Optimized Enhanced Spatial Modulation for Large-Scale MIMO Systems

Journal:	*IEEE Transactions on Vehicular Technology*
Manuscript ID	VT-2025-04226
Manuscript Type:	Correspondence
Date Submitted by the Author:	25-Jul-2025

Complete List of Authors:	Le, Minh-Tuan; Posts and Telecommunications Institute of Technology Nguyen, Long; Hanoi University of Science and Technology Nguyen, Thi Lien; Hanoi University of Science and Technology Nguyen, Hoa; Hanoi University of Science and Technology

Keywords:	MIMO systems, Modulation coding, Radio communication, Signal processing

Optimized Enhanced Spatial Modulation for Large-Scale MIMO Systems

Minh-Tuan Le, Hoang Khanh Long Nguyen, Thi Lien Nguyen, Tien Hoa Nguyen, *Member IEEE*

***Abstract*—Spatial Modulation (SM) and Enhanced Spatial Modulation (ESM) enhance MIMO efficiency by encoding information via antenna indices and signal constellations but face limitations due to rigid antenna selection and fixed constellation structures, reducing flexibility in large-scale MIMO. This paper introduces Optimized Enhanced Spatial Modulation (O-ESM), a new scheme utilizing single- and dual-antenna activation for 4TX, 8TX, and 16TX setups. O-ESM removes power-of-two constraints through a refined lookup table enabling flexible antenna group selection and features optimized constellations that lower signal point counts and average transmit energy. To boost detection performance, it maximizes the minimum Euclidean distance between codewords. Analysis and simulation results show that O-ESM surpasses conventional ESM and Multistream SM in Codeword Error Rate, SNR gain, and energy efficiency.**

***Index Terms*—Spatial Modulation (SM), MIMO, Multistream SM (MSM), Signal Design, Enhanced Spatial Modulation (ESM)**

I. Introduction

As wireless systems evolve toward large-scale MIMO and beyond-5G networks, achieving optimal spectral efficiency (SE) and energy efficiency (EE) becomes a critical challenge. Spatial Modulation (SM) encodes data through antenna indices, reducing interference and simplifying receiver design [1], but its one-antenna-per-slot operation limits SE in high-data-rate scenarios.

Enhanced Spatial Modulation (ESM) [2] addresses this by combining multiple constellations with antenna indexing, albeit at the cost of requiring an additional RF chain compared to SM [3]. However, existing ESM schemes typically adopt fixed constellation structures and impose power-of-two constraints on antenna selection, limiting flexibility. These constraints – allowing only 2, 4, 8, etc., antenna groups – hinder non-binary spatial encoding, reducing adaptability and potential throughput in large-scale MIMO systems.

Numerous efforts have been made to enhance SM and ESM schemes. For example, [4] proposed activating two antennas per symbol to boost throughput while maintaining low detection complexity. Antenna selection methods in [5], [6] improve performance under fading by dynamically choosing antennas based on channel state information (CSI), though they often assume ideal CSI, require feedback, or impose fixed activation patterns.

In modulation and constellation design, frequency-domain ESM in [7] improves capacity via subcarrier multiplexing but demands tight synchronization. [8] integrates frequency-phase modulation for greater signal diversity. Hybrid techniques in [9], [10] use constellation-pairing and code-index mapping to boost data density and detection reliability. [11] applies AI-driven adaptive antenna selection and constellation optimization to balance SE and EE. However, many approaches still rely on complex mappings or power-of-two antenna grouping constraints.

Classical space-time block codes [12] offer robust performance guarantees but are constrained by orthogonal structure requirements, making them less suitable for flexible MIMO architectures. For future-generation wireless systems, large-scale and dynamic MIMO configurations have gained interest. Spatial Modulation for Dynamic Metasurface Antennas [13] showcases significant improvements in SE and EE via adaptive spatial wavefront control. However, practical implementation remains challenging due to hardware complexity and real-time processing demands.

To overcome existing limitations in spatial modulation (SM) frameworks, especially under large-scale MIMO scenarios, we propose a more flexible and energy-efficient solution called *Optimized Enhanced Spatial Modulation (O-ESM)*. This novel scheme adopts dual-antenna activation and a scalable design approach, addressing the constraints of traditional ESM methods. Unlike previous schemes, O-ESM leverages all possible antenna combinations, removing the conventional power-of-two restriction on antenna group selection. Additionally, it introduces multiple secondary constellations derived from a single primary constellation to reduce the number of signal points and lower the average transmit power. The system embeds both antenna and constellation indices into a generalized look-up table, which is used to map input bits to transmitted codewords.

