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Mirror activation pattern selection for energy efficient hexagonal QAM aided media-based modulation

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Abstract

In this article, three mirror activation pattern (MAP) selection techniques are used to improve the performance of energy-efficient hexagonal quadrature amplitude modulation (HQAM) aided media-based modulation (MBM) system called HMBM. These three MAP selection (MS) aided HQAM techniques: (i) capacity-optimized MS-based HMBM (CMS-HMBM) scheme, (ii) MAP correlation (MC) aided MS-based HMBM (MMS-HMBM) scheme, (iii) Euclidean distance (ED) based MS aided HMBM (EMS-HMBM) scheme. MBM technique, one of the newest and most competitive candidates of the index modulation family, increases spectral efficiency linearly and significantly improves error performance. When MS techniques are integrated into telecommunication techniques, they significantly increase the performance of the system. Extensive computer simulations with Monte Carlo for the considered systems are performed on Rayleigh fading channels. The suggested system offers superior error performance than the conventional MBM scheme since it incorporates CMS, MMS, and EMS techniques. Additionally, the suggested new method offers greater energy efficiency than M-QAM constellation schemes since HQAM constellation schemes are by their very nature high energy efficiency. It is shown that the proposed CMS-HMBM, MMS-HMBM, and EMS-HMBM systems provide better error performance than capacity-optimized antenna selection (COAS) aided hexagonal spatial modulation (COAS-HSM), antenna correlation-based AS aided HSM (ACAS-HSM), Euclidean distance optimized AS aided HSM (EDAS-HSM), SM, and MBM systems for the same spectral efficiency. The suggested systems are envisaged for usage in sixth-generation and later wireless networks because of their high performance provided by the CMS, MMS, and EMS methods in the proposed system and the high spectral efficiency provided by the HMBM approach.

1 | INTRODUCTION

Recently, wireless network services, the number of mobile subscribers, and the number of developed applications/devices have increased data traffic and the pressure on current wireless communication systems has been increasing. According to a prediction made by the International Telecommunication Union (ITU), mobile data traffic on a global scale will reach 5 zettabytes by 2030. As a result of all these, needs such as low-latency communication, high data rate, low power consumption, high energy efficiency (EE), and high performance arise. Therefore, researchers continue to develop new transmission protocols and techniques to increase the spectral efficiency (SE), performance, and data rates of wireless communication systems.[1-3]

Index modulation (IM) techniques are widely used in integration with many communication systems due to their numerous advantages such as high SE and EE.[4] In the IM technique, by using the indices of the system elements, extra information is transmitted as embedded into the transmitted signal.[5] Since information is carried in the indices of communication elements in addition to the bits traditionally carried in the symbol, IM considerably increases the data rates of the systems. In the IM technique, since the indices carrying extra information are embedded in the transmitted signal, the energy consumption for extra information transmission is either no or very little. The IM technique reduces inter-channel interference (ICI) and system complexity, improves error performance, and provides low energy consumption.[6-9]

The most major disruptive factor in wireless communication is the fading effect. In the wireless channel, multiple-input multiple-output (MIMO) systems minimize this disruptive effect with diversity techniques.[10] MIMO system is an essential technique that is recommended to improve the received signal quality and deal with multipath fading and is at the base of many communication systems. MIMO systems are a pioneering technology in wireless networks because they increase data throughput without the need for extra bandwidth or transmission power. However, due to multiple antennas in MIMO systems, system complexity, ICI, power consumption, and cost increases.[11] Integrating IM techniques into MIMO systems reduces these negative effects.

Media-based modulation (MBM) scheme, one of the prominent members of the IM family, is an innovative technique that provides high SE and error performance.[12] The MBM technique is proposed by Khandani in Reference 13 as a new transmission approach. MBM technique is based on the idea of creating different channel fading realizations by switching radio frequency (RF) mirrors on/off.[14] To increase the SE in the MBM technique, it is sufficient to increase the number of RF mirrors while the number of transmit antennas is fixed. For example, while modulation order $M = 4$, to determine the SE to be 10 a single antenna and only 8 RF mirrors are sufficient in the MBM technique, whereas 256 transmit antennas are needed in the spatial modulation (SM) technique. Therefore, as the SE increases, the use of the SM technique is quite difficult due to physical limitations. In the MBM technique, it is possible to achieve high SE with a fair amount of RF mirrors. The hexagonal quadrature amplitude modulation assisted media-based modulation system, which is shortly called HQAM-MBM, is proposed in Reference 15. In Reference 16, a novel system is proposed, combining MBM, SM, and dual-polarized antennas in a MIMO system. A non-orthogonal multiple access-based decode-and-forward relaying system, in which the MBM technique is applied to the source, is recommended in Reference 17. In Reference 18, a differential MBM system is proposed, which does not require estimation of channel modulation alphabet for detection.

The mirror activation pattern (MAP) selection (MS) techniques play an important role in enhancing the performance of communication systems in the field of wireless communication. The MS technique is based on basis of selecting the MAPs with the best channel condition from the MAP array and transmitting over only these selected MAPs. The MS technique increases the diversity gain as much as the number of MAPs in the transmitter. This greatly improves system performance by using a reasonable number of extra RF mirrors in the transmitter. The capacity-optimized based MS (CMS), MAP correlation (MC) based MS (MMS), and Euclidean distance (ED) based MS (EMS) techniques attract attention in terms of complexity and performance balance. Among these three MS techniques, the EMS technique has the best performance and the highest complexity. Similarly, the technique with the lowest performance and complexity is the CMS technique. The MMS technique, on the other hand, is in the middle of EMS and CMS techniques at the level of complexity and error performance. In Reference 19, the EMS technique is applied to the traditional MBM system. The results show that the bit error performance of the EMS-based MBM system is greatly improved. To improve the performance of the spatial media-based modulation (SMBM) system existing in the literature, low complexity MS methods are presented in Reference 20. A low complexity detection technique is offered for the MBM-based space-time block-coded spatial modulation (STBC-SM) system in Reference 21. In addition, three different MS techniques in the literature have been used that increase the performance of the proposed system. The digitally reconfigurable metasurface (DRM) array is proposed for the MBM technique enabling multipath communication in Reference 22. Furthermore, a DRM array prototype and hardware interface are developed and an important scheme for data transmission with DRM is discussed.

