM are selected from a 512 discrete set, whereas the TPC parameters are chosen from the 513 complex-valued field. As expected, the performance gain of 514 the proposed scheme over ASM is seen to be about 2 dB at 515 $\text{FER} = 10^{-3}$ 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...
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 conv-
ventional 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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