The key contributions of this work are as follows:

- A comprehensive antenna selection method that utilizes all valid combinations and integrates multiple secondary constellations, removing power-of-two limitations.
- A generalized look-up table design that maps information bits directly to codewords.
- A joint optimization framework for primary and secondary constellations to minimize signal points and transmission energy, while maximizing the minimum Euclidean distance between codewords. This leads to enhanced Codeword Error Rate (CER) performance under Rayleigh fading environments.

M.T Le is with the Posts and Telecommunications Institute of Technology (PTIT), Hanoi 12110, Vietnam. (Email: tuanlm@ptit.edu.vn.)

H.K.L Nguyen, T.L Nguyen and T.H Nguyen are with the School of Electrical and Electronic Engineering, Hanoi University of Science and Technology, Hanoi 100000, Vietnam. (Email: {Long.NHK210539, Lien.NT213762}@sis.hust.edu.vn, hoa.nguyentien@hust.edu.vn.)

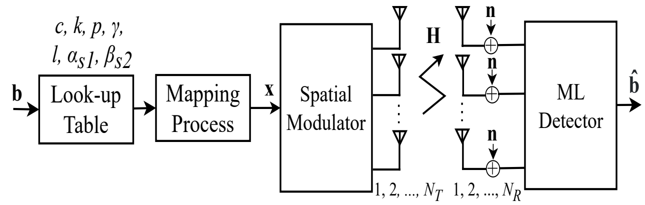

Fig. 1: System Model of proposed O-ESM Scheme

II. System Model and Problem Formulation

A. System Model

We consider an O-ESM MIMO system with N_T transmit antennas and N_R receive antennas, as illustrated in Fig. 1. The proposed scheme incorporates the conventional SM method, which activates one antenna per time slot and employs M-QAM modulation ($N_A = 1$). In addition, it also allows transmission with two activated antennas ($N_A = 2$), modulated with M_{s_1}-QAM and M_{s_2}-QAM, i.e., the tuple $(s_1, s_2) = (2\lambda+1, 2\lambda+2)$ where $\lambda \in 0, 1, 2$, respectively.

A look-up table first maps each c-bit binary input from the bitstream $\mathbf{b}$ to one of 2^c integer values, indexed by k. Then these are mapped one-to-one with the following parameters: antennas group selection indices p and l, primary constellation point indices γ, and secondary constellation point indices $\alpha_1, \beta_2, \alpha_3, \beta_4$ (and α_5, β_6 if $M = 64$). Every index is incremented along with k until its maximal value, and set to 0 whenever its respective spatial codeword or constellation is not in use. Therefore, the transmitted symbol codeword $\mathbf{x}$ can be represented as:

$$\mathbf{x} = [0, ..., 0, x_p^{\gamma}, 0, ..., 0]^T, \tag{1}$$

when $N_A = 1$, or:

$$\mathbf{x} = [0, ..., 0, x_m^{\alpha_{s_1}}, 0, ..., 0, x_n^{\beta_{s_2}}, 0, ..., 0]^T, \tag{2}$$

when $N_A = 2$. The codeword contains a total of N_T elements, with only the p^{th}, or m^{th} and n^{th} elements being non-zero, respectively $(m \neq n \mid 1 \leq (p, m, n) \leq N_T \mid (p, m, n) \in \mathbb{N})$. x_p^{γ} denotes the symbol that is encoded with the γ^{th} constellation point from the signal constellation Ω_M and transmitted from the p^{th} antenna. Likewise, the same applies to $x_m^{\alpha_{s_1}}$ and $x_n^{\beta_{s_2}}$ with signal constellations $\Omega_{M_{s1}}$ and $\Omega_{M_{s2}}$ $\big(1 \leq \gamma \leq M$ and $1 \leq \alpha_{s1} \leq M_{s_1}, 1 \leq \beta_{s2} \leq M_{s_2} \big| \, (\gamma, \alpha_{s1}, \beta_{s2}) \in \mathbb{N}\big)$.