In addition to all these mentioned techniques, M-ary QAM (M-QAM) constellations are commonly employed in next-generation communication systems because they are straightforward to construct and estimate. Although the M-QAM constellation structure is simple, one issue is that it does not adequately combine symbols in terms of EE. Furthermore, unlike HQAM approaches, M-QAM constellations cannot effectively identify one symbol from another with the identical symbol energy assumption. Because of the quantity of energy carried by the symbols, M-QAM constellations are referred to as sub-optimal in this context. Since the HQAM technique employs a denser hexagonal lattice, HQAM is the optimal two-dimensional constellation technique in the context of EE. The HQAM technology's main purpose is to minimize transmission power.[23] In Reference 24, to increase the performance of the HQAM-SM system, a new system supported by the capacity-optimized antenna selection (COAS) technique, shortly called COAS-HSM, is proposed.

Recently, AS techniques that increase the performance of wireless communication systems have drawn the attention of researchers.[25,26] In Reference 27, AS techniques are integrated into the STBC-SM system. It has been observed that the proposed system provides a better bit error rate (BER) performance than the traditional STBC-SM method. Transmit AS (TAS) based quadrature spatial modulation (QSM) system is presented in Reference 28. In Reference 29, TAS techniques were applied to double spatial modulation (DSM). The results showed that the BER performance improved. The cooperative QSM (CQSM) system supported by EDAS/COAS techniques has been investigated in Reference 30. It has been seen that the proposed system has better error performance at the same SE than the cooperative spatial modulation (CSM) and CQSM systems. A code index modulation (CIM) supported SM technique based on EDAS and COAS techniques is proposed by Aydin in Reference 31.

1.1 | Contributions

In this article, three high-performance MAP selection techniques are introduced for the EE HMBM system. The CMS, MMS, and EMS techniques are combined with the HMBM system. The contributions of this article can be summarized as follows:

1. The CMS-HMBM, MMS-HMBM, and EMS-HMBM systems are proposed for next-generation EE communication systems.
2. BER performances of the proposed systems are compared with the BER performance of the SM, MBM, COAS-aided hexagonal spatial modulation (COAS-HSM), antenna correlation-based AS aided HSM (ACAS-HSM), and EDAS-aided HSM (EDAS-HSM) systems over Rayleigh fading channels, and it is shown that the proposed systems provided better BER performance at the same SE. Also, it is shown that the proposed systems provide higher EE and SE than benchmark systems.
3. BER performances of CMS-HMBM, MMS-HMBM, and EMS-HMBM systems are given according to the varying RF mirror numbers (n_{rf}) and HQAM constellations. Also, as the number of n_{rf} increases, the SE of the proposed system increases linearly.

1.2 | Organization

The remainder of the article continues as follows. The system model of the proposed scheme is given in Section 2. MAP selection techniques for HMBM scheme are introduced in Section 3. Section 4 is allocated to simulation results and HQAM structure. Finally, the conclusion of the article is in Section 5.

1.3 | Notation

The notations used in this article are given as follows: (i) bold lower/upper case symbols stand for vectors/matrices; (ii) $(\cdot)^H$, $(\cdot)^T$, $\|\cdot\|$, $|\cdot|$ and $E[\cdot]$ express Hermitian, transpose, Frobenius norm, Euclidean norm, and expectation operators, respectively. $\Re(.)$ and $\Im(.)$ are the real and imaginary parts of a complex number; (iii) $\binom{\cdot}{\cdot}$ denotes the binomial coefficient. $\mathbb{C}^{i \times j}$ denotes the space of $i \times j$ complex-valued matrices. $\mathcal{CN}(\mu, \sigma^2)$ expresses the complex Gaussian distribution with mean μ and variance σ^2.

2 | SYSTEM MODEL

In this section, traditional MBM and the proposed MS-HMBM schemes are presented.

2.1 | Traditional MBM scheme

For the traditional MBM scheme, the transmission vector containing the selected symbol x_i and the kth index of the active RF mirror can be expressed as:

$$\mathbf{x}_{ki} \triangleq \begin{bmatrix} 0 & 0 \cdots 0 & \underset{k\text{th position}}{\underset{\uparrow}{x_i}} & 0 & \cdots 0 & 0 \end{bmatrix}^T, \tag{1}$$

where, $i \in \{1, 2 \ldots M\}$ and $k \in \left\{1, 2 \ldots 2^{n_{rf}}\right\}$. The transmission vector expressed in (1) is conveyed over the Rayleigh flat fading channel during one symbol period. The faded and noisy signal arriving at the receiver is expressed as:

$$\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{n}, \tag{2}$$

where $\mathbf{r} \in \mathbb{C}^{n_R \times 1}$ is the received signal vector and n_R is the number of receive antennas. $\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{\mathcal{M}}] \in \mathbb{C}^{n_R \times \mathcal{M}}$ is the channel matrix with the Rayleigh distribution, zero-mean, and unit variance, $\mathbf{x} \in \mathbb{C}^{2^{n_{rf}} \times 1}$ is the transmission vector, and $\mathbf{n} \in \mathbb{C}^{n_R \times 1}$ is the complex Gaussian noise vector with zero-mean and variance σ_n^2. Here, $\mathbf{H}$ with size of $n_R \times \mathcal{M}$ is described as follows:

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,\mathcal{M}} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,\mathcal{M}} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_R,1} & h_{n_R,2} & \cdots & h_{n_R,\mathcal{M}} \end{bmatrix}_{n_R \times \mathcal{M}}. \tag{3}$$

2.2 | Proposed MS-HMBM scheme

The system model of the proposed MS-HMBM technique is depicted in Figure 1. In this system model, the transmitter contains one transmit antenna surrounded by n_{rf} RF mirrors, while the receiver is equipped with n_R receive antennas.