For a MIMO system operating on a Rayleigh fading channel, the baseband received signal codeword at the receiver can be depicted as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{3}$$

where $\mathbf{H}$ denotes the $N_R \times N_T$ channel matrix with independent and identically distributed (i.i.d.) complex circularly symmetric Gaussian entries, $\mathcal{N}_c(0, 1)$. The codeword $\mathbf{x}$ represents the $N_T \times 1$ transmitted codeword vector, and $\mathbf{n}$ is the $N_R \times 1$ additive white Gaussian noise (AWGN) vector with i.i.d. entries distributed as $\mathcal{N}_c(0, N_0)$. The average transmit power is given by $P_t = \text{trace}(\mathbb{E}[\mathbf{x}\mathbf{x}^H])$, where $\mathbf{a}^H$ denotes the conjugate transpose of vector $\mathbf{a}$. Consequently, the average signal-to-noise ratio (SNR) is P_t/N_0.

TABLE I: Look-up Table For $N_T = 4$ and $c = 10$ bpcu

$\mathbf{b}$	k	p	γ	l	α_1	β_2	α_3	β_4
0000000000	1	1	1	0	0	0	0	0
0000000001	2	1	2	0	0	0	0	0
...	...	...	...	...	...	...	...	...
0000011111	64	4	16	0	0	0	0	0
0000100000	65	0	0	1	1	1	0	0
0000100001	66	0	0	1	1	2	0	0
...	...	...	...	...	...	...	...	...
1100111111	832	0	0	12	8	8	0	0
1101000000	833	0	0	1	0	0	1	1
1101000001	834	0	0	1	0	0	1	2
...	...	...	...	...	...	...	...	...
1111111111	1,024	0	0	12	0	0	4	4

The Maximum-Likelihood (ML) detector recovers the transmitted codeword by performing an exhaustive search for the codeword in the signal space $\mathbb{X}$ that minimizes the Euclidean distance to the received signal. Assuming perfect CSI at the receiver, it identifies the index $\hat{k}$ as:

$$\hat{k} = \arg\min_{\mathbf{x}_k \in \mathbb{X}} ||\mathbf{y} - \mathbf{H}\mathbf{x}_k||^2. \tag{4}$$

The estimated bitstream $\hat{\mathbf{b}}$ is then retrieved via the look-up table using $\hat{k}$.

B. Problem Formulation

The O-ESM system aims to maximize the minimum Euclidean distance between any two signal codewords, denoted by $D_{\min}$, thereby improving the CER performance compared to MSM and multi-stream ESM methods, especially ESM-Type 2 [3]. This improvement is only achievable if the minimum Euclidean distance δ_0 between constellation points in each signal constellation is maximized, and the average energy per transmitted codeword, $\overline{E}_s$, is minimized. Given a spectral efficiency of c, this optimization problem can be formulated as follows:

$$\max_{\delta_0, \overline{E}_s} \; D_{\min} \tag{5a}$$

$$\text{s.t.} \; \max_{s \in \mathcal{S}} \delta_0 \;\; \forall \Omega_M, \Omega_{M_s} \tag{5b}$$

$$\delta_1 \geq \delta_0/\sqrt(2) \;\; \forall \Omega_M, \Omega_{M_s} \tag{5c}$$

$$\min_{s \in \mathcal{S}} M_s \;\; \forall \Omega_{M_s} \tag{5d}$$

$$\overline{E}_s < \overline{E}_s^{\text{ESM-Type2}}, \tag{5e}$$

where $\overline{E}_s = \frac{1}{2^c} \sum_{i=1}^{2^c} \mathbf{x}_i^H \mathbf{x}_i$, and $\mathbf{x}_i$ is the i^{th} codeword in the signal space, $\mathbb{X}$, consisting of 2^c signal codewords. The constraint in (5b) ensures that δ_0 is preserved within both the primary constellation and the additional secondary constellations Ω_{M_s}, indexed by $s \in \mathcal{S} = \{1, 2, 3, 4, 5, 6\}$. Furthermore, these secondary constellations, generated through interpolation of the primary constellation points, guarantee a minimum distance of $\delta_1 \geq \delta_0/\sqrt{2}$, as specified in (5c), between the two constellations used when $N_A = 2$.

Unlike most previous works (e.g., [2] and [7]), which require a power-of-two number of antenna group selections to represent spatial information bits, our design approach removes the constraint and maximizes this number thanks to the use of the look-up table, thereby reducing the reliance on large constellations (5d) and lowering $\overline{E}_s$ as a result. Section III analyzes specific cases of the look-up table along with the proposed constellation designs, and further elaborates on how optimizing δ_0 and $\overline{E}_s$ leads to the desired optimal $D_{\min}$.