According to the on/off status of the RF mirrors in the transmitter, $\mathcal{M} = 2^{n_{rf}}$ MAPs can be created. Therefore, the SE increases linearly depending on the number of RF mirrors used in the MBM technique. Hence, the MBM technique provides high SE compared to the SM technique, in which SE increases logarithmically. The SE of the MS-HMBM system is given as follows:

$$\eta \; = \; \log_2(M) + n_{rf} \text{ (bits/s/Hz)}. \tag{4}$$

In CMS, MMS, and EMS techniques, $\mathcal{M}_S$ MAPs with the best channel condition are selected out of $\mathcal{M}$ MAPs under the condition $\mathcal{M}_S \leq \mathcal{M}$. Therefore, the MS-HMBM system provides better BER performance than the traditional MBM system. Similarly, for COAS, ACAS, and EDAS techniques in the SM scheme, $\mathcal{N}_S$ transmit antennas with the best channel condition are selected from all $\mathcal{N}$ transmit antennas in the transmitter under the condition $\mathcal{N}_S \leq \mathcal{N}$.

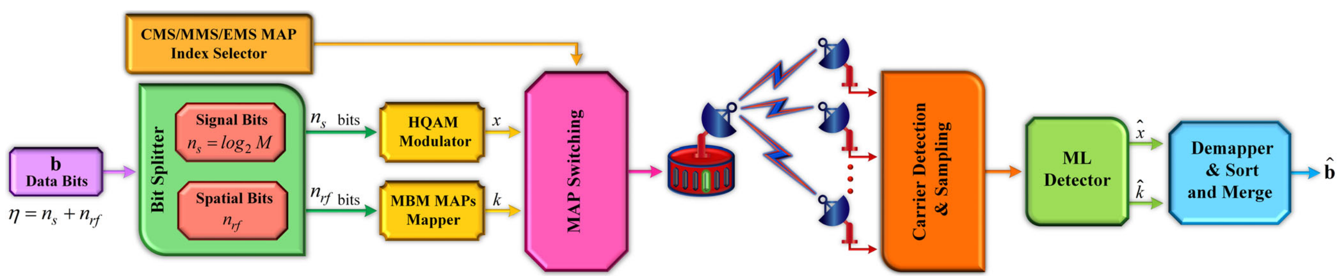

FIGURE 1 System model of the MS-HMBM scheme.

As can be seen in Figure 1, the data bits vector is represented by **b**. First, **b** is divided by the bit splitter into two subgroup vectors consisting of $n_s = \log_2(M)$ and n_{rf} bits. Then, according to the value of the information bit streams, the n_s bits are mapped to the modulated symbol selected from the HQAM consensus, while the n_{rf} bits select the kth channel state of the RF mirrors. For example, suppose that while $M = 8$ and $n_{rf} = 2$, $\mathbf{b} = [01010]$ bits are transmitted. In this case, $\log_2(M) = 3$ bits ([010]) map to the symbol HQAM $x_3 = -1 + j$, $n_{rf} = 2$ bits ([10]) map to third MAP of the RF mirrors.

Considering the MAP selection technique, the best columns of channel matrix **H** are selected according to the CMS, MMS, and EMS techniques. With these selected columns, the $\mathbf{H}_{\mathrm{S}}^{\mathrm{CO/MC/ED}}$ ($\mathbf{H}_{\mathrm{S}}^{\mathrm{CO}}$ for CMS, $\mathbf{H}_{\mathrm{S}}^{\mathrm{MC}}$ for MMS, $\mathbf{H}_{\mathrm{S}}^{\mathrm{ED}}$ for EMS) matrix is created and then, the transmission is performed over the selected MAPs only. Then, (2) can be rewritten after the MAP selection process as follows:

$$\begin{aligned} \mathbf{r} &= \mathbf{H}_{\mathrm{S}}\mathbf{x} + \mathbf{n}, \\ &= \mathbf{h}_k x_i + \mathbf{n}, \end{aligned} \tag{5}$$

where, $\mathbf{H}_{\mathrm{S}} = \left[\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{\mathcal{M}_S}\right] \in \mathbb{C}^{n_R \times \mathcal{M}_{\mathrm{S}}}$ is the selected channel matrix with size of $n_R \times \mathcal{M}_{\mathrm{S}}$ is described as follows:

$$\mathbf{H}_{\mathrm{S}}^{\mathrm{CO/MC/ED}} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,\mathcal{M}_{\mathrm{S}}} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,\mathcal{M}_{\mathrm{S}}} \\ \vdots & \vdots & \ddots & \vdots \\ h_{n_R,1} & h_{n_R,2} & \cdots & h_{n_R,\mathcal{M}_{\mathrm{S}}} \end{bmatrix}_{n_R \times \mathcal{M}_{\mathrm{S}}}. \tag{6}$$

In this article, the maximum likelihood (ML) detector is used to provide optimum performance for the detection process at the receiver side. The ML detector estimates jointly the selected channel state $\hat{k}$ of MAPs and $\hat{x}$ symbol of HQAM constellation using all possible combinations of MAPs and HQAM constellation symbols. The ML detector for the CMS-MBM, MMS-MBM, and EMS-MBM systems can be written as follows:

$$\left[\hat{x}, \hat{k}\right] = \arg\min_{x,k} \left|\left|\mathbf{r} - (\mathbf{h}_k x)\right|\right|^2. \tag{7}$$

By using the $\hat{x}$ and $\hat{k}$ parameters, the estimated bit sequence $\hat{\mathbf{b}}$ is obtained with the help of the demapper ς sort and merge block shown in Figure 1.

3 | MAP SELECTION TECHNIQUES FOR HMBM SCHEME

In this section, CMS, MMS, and EMS techniques integrated into the MBM technique are introduced, respectively.

3.1 | CMS technique for HMBM system

The CMS technique is based on the selection of the channel coefficients with the highest squared norm among all available channel coefficients and the transmission is carried out only over these channels. The CMS technique is a selection scheme that selects the $\mathcal{M}_S$ MAPs subset corresponding to the best channel condition from all $\mathcal{M}$ MAPs in the transmitter. The CMS technique provides lower error performances than MMS and EMS techniques but also has lower complexity.

The step-by-step implementation of the CMS algorithm can be given briefly as follows:[20,32]

Step 1: The squared Frobenius norm of all column vectors of the channel matrix **H** is calculated individually:

$$\left|\left|\mathbf{h}_i\right|\right|_F^2, \; i = 1, 2, \ldots, \mathcal{M}. \tag{8}$$

Step 2: Column vectors whose squared Frobenius norms have been calculated are sorted from largest to smallest according to their squared norm values:

$$\left\|\mathbf{h}_1\right\|_F^2 \geq \left\|\mathbf{h}_2\right\|_F^2 \geq \cdots \geq \left\|\mathbf{h}_{\mathcal{M}_\text{S}}\right\|_F^2 \geq \left\|\mathbf{h}_{\mathcal{M}_{\text{S}+1}}\right\|_F^2 \geq \cdots \geq \left\|\mathbf{h}_{\mathcal{M}}\right\|_F^2. \tag{9}$$

Step 3: $\mathcal{M}_S$ MAPs column vectors in $\mathbf{H}_\text{S}^\text{CO} \in \mathbb{C}^{n_R \times \mathcal{M}_\text{S}}$ is selected from $\mathcal{M}$ MAPs column vectors in $\mathbf{H} \in \mathbb{C}^{n_R \times \mathcal{M}}$ with the highest squared norm among the vector set of channel coefficients ordered from the largest to the smallest according to the squared norm. Finally, CMS based selected channel matrix $\mathbf{H}_\text{S}^\text{CO}$ can be expressed as follows:

$$\mathbf{H}_\text{S}^\text{CO} = \left[\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{\mathcal{M}_s}\right]. \tag{10}$$

3.2 | MMS technique for HMBM system

In wireless communication, the more different channels are from each other, the better the error performance is provided since the signal is subject to different fading. Therefore, the MMS technique selects the channels that differ most from each other among the channel coefficient sets. In this technique, the cosine similarity formula is used to calculate the measure of similarity. The similarity between the any two channel vectors $\mathbf{h}_a$ and $\mathbf{h}_b$ can be expressed by their cosine similarity as follows:[33]

$$\cos(\phi_a) = \frac{\left|\mathbf{h}_a^H \mathbf{h}_b\right|}{\left\|\mathbf{h}_a\right\|_F \left\|\mathbf{h}_b\right\|_F}, \tag{11}$$

where, $\mathbf{h}_a$ and $\mathbf{h}_b$ are ath and bth column vectors of the channel matrix $\mathbf{H}_\text{S} \in \mathbb{C}^{n_R \times \mathcal{M}_\text{S}}$, respectively. The similarity between any two channel vectors is determined in (11). Using (11), the MMS-based selection scheme is defined as follows:[33]

$$\mathbf{H}_\text{S}^\text{MC} = \arg \min_{\mathbf{H}_\text{S} \in \mathcal{S}(\mathbf{H}_\text{S})} \left\{ \max_{\substack{a,b \in \mathcal{S}_h \\ a \neq b}} \frac{\left|\mathbf{h}_a^H \mathbf{h}_b\right|}{\left\|\mathbf{h}_a\right\|_F \left\|\mathbf{h}_b\right\|_F} \right\}, \tag{12}$$

where, $\mathcal{S}_h$ represents the column indices of $\mathbf{H}_\text{S}$, and $\mathcal{S}_h \in \{1, 2 \ldots \mathcal{M}_S\}$. Also, $\mathcal{S}(\mathbf{H}_\text{S})$ is the set of $\mathbf{H}_\text{S}$.

3.3 | EMS technique for HMBM system

In the traditional MBM method, modulation is performed over all MAPs according to information bit streams. However, in the EDAS-based MBM system, $\mathcal{M}_\text{S}$ MAPs with the best channel condition are selected among the $m = \binom{\mathcal{M}}{\mathcal{M}_\text{S}}$ combination arrays and the transmission is made over these selected $\mathcal{M}_\text{S}$ MAPs.

The implementation steps of the EDAS algorithm can be given briefly as follows:

Step 1: All $m = \binom{\mathcal{M}}{\mathcal{M}_\text{S}}$ sets of combinations are generated.

Step 2: The combination sets with the best conditions given in (14) are selected out of all available $m = \binom{\mathcal{M}}{\mathcal{M}_\text{S}}$ sets of combinations.

Step 3: Finally, transmission is only performed over these selected combination sets.

In the EDAS-based MBM technique, by using all $\binom{\mathcal{M}}{\mathcal{M}_\text{S}}$ sets of combinations, the $\mathcal{M}_\text{S}$ MAPS that maximizes the minimum Euclidean distance is selected. All sets of MAPs generated by the EDAS technique are expressed in general equation form as follows:[19]

$$\mathcal{A}_{ED} = \arg \max_{\mathcal{A} \in \mathcal{K}} \left\{ \min_{\substack{\mathbf{s}_1, \mathbf{s}_2 \in \mathcal{S} \\ \mathbf{s}_1 \neq \mathbf{s}_2}} \left\|\mathbf{H}_{\mathcal{A}} \left(\mathbf{s}_1 - \mathbf{s}_2\right)\right\|_F^2 \right\}, \tag{13}$$

where, $\mathbf{H}_{\mathcal{A}} \in \mathbb{C}^{n_R \times \mathcal{M}_S}$ is a matrix with n_R row and $\mathcal{M}_S$ columns given by $\mathcal{A}_{ED}$ and $\mathcal{K} = \{\mathbf{e}_k x_i\}_{k=1}^{\mathcal{M}_S}$ is the array of all possible transmission vectors. Also, $x_n \in M$-QAM and $\mathbf{e}_k$ is a $\mathcal{M}_S \times 1$ vector with 1 as the non-zero element at the kth location and $|\mathcal{K}| = \mathcal{M}_S M$. Let $d_{\min}(\mathbf{H}_{\mathcal{A}})$ be described as $\min_{\mathbf{s}_1 \mathbf{s}_2 \mathcal{K} \in \mathbf{s}_1 \neq \mathbf{s}_2} \left\| \mathbf{H}_{\mathcal{A}} (\mathbf{s}_1 - \mathbf{s}_2) \right\|_F^2$, in this case, (13) can be expressed in terms of Euclidean distance as follows:[32]

$$\mathcal{A}_{ED} = \arg \max_{\mathcal{A} \in \mathcal{K}} \{ d_{\min} (\mathbf{H}_{\mathcal{A}}) \} . \tag{14}$$

As seen in (14), the system performance enhances when $d_{\min}(\mathbf{H}_{\mathcal{A}})$ is maximized. Therefore, since $d_{\min}$ is maximized in the EDAS technique, the EDAS-assisted MBM technique has higher performance than the traditional MBM scheme. Although the EDAS technique has high complexity as a disadvantage, it provides the highest performance compared to CMS and MMS techniques.