III. Optimized ESM (O-ESM) Scheme Design

A. O-ESM Constellation Design

In this section, we focus on the design of the signal constellations and the antenna group selections, depicted through the spatial codeword space $\mathbb{S}_{\text{single}}$ and $\mathbb{S}_{\text{dual}}$, with respect to the aforementioned optimization problem. This forms the basis for the design philosophy of the proposed scheme.

Regarding the case of a 4TX and $c = 10$ bits per channel use (bpcu) system, we would utilize the primary constellation of 16-QAM, and the secondary constellation tuple Ω_{M_s} in this case is that of 4 constellations (P_8, Q_8, R_4, S_4). The Look-up Table for 4TX with $c = 10$ bpcu can be represented in Table I. In single-antenna mode ($N_A = 1$), there are $N_{\text{SSC}} = N_T = 4$ possible antenna selections, with $1 \leq p \leq N_{\text{SSC}}$. In dual-antenna mode ($N_A = 2$), the number of antenna group selections become:

$$N_{\text{DSC}} = \frac{N_T!}{(N_T - N_A)!}, \tag{6}$$

with $1 \leq l \leq N_{\text{DSC}}$.

As $N_A = 1$, the only active antenna transmits a symbol from the primary constellation Ω_M. For the primary constellation Ω_{16}, the codeword $\mathbf{x}_k$ is constructed as:

$$\mathbf{x}_k = \mathbf{S}_p \times x^{\gamma}, \quad \forall k \leq (N_T \times M), \tag{7}$$

where:

$$\mathbf{S}_p \in \mathbb{S}_{\text{single}} = \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}. \tag{8}$$

For $N_A = 2$, the codeword $\mathbf{x}_k$ is given by:

$$\mathbf{x}_k = \mathbf{S}_l \times \begin{bmatrix} x^{\alpha_{s_1}} \\ x^{\beta_{s_2}} \end{bmatrix}, \quad \forall k > (N_T \times M), \tag{9}$$

where $(x_m^{\alpha_{s_1}}, x_n^{\beta_{s_2}}) \in (\Omega_{M_{s_1}}, \Omega_{M_{s_2}})$ and

$$\mathbf{S}_l \in \mathbb{S}_{\text{dual}} = \left\{ \begin{matrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 1 & 0 \\ 0 & 0 \end{bmatrix} \\ \begin{bmatrix} 0 & 1 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix} \end{matrix} \right\}. \tag{10}$$

As mentioned earlier, the secondary constellations are geometrically interpolated from the original primary constellation Ω_M. In fact, our design further reduces the average symbol energy $\overline{E}_s$ by reusing the same low-energy points across different constellations, resulting in overlapping points within the constellation space. The designed signal constellations are illustrated in Fig. 2 for $M = 16$ and $M = 64$.

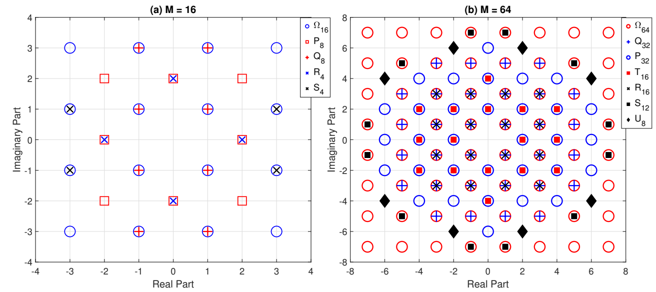

Fig. 2: Designed constellations for (a) $M = 16$ and (b) $M = 64$.

For $M = 16$, the secondary signal constellation Q_8 is the conventional 8-QAM defined as $Q_8 = \{\pm 1 \pm 1i, \pm 1 \pm 3i\}$, while P_8, R_4, and S_4 are represented as follows:

$$\begin{aligned} P_8 &= \{R_4, \pm 2 \pm 2i\}, \\ R_4 &= \{\pm 2, \pm 2i\}, \\ S_4 &= \{\pm 3 \pm 1i\}. \end{aligned}$$

In this case, two active antennas simultaneously transmit symbols from different secondary constellations. Specifically, for the constellation pair (P_8, Q_8), one antenna transmits symbols from the P_8 constellation, while the other transmits symbols from Q_8. Similarly, for the pair (R_4, S_4), the two active antennas transmit symbols from R_4 and S_4, respectively.