4 | SIMULATION RESULTS AND HQAM STRUCTURE

In this section, simulation results including performance results and interpretations of the proposed wireless communication schemes and their counterparts in the literature, and various energy efficient HQAM constellations including summary information about the HQAM structure used in the article are presented.

4.1 | Various energy efficient HQAM constellations

Researchers' interest in power-efficient and hexagonal-shaped constellation schemes known as HQAM has grown in response to the requirement for EE and high data-rated systems. HQAM constellations lower peak and average power, making constellations more EE than traditional constellation systems. Traditional QAM and PSK constellation schemes are chosen in most existing communication systems because they feature less complicated ML detection structures and have simple theoretical analyses. However, recent advancements, particularly in microprocessor technology, have significantly decreased the difficulty of ML detecting HQAM constellation designs. As a result of HQAM's superiority over other traditional constellation schemes, researchers have recently begun to investigate HQAM constellations in a variety of fields, including MIMO systems, multi-carrier systems, small cell communication, channel coding, and optical communication systems.[23,34,35]

Figure 2 depicts various HQAM constellation systems. As previously stated, HQAM constellation systems are more EE than traditional QAM constellations and have about the same bit-error and symbol-error performance rates as QAM at high signal-to-noise ratio (SNR) values. It is clear that the usage of HQAM systems is more crucial in terms of EE. Figure 3 compares the EE of QAM and HQAM schemes in terms of minimum unit symbol separation. Here, the power comparisons were carried out in *watts*/*unit*^{2}. Please refer to the paper 34 for further details.

Besides, when HQAM constellations are compared to QAM constellations, it is clear that many of the constellation points' real and/or imaginary parts are zero. As a result, it is impossible to acquire the bits held in the indices where the

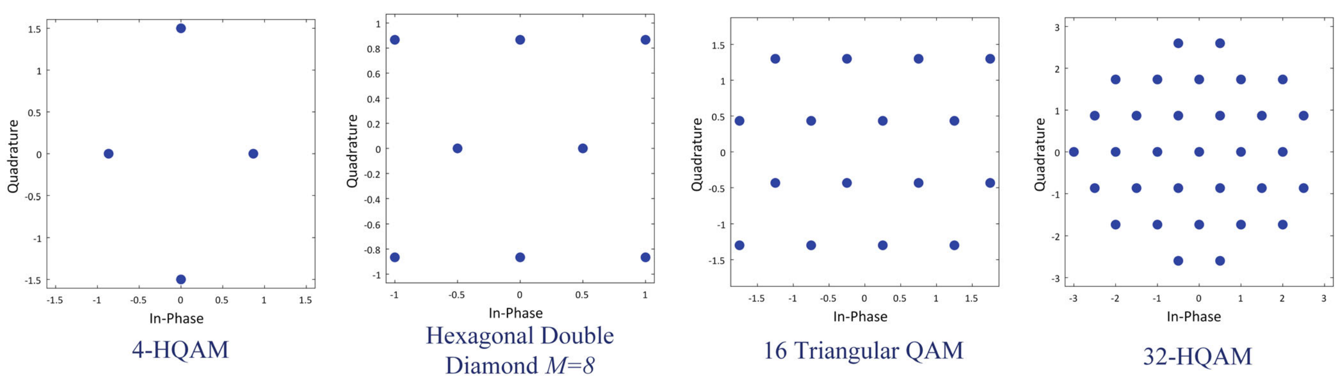

FIGURE 2 Various HQAM constellations.

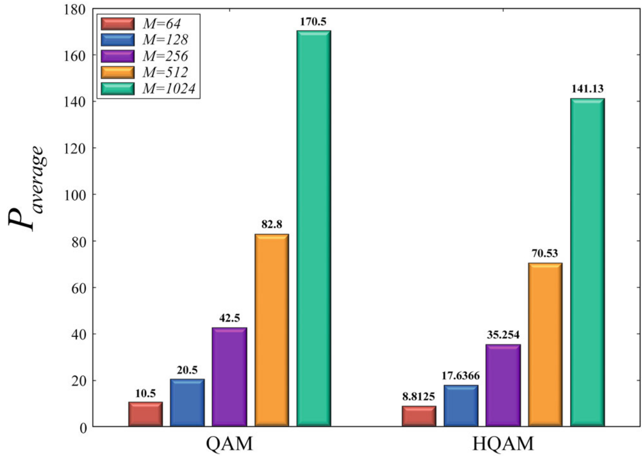

FIGURE 3 P_{average} (average power) comparisons of HQAM and QAM when $M = 64{,}128, 256$, and 1024.

zero components are transmitted if these structures are employed directly in index modulated systems. The error floor occurs in such a situation. Cogen et al propose to rotate the HQAM symbols to obtain the best angle in order to resolve this issue in Reference 35. Additionally, the ideal angle values of several HQAM constellations have been discovered, and these values have been supported by the simulation results. Please see Reference 35 for more information.

4.2 | Simulation results

In this section, we present simulation results and comparison curves of CMS-MBM, MMS-MBM, and EMS-MBM systems over Rayleigh fading channels and for the M-QAM constellation. Also, CMS-MBM, MMS-MBM, and EMS-MBM systems are compared with SM, MBM, COAS-SM, ACAS-SM, and EDAS-SM systems in terms of BER performance at the same SE. In all comparisons, it is seen that the MBM-based systems provide better performance. The Monte Carlo method is used in the performance results given in this section. The SNR value in the BER curves is defined as $\text{SNR(dB)} = 10\log_{10}(E_s/N_0)$ and where E_s is described as the average symbol energy. Also, all performance comparisons have been evaluated at a BER of 10^{-5} values.

Performance comparisons of the MBM, SM, CMS-MBM, MMS-MBM, EMS-MBM, HMBM, HSM, CMS-HMBM, MMS-HMBM, and EMS-HMBM systems for $n_R = 2$, $\mathcal{M}_S = 4$, and $\mathcal{M} = 8, 16$ are given in Figure 4. The BER performance for MBM, SM, HSM, and HMBM systems is presented in Figure 4A, the BER performance for CMS-MBM, MMS-MBM, EMS-MBM, CMS-HMBM, MMS-HMBM, and EMS-HMBM systems is offered for $\mathcal{M} = 8$ in Figure 4B and for $\mathcal{M} = 16$ in Figure 4C. It is seen that the CMS-MBM, MMS-MBM, EMS-MBM, CMS-HMBM, MMS-HMBM, and EMS-HMBM systems provide better error performance than MBM, SM, HMBM, and HSM systems. Also, the performance results of HMBM, HSM, CMS-HMBM, MMS-HMBM, and EMS-HMBM which are HQAM-based systems are very close to the performance results of MBM, SM, CMS-MBM, MMS-MBM, and EMS-MBM which are QAM-based systems. The ranking of the BER performance of the systems from best to worst is as follows: EMS-MBM, MMS-MBM, CMS-MBM, MBM, and SM. Also, the effect of different $\mathcal{M}$ and $\mathcal{M}_S$ parameters on performance is investigated. It is observed that the performance of systems improves as the value of the $\mathcal{M}$ parameter increases.

The BER performance comparisons of CMS-MBM with COAS-SM systems are given for $n_R = 2$ in Figure 5A and for $n_R = 4$ in Figure 5B. As can be seen from Figure 5A,B, the CMS-MBM system provides better performance than the COAS-SM system. Also, the SNR gains of the CMS-MBM system are 2.50 dB for $n_R = 2$ and .99 dB for $n_R = 4$ compared to the COAS-SM system. This means that the CMS-MBM system requires lower SNR values than the COAS-SM system to achieve the same error performance. However, considering the results obtained, the number of receive antennas used should be optimized. The performance comparisons of MMS-MBM with ACAS-SM systems are presented for $n_R = 2$ in Figure 5C and for $n_R = 4$ in Figure 5D. It is observed from Figure 5C,D that the MMS-MBM system has a higher SNR gain than the ACAS-SM system. Also, the MMS-MBM system has SNR gains of 1.81 dB for $n_R = 2$ and 2.61 dB for $n_R = 4$ compared to the ACAS-SM system. Finally, the effect of the change in the number of n_R on the performance of the systems is observed in Figure 5. It is understood that the performance improves as the number of n_R increases.

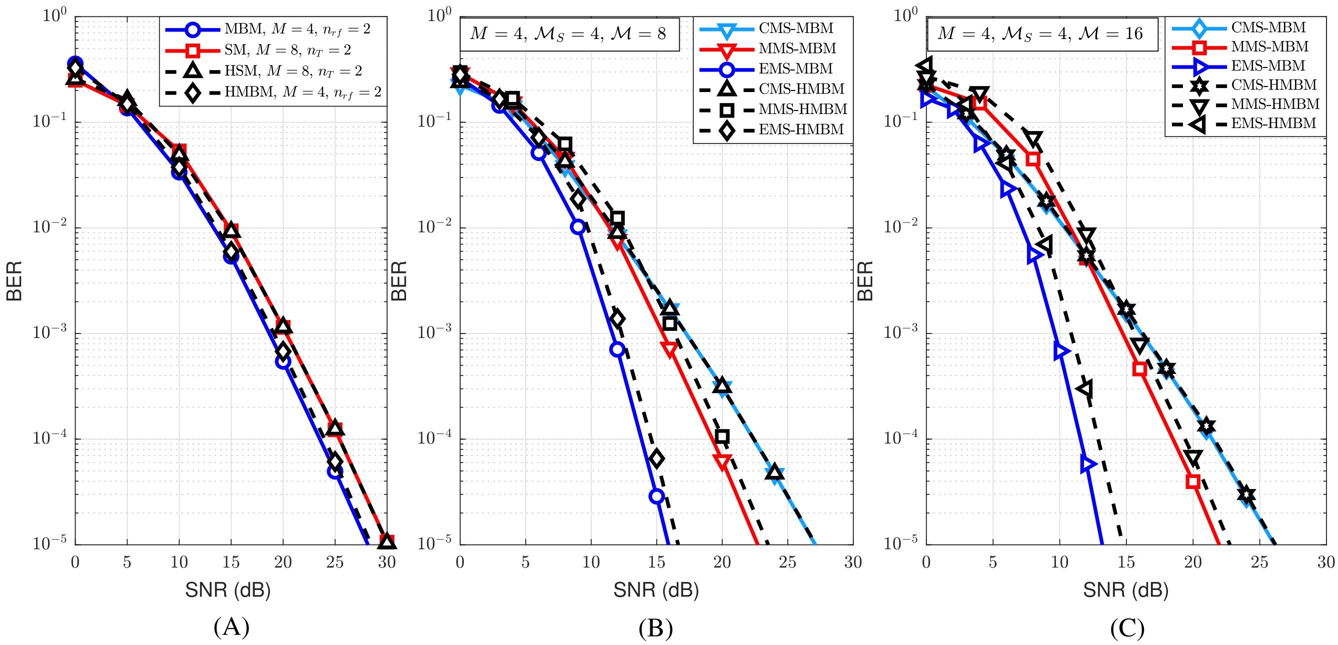

FIGURE 4 Performance comparisons of the MBM, SM, CMS-MBM, MMS-MBM, EMS-MBM, HMBM, HSM, CMS-HMBM, MMS-HMBM, and EMS-HMBM systems for $n_R = 2$, $\mathcal{M}_S = 4$, and $\mathcal{M} = 8, 16$. (A) Performance comparisons of SM, MBM, HSM, and HMBM. (B) Performance comparisons of CMS-MBM, MMS-MBM, EMS-MBM, CMS-HMBM, MMS-HMBM, and EMS-HMBM. (C) Performance comparisons of CO-MS-MBM, MC-MS-MBM, ED-MS-MBM, CO-MS-HMBM, MC-MS-HMBM, and ED-MS-HMBM.