Likewise, for $M = 64$ and $c = 14$ bpcu, the codeword $\mathbf{x}_k$ is generated using the same procedure and the same sets $\mathbb{S}_{\text{single}}$ and $\mathbb{S}_{\text{dual}}$, albeit with six secondary constellations: Q_{32} is a conventional 32-QAM, R_{16} is a conventional 16-QAM, and the remaining four constellations, P_{32}, S_{12}, T_{16}, and U_8, are defined as follows:

$$\begin{aligned} P_{32} &= \{T_{16}, \pm 6, \pm 6i, \ \pm 2 \pm 4i, \pm 4 \pm 4i, \pm 6 \pm 2i\}, \\ S_{12} &= \{\pm 1 \pm 7i, \pm 5 \pm 5i, \pm 7 \pm 1i\}, \\ T_{16} &= \{P_8, \pm 4, \pm 4i, \pm 4 \pm 2i\}, \\ U_8 &= \{\pm 2 \pm 6i, \pm 6 \pm 4i\}. \end{aligned}$$

The two active antennas will now simultaneously transmit symbols from two secondary constellations at a time, which correspond to the set (P_{32}, Q_{32}), (T_{16}, S_{12}), or (R_{16}, U_8).

B. Asymptotic Performance

Let us now consider the criteria with which we shall assess the proposed scheme's performance. The O-ESM schemes are designed such that both the SE c and the minimum Euclidean distance δ_0 of the primary signal constellation are maintained as with the previous methods. Therefore, the system's CER performance is primarily determined by $D_{\min}$. By adopting the rank and determinant criteria used in the design of space-time codes, as presented in [12], the expression for $D_{\min}$ is derived as the minimum of the components in the following equations:

$$D_{\min} = \min_{\mathbf{x}_k \neq \hat{\mathbf{x}}_k} \left({\Delta^{(\tau)}}^H \Delta^{(\tau)} \right), \tag{11}$$

where:

$$\Delta^{(\tau)} = \mathbf{x}_k - \hat{\mathbf{x}}_k = \frac{1}{\sqrt{\overline{E}_s}}\Big(\mathbf{S}^{(\tau)}\,\mathbf{u}^{(\tau)} \;-\; \hat{\mathbf{S}}^{(\tau)}\,\hat{\mathbf{u}}^{(\tau)}\Big), \quad (12)$$

and:

$$(\mathbf{S}^{(\tau)}, \mathbf{u}^{(\tau)}, \hat{\mathbf{S}}^{(\tau)}, \hat{\mathbf{u}}^{(\tau)}) = \begin{cases} (\mathbf{S}_p,\ x^{\gamma}, \hat{\mathbf{S}}_p,\ \hat{x}^{\gamma}), & \tau = \text{single}, \\ \left(\mathbf{S}_l,\ \begin{bmatrix} x^{\alpha} \\ x^{\beta} \end{bmatrix}, \hat{\mathbf{S}}_l,\ \begin{bmatrix} \hat{x}^{\alpha} \\ \hat{x}^{\beta} \end{bmatrix}\right), & \tau = \text{dual}, \\ \left(\mathbf{S}_p,\ x^{\gamma},\ \hat{\mathbf{S}}_l,\ \begin{bmatrix} \hat{x}^{\alpha} \\ \hat{x}^{\beta} \end{bmatrix}\right), & \tau = \text{mixed}. \end{cases} \quad (13)$$

As defined in (12), Δ represents the normalized Euclidean distance between two signal codewords in the signal space. According to (13), Δ^{single}, Δ^{dual}, and Δ^{mixed} denote distances between $\mathbf{x}_k$ and another codeword $\hat{\mathbf{x}}_k$ in three scenarios: both codewords are single-streamed, both are dual-streamed, and one is single-streamed while the other is dual-streamed. Each codeword $\mathbf{x}_k$ is constructed by multiplying a spatial codeword with a modulated signal vector $\mathbf{u}$: either $\mathbf{S}_p x^{\gamma}$ or $\mathbf{S}_l[x^{\alpha}, x^{\beta}]^T$.

To maximize $D_{\min}$, we must increase δ_0 and reduce $\overline{E}_s$, which enhances the separation between constellation points and lowers the probability of incorrect detection. This design principle improves detection robustness while keeping $\overline{E}_s$ sufficiently low, ensuring that the required transmit power $P_t \propto \overline{E}_s$ remains reasonable.

In this paper, the asymptotic SNR gain is evaluated using $D_{\min}$ with $\delta_0 = 2$ for the proposed O-ESM and its existing counterparts. The asymptotic gain of a scheme with $D_{\min}$ over another scheme with $D'_{\min}$ is given by [2]:

$$\mathcal{G} = 20\log_{10}\left(\frac{D_{\min}}{D'_{\min}}\right). \quad (14)$$

Using (14), we can easily verify that the proposed O-ESM offers asymptotic SNR gains of approximately 2.05 dB for 10 bpcu and 2.40 dB for 14 bpcu over MSM. Thus, with O-ESM, only 61.25% and 53.89% of transmit power are needed for the two cases compared to when MSM is implemented. In addition, compared to ESM-Type 1 and ESM-Type 2, which have $D_{\min}$ values of 0.50 and 0.55 for 10 bpcu (0.25 and 0.28 for 14 bpcu, respectively), the O-ESM scheme is noticeably more effective, achieving $D_{\min} = 0.57$ for 10 bpcu and 0.29 for 14 bpcu. This implies that at 10 bpcu, the proposed O-ESM provides asymptotic SNR gains of nearly 1.14 dB and 0.30 dB over ESM-Type 1 and ESM-Type 2, respectively, while at 14 bpcu, the corresponding gains are 1.29 dB and 0.31 dB.

IV. Design Scaling for More Transmit Antennas

In this section, we extend the O-ESM design to support larger antenna configurations, specifically 8TX and 16TX systems. We detail the extension process, a pruning algorithm tailored to various spectral efficiency (SE) requirements, and the design methodology for an 8×8 MIMO system.

Following the extension approach in [3], for $N_T = 8$ and $N_A = 2$, SE reaches $c = 12$ bpcu for $M = 16$ and $c = 16$ bpcu for $M = 64$, resulting in $2^{12} = 4{,}096$ and $2^{16} = 65{,}536$ codewords, respectively. With increased N_T, the number of single- and dual-stream combinations, N_{SSC} and N_{DSC}, expands to 8 and 56. The corresponding spatial mapping sets are defined as:

Algorithm 1: Power-Based Pruning of O-ESM Codewords

Input: N_T, M, c, N_{DSC}, data sets: $\Omega_{M_{s1}}$, $\Omega_{M_{s2}}$, $\lambda \in 0, 1$

Initialize empty table $\mathcal{T} \leftarrow \emptyset$, index $j \leftarrow 1$;
foreach $x_m^{\alpha_{s_1}} \in \Omega_{M_{s_1}}, x_n^{\beta_{s_2}} \in \Omega_{M_{s_2}}$ **do**
  Add row $(j, N_{\text{DSC}}, x_m^{\alpha_{s_1}}, x_n^{\beta_{s_2}})$ to $\mathcal{T}$, increment j;
Compute codeword energy E_s for each row, and append as column 5;
Sort $\mathcal{T}$ in ascending order of E_s;
$v \leftarrow \lceil (2^c - N_T \times M)/N_{\text{DSC}} \rceil$;
Remove the last (total rows $- v$) entries from $\mathcal{T}$;
Subtract $N_{\text{DSC}} \times v - (2^c - N_T \times M)$ from column N_{DSC} of the last entry;
return pruned and re-indexed $\mathcal{T}$ as O-ESM codebook

$$\mathbb{S}_{\text{single}} = \left\{[1,0,0,0,0,0,0,0]^T, \ldots, [0,0,0,0,0,0,0,1]^T\right\}, \quad (15)$$

$$\mathbb{S}_{\text{dual}} = \left\{ \begin{bmatrix} 1, & 0, & 0, & 0, & 0, & 0, & 0, & 0 \\ 0, & 1, & 0, & 0, & 0, & 0, & 0, & 0 \end{bmatrix}^T, \ldots, \begin{bmatrix} 0, & 0, & 0, & 0, & 0, & 0, & 1, & 0 \\ 0, & 0, & 0, & 0, & 0, & 0, & 0, & 1 \end{bmatrix}^T \right\}. \quad (16)$$

For $M = 16$, using the same constellations from Section III, the single-stream codewords count is $16 \times 8 = 128$, while the enlarged N_{DSC} results in $56 \times (8 \times 8 + 4 \times 4) = 4480$ dual-stream codewords. To retain the target SE, 512 codewords must be pruned.