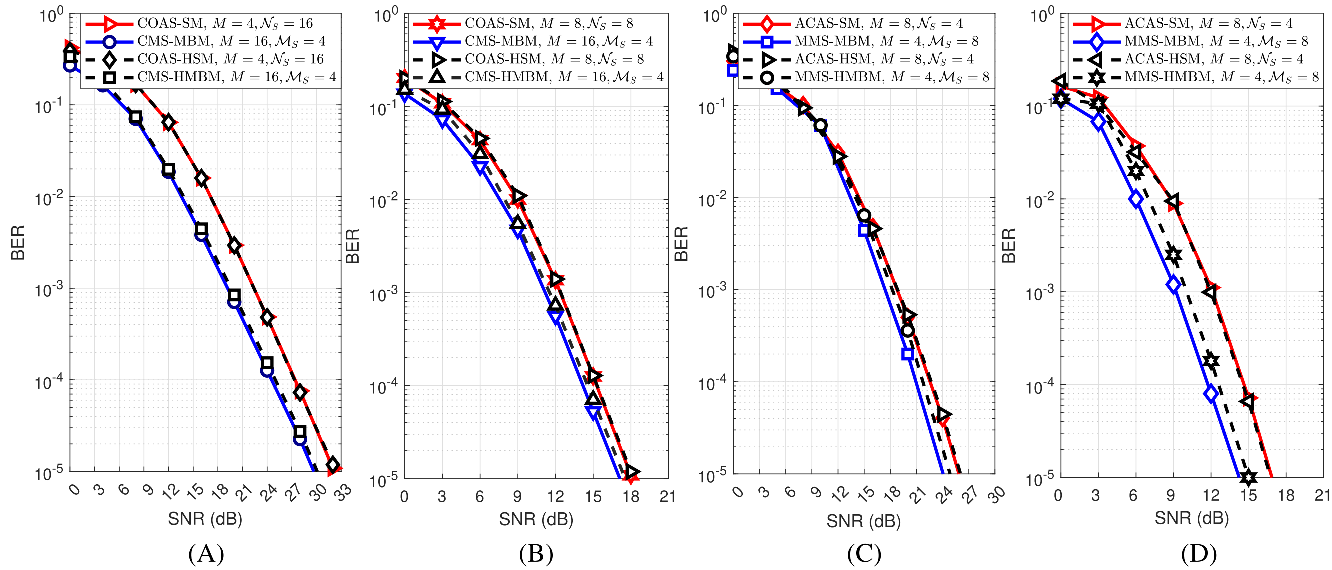

FIGURE 5 Performance comparisons COAS-SM, COAS-HSM, CMS-MBM, CMS-HMBM, ACAS-SM, ACAS-HSM, MMS-MBM, and MMS-HMBM systems when $\mathcal{M} = \mathcal{N} = 16$ and $n_R = 2, 4$. (A) Performance comparisons of COAS-SM, CMS-MBM, COAS-HSM, CMS-HMBM, for $n_R = 2$. (B) Performance comparisons of COAS-SM, CMS-MBM, COAS-HSM, CMS-HMBM, for $n_R = 4$. (C) Performance comparisons of ACAS-SM, MMS-MBM, ACAS-HSM, MMS-HMBM for $n_R = 2$. (D) Performance comparisons of ACAS-SM, MMS-MBM, ACAS-HSM, MMS-HMBM for $n_R = 4$.

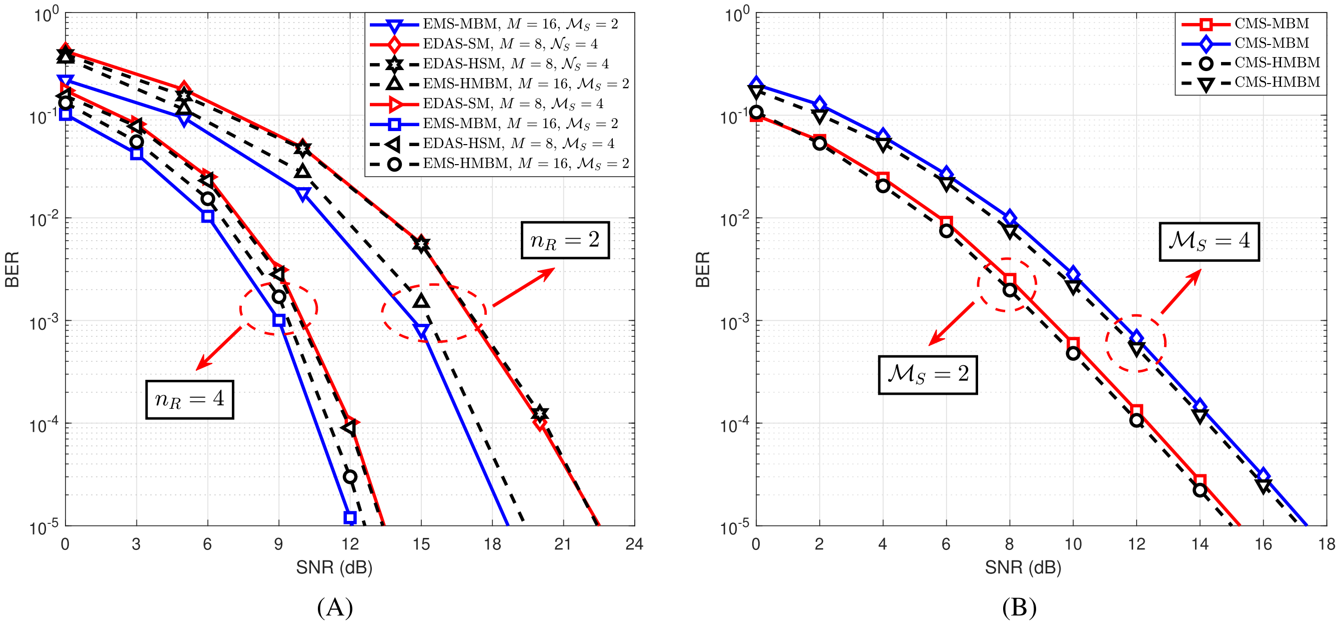

FIGURE 6 Performance comparisons (A) EDAS-SM, EDAS-HSM, EMS-MBM, and EMS-HMBM systems while $\mathcal{M} = \mathcal{N} = 8$, and $n_R = 2, 4$, (B) CMS-MBM and CMS-HMBM systems for varying $\mathcal{M}_S$ values while $\mathcal{M} = M = 8$, and $n_R = 4$.