Specifically, all symbol pairs for $N_A = 2$ are sorted by transmit energy, and those with the highest energy are pruned. This is detailed in Algorithm 1, where 9 out of 80 constellation pairs are discarded, removing 504 codewords. The remaining 8 codewords are trimmed from the 71st pair to meet the exact total of 4,096 codewords.

After pruning, the minimum distance $D_{\min}$ is 0.59, offering SNR gains of 2.36 dB and 0.31 dB over MSM and ESM-Type 2. Similarly, for $M = 64$, with $\lambda \in \{0, 1, 2\}$ representing six secondary constellations, 75,776 codewords are initially generated. To achieve the desired SE, 10,240 dual-stream codewords are removed using the same algorithm. The resulting $D_{\min} = 0.31$ yields an SNR gain of nearly 3 dB over MSM and 0.32 dB over ESM-Type 2.

For the 16TX configuration, detailed discussion is omitted due to space limitations. The design follows the same principles as the 8TX case, with adjusted values: $N_{\text{SSC}} = 16$, $N_{\text{DSC}} = 240$, and the signal space contains $2^{14} = 16{,}384$ codewords for $M = 16$ and $2^{18} = 262{,}144$ for $M = 64$. To maintain the desired SE, 3,072 and 60,672 high-energy codewords must be pruned, respectively. The minimum distance $D_{\min}$ is 0.59 for $M = 16$ and 0.31 for $M = 64$, resulting in SNR gains of 2.53 dB and 3.15 dB over MSM, respectively.

Increasing the number of transmit antennas to 8TX and 16TX significantly enhances performance over 4TX schemes. This gain stems from the large number of distinct dual spatial codewords (N_{DSC}): 56 for 8TX and 240 for 16TX, far exceeding those in MSM and ESM, which are limited by power-of-two constraints. Beyond the improved asymptotic gain, the proposed O-ESM also boosts energy efficiency. For 8TX, it requires only 56.65% and 49.95% of the transmit power of MSM. For 16TX, the corresponding values are 55.83% and 48.48%.

V. Simulation Results

We present Monte Carlo simulation results conducted over Rayleigh fading MIMO channels, assuming perfect CSI at the receiver. In the simulations, transmit symbol codewords are randomly generated and passed through the MIMO channel. ML detection is then applied to the received noisy signal samples. CER is evaluated and used as the performance metric to compare conventional SM, baseline MSM, multi-stream ESM schemes (Type 1 and Type 2), and the proposed O-ESM schemes.

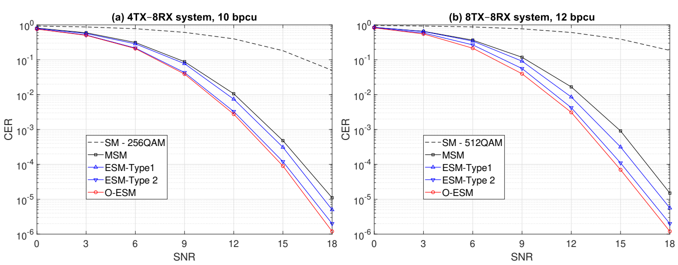

Fig. 3: CER performance of SM, MSM, ESM Type 1 & 2, and proposed O-ESM.

Fig. 3(a) shows the simulation results for a 10 bpcu transmission system using a 4×8 MIMO configuration. The proposed O-ESM scheme employs 16-QAM as the primary constellation. The results indicate that, at a CER of 10^{-4}, O-ESM achieves SNR gains of approximately 1.54 dB, 1.1 dB, and 0.2 dB over MSM, ESM-Type 1, and ESM-Type 2, respectively.

Fig. 3(b) illustrates the CER performance for a 12 bpcu transmission system using an 8×8 MIMO configuration, with 16-QAM being the primary constellation. At CER = 10^{-4}, the proposed O-ESM outperforms MSM, ESM-Type 1, and ESM-Type 2 by approximately 2 dB, 1.1 dB, and 0.3 dB, respectively. These improvements can be primarily attributed to the optimized symbol selection and power-aware pruning strategies.

The improvements observed in both figures confirm that O-ESM effectively leverages optimized signal pairings and constellation pruning, yielding lower error rates even when operating under constrained modulation formats like 16-QAM. Moreover, the use of consistent primary constellations in all ESM-based schemes ensures a fair comparison, emphasizing the structural and energy efficiency advantages of the proposed method over traditional SM and other ESM variants.

According to the findings reported in [3], achieving near-theoretical CER performance – defined with respect to average transmit energy – typically requires a large number of receive antennas. Nevertheless, the study showed that even with only 8 receive antennas, a system can achieve approximately 65% to 75% of the theoretical performance. Consistent with these observations, the proposed O-ESM scheme achieves a normalized performance ranging from 72% to 83% of the theoretical limit, demonstrating its effectiveness in balancing energy efficiency and practical deployment under realistic antenna configurations.

VI. Conclusion

In this work, we have proposed an Optimized ESM scheme for large-scale MIMO systems based on the principle of reusing constellation points across multiple different constellations. Compared to conventional methods, the proposed scheme retains the same spectral efficiency while making better use of all possible antenna group selections through the use of a look-up table. Moreover, the advantages of the O-ESM scheme are also further amplified with a higher number of transmit antennas. Monte Carlo simulations over Rayleigh fading channels prove that O-ESM delivers significant performance improvements, streamlined operation, and reduced transmit power compared to conventional schemes.

References

[1] R. Y. Mesleh, et. al, "Spatial Modulation," *IEEE Trans. Veh. Technol.*, vol. 57, pp. 2228–2241, Jul. 2008.

[2] C.-C. Cheng, H. Sari, S. Sezginer, and Y. T. Su, "Enhanced Spatial Modulation With Multiple Signal Constellations," *IEEE Trans. Commun.*, vol. 63, no. 6, pp. 2237–2248, Apr. 2015.

[3] C. -C. Cheng, H. Sari, S. Sezginer and Y. T. Su, "New Signal Designs for Enhanced Spatial Modulation," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 11, pp. 7766–7777, Sep. 2016.

[4] P. Zhang, S. Guo, and Y. Zhou, "Spatial Modulation Scheme With Two Activated Transmit Antennas," in *IEEE International Conference on Communication Systems (ICCS)*, Chengdu, China, 2018, pp. 94–98.

[5] M. A. Kurt and E. Basar, "Flexible Spatial Modulation With Transmit Antenna Selection for MIMO Systems," *IEEE Syst. J.*, vol. 17, no. 2, pp. 2315–2318, Jun. 2023.

[6] Z. Sun, et. al, "Transmit Antenna Selection Schemes for Spatial Modulation Systems: Search Complexity Reduction and Large-Scale MIMO Applications," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8010–8021, Sep. 2017.

[7] M. Wei, S. Sezginer, G. Gui, and H. Sari, "Bridging Spatial Modulation with Spatial Multiplexing: Frequency-Domain ESM," *IEEE J. Sel. Top. Signal Process.*, vol. 13, no. 6, pp. 1326–1335, Oct. 2019.

[8] N. Ugrelidze, S. Shavgulidze, and J. Freudenberger, "Generalized Multistream Spatial Modulation Based on Frequency-Phase Modulated Signals," *IEEE Wirel. Commun. Lett.*, vol. 11, no. 4, pp. 786–790, Apr. 2022.

[9] P. Yu and F. Huang, "Spatial Index Modulation With the Combination of Both Antenna Indexes and Two Constellations," *IEEE Access*, vol. 10, pp. 133 778–133 788, Dec. 2022.

[10] G. Zhang, et. al, "Joint Code Index Modulation Aided Enhanced Spatial Modulation for High-Rate MIMO Systems," *IEEE Trans. Green Commun. Netw.*, vol. 7, no. 3, pp. 1383–1393, Sep. 2023.

[11] F. Huang and Z. Zhou, "Joint Multiple Constellations and Variable Active Antennas Selection for Signal Spaces Design in MIMO Systems," *IEEE Trans. Commun.*, vol. 72, no. 2, pp. 1239–1251, Feb. 2024.

[12] V. Tarokh, H. Jafarkhani, and A. Calderbank, "Space-time Block Codes from Orthogonal Designs," *IEEE Trans. Inf. Theory.*, vol. 45, pp. 1456–1467, Jul. 1999.

[13] A. E. Matemu and K. Lee, "Spatial Modulation and Generalized Spatial Modulation for Dynamic Metasurface Antennas," *IEEE Trans. Wirel. Commun.*, vol. 24, no. 1, pp. 783–795, Jan. 2025.