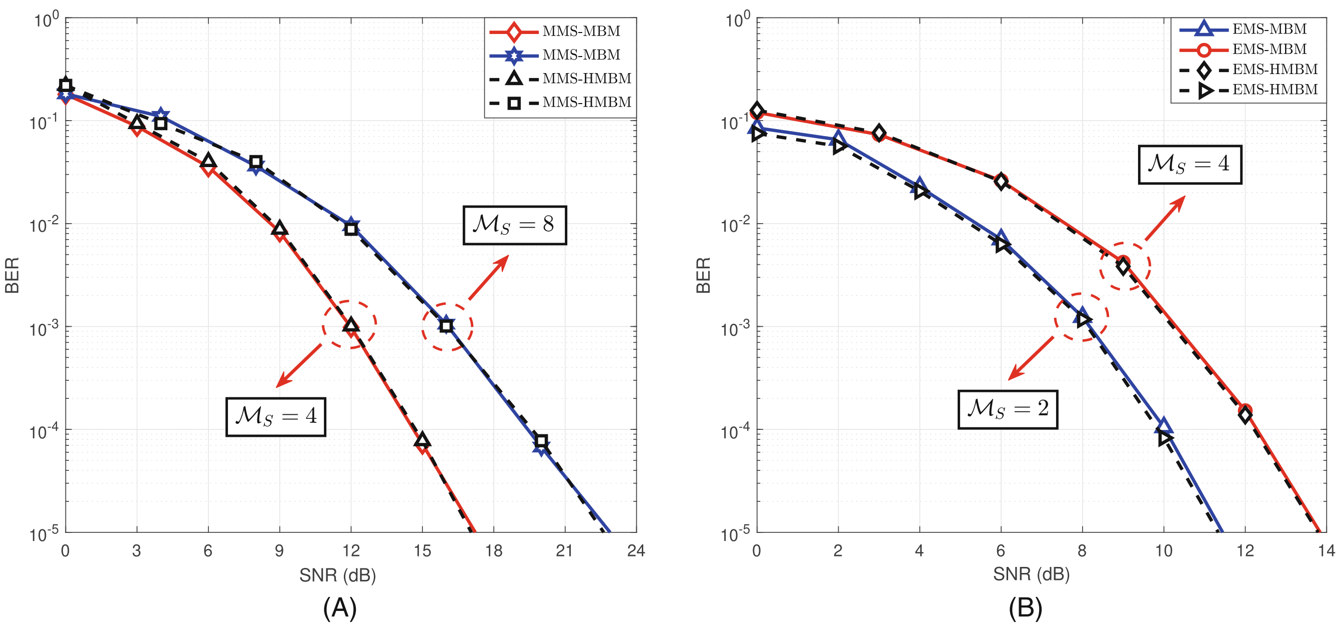

FIGURE 7 Simulation performance results of the MMS-MBM and MMS-HMBM system at varying $\mathcal{M}_S$ values while $\mathcal{M} = 16$, $M = 8$, and $n_R = 4$ for (A) and simulation performance results of the EDAS-MBM and EDAS-HMBM system at varying $\mathcal{M}_S$ values for $\mathcal{M} = 8$, $M = 8$, and $n_R = 4$ for (B).

TABLE 1 Data rate comparisons of the SM, and MBM systems (bits/s/Hz).

M	N_T	n_{rf}	SM	MBM
4	2	3	3	5
8	4	5	5	8
16	8	7	7	11

Performance curves of EDAS-SM, EDAS-HSM, EMS-MBM, and EMS-HMBM systems are given in Figure 6A. It is seen that the EMS-MBM and EMS-HMBM systems have better performance than the EDAS-SM and EDAS-HSM systems. It is observed that the performance obtained for the $n_R = 4$ case provides a higher SNR gain than the results obtained for the $n_R = 2$ case. According to the results obtained, the EMS-MBM system provides SNR gains of 3.85 dB for $n_R = 2$ and 1.35 dB for $n_R = 4$ compared to the EDAS-SM system. Also, the performance curves of the CMS-MBM system are presented at varying $\mathcal{M}_S$ values in Figure 6B. The performance results show that while BER performance deteriorates as $\mathcal{M}_S$ value increases, BER performance improves as $\mathcal{M}_S$ value decreases.

Figure 7A presents the performance results for the different $\mathcal{M}_S$ values of the MMS-MBM and MMS-HMBM systems. Also, in Figure 7B, performance curves of the EMS-MBM and EMS-HMBM systems are given for varying $\mathcal{M}_S$ values. According to all performance results, it is observed that as the $\mathcal{M}_S$ value increases, the performance deteriorates, but the data rate increases. Therefore, considering the system requirements, the number of $\mathcal{M}_S$ should be chosen reasonably.

In Table 1, the data rates of SM, QSM, and MBM systems are compared for varying M, n_T, and n_{rf} values in (bits/s/Hz). As can be seen from Table 1, the data rate of the MBM system increases faster than the SM system due to the increase in M, n_T, and n_{rf} values. Therefore, since the CMS-MBM, MMS-MBM, and EMS-MBM systems proposed in this article are based on MBM systems, these proposed systems provide high data rate and high SE.

In conclusion, it has been observed that the proposed EMS-MBM, CMS-MBM, and MMS-MBM systems have better error performance than EDAS-SM, COAS-SM, ACAS-SM, MBM, and SM systems. Also, in all performance results, it is seen that QAM and HQAM-based systems have similar BER performance.

5 | CONCLUSIONS

In this article, new high-performance and high data rate CMS-HMBM, MMS-HMBM, and EMS-HMBM systems are presented. When CMS, MMS, and EMS techniques are integrated into the HMBM system, it is seen that the system performance improves significantly. Also, it is observed that CMS-HMBM, MMS-HMBM, EMS-HMBM, CMS-MBM, MMS-MBM, and EMS-MBM systems have provided SNR gains compared to SM, MBM, HSM, HMBM, COAS-SM, ACAS-SM, EDAS-SM, COAS-HSM, ACAS-HSM, and EDAS-HSM systems for the same SE. Moreover, since the proposed systems are based on MBM, they are high data rate systems, and also, since they are based on CMS, MMS, and EMS, they are high-performance systems. The performance of energy efficient HQAM-based systems and QAM-based systems are compared. According to the results obtained, it is observed that HQAM-based and QAM-based systems provide very close performance to each other. As a result, the proposed CMS-HMBM, MMS-HMBM, and EMS-HMBM systems provide better performance and higher SE than COAS-SM, COAS-HSM, ACAS-SM, ACAS-HSM, EDAS-SM, EDAS-HSM, SM, HSM, MBM, and HMBM systems for equivalent system parameters.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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