

Reconfigurable Intelligent Surface-Aided Spatial Media-Based Modulation

Burak Ahmet Ozden^{1b}, Erdogan Aydin^{1b}, and Fatih Cogen

Abstract—The demands for high data rate, reliability, high energy efficiency, high spectral efficiency, and low latency communication have been increasing rapidly. For this reason, communication models that use limited resources in the best way, allow fast data transmission, and increase performance have become very important. In this work, a novel high energy and spectral efficient reconfigurable intelligent surface-aided spatial media-based modulation system (RIS-SMBM) is proposed for Rayleigh fading channels. In addition to the bits carried in the M -ary quadrature amplitude modulation (M -QAM) symbol while media-based modulation (MBM) provides data bits to be carried in the indices of different channels according to the radio frequency (RF) mirrors are on or off, spatial modulation (SM) provides data bits to be carried in the indices of the transmit antennas. By combining these two modulation schemes, the spectral efficiency increases considerably since the amount of information transmitted in the same time interval is substantially increased. The optimal maximum-likelihood (ML) detector and the enhanced low-complexity (ELC) detector for the RIS-SMBM system are proposed. The ELC detector achieves near ML performance while reducing the complexity of the optimal ML detector for the proposed RIS-SMBM system. We analyze the average bit error rate (ABER), throughput, complexity, and energy efficiency for the RIS-SMBM scheme and verify the analytical and theoretical results with Monte Carlo simulations. It has been observed that the proposed system provides better error performance as well as providing higher spectral and energy efficiency than benchmark systems. Also, the effect of imperfect channel state information on the performance of the proposed RIS-SMBM system is investigated.

Index Terms—Media-based modulation, index modulation, spatial modulation, spatial media-based modulation, reconfigurable intelligent surface.

I. INTRODUCTION

SINCE advanced communication technologies such as 5G and 6G have been mentioned in the communication literature, and systems that can be used in integration with these technologies have become much more essential. These

systems focus on features such as low energy consumption, high bandwidth, high data rate, and low latency. In wireless communication, obstacles in the communication path between the receiver and the transmitter and random changes in the communication channel is a severe problem that reduces the quality of the signal. Thus, many communication architectures and models have been presented to minimize the disruptive effects of the wireless channel on the signal [1], [2].

Index modulation (IM) schemes have a very important place in wireless communication due to the advantages they offer and their common use. The IM technique is a technique that makes it possible to carry information in the indices of the basic elements used in wireless communication systems [3], [4], [5]. IM-based systems provide high spectral efficiency, low complexity, high performance, high data rate, hardware simplicity, and high energy efficiency [6], [7], [8], [9], [10]. Among the various IM schemes, the spatial modulation (SM) system is a prominent member that distinguishes itself with its widespread usage and numerous advantages [11]. The SM technique is a modulation technique based on the principle of transmitting some of the data bits through the index of the active transmit antenna, in addition to carrying information in symbols [12]. According to the symbol selected in the SM, the antenna that will be active in the transmission is determined. The SM technique provides significant benefits such as increasing spectral and energy efficiency, reducing receiver complexity, eliminating inter-channel interference (ICI), and increasing error performance [13], [14], [15]. The quadrature SM (QSM) technique doubles the amount of information carried in the transmitter antenna indices by activating two antennas instead of one in the transmitter compared to the SM technique [14]. The QSM technique is remarkable for its higher spectral efficiency and better performance than its counterpart, the SM technique. Performance analysis of the QSM integrated into a multiple-input multiple-output (MIMO) system over Nakagami- m channels is presented in [16]. A new system combining QSM and media-based modulation (MBM) is proposed in [17]. It is observed that the proposed system provides higher spectral efficiency and better error performance than QSM and MBM systems.

The MBM technique, which is the new and outstanding scheme of the IM family, is a digital communication method that draws attention to the benefits it provides to wireless communication schemes. In the MBM, data bits are carried in the indices of different channels, which are formed due to the change of the radiation pattern according to the on-off state of the radio frequency (RF) mirrors [18], [19], [20]. The spectral

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efficiency in the MBM directly depends on the number of RF mirrors. This means that it is possible to significantly increase energy efficiency by keeping the number of transmit antennas constant and only increasing the number of RF mirrors [21]. For this reason, MBM is seen to be much better in terms of performance when compared to other IM techniques. The RF mirrors used in the MBM system do not need hardware structures such as mixers and filters [22]. The fact that there is no need for complex hardware structures will bring advantages such as hardware simplicity and low cost. In [21], important works such as MBM with generalized SM (GSM-MBM) and mirror activation pattern (MAP) selection for the MBM system are presented. According to the results obtained, it is seen that the GSM-MBM system provides better performance than the traditional MBM system. The performance results of a system called SM-aided MBM (SMBM), which is obtained by combining SM and MBM techniques in a MIMO system, are presented in [23]. Also, low-complexity MAP selection techniques are presented for the SMBM system.

Reconfigurable intelligent surface (RIS) which is a new technology with significant communication capabilities is an effective solution to combat the wireless channel's disruptive effects. Thanks to RIS technology, the negative effects of the channel on the signal can be decreased by controlling the scattering and reflection properties of the signals that are exposed to disruptive effects in the wireless channel. RISs are distinguished from others by the many advantages they offer when compared to counterpart technologies. They stand out with their serious advantages such as not needing any signal processing, power amplification, and filtering processes. Also, they are very low cost, support full-duplex, and full-band transmission, and have flexible usage areas [24], [25]. It is predicted that RIS technology will be widely used in advanced new-generation communication networks, as it has the potential to meet the requirements brought by technological developments. Performance analysis of the SM scheme is investigated for the rapidly time-varying Rayleigh fading channels in [26]. In [27], RIS-assisted IM schemes including RIS-aided SM (RIS-SM) and RIS-aided space shift keying (RIS-SSK) techniques are introduced. RIS-based MBM scheme is presented and RIS has been designed, aiming to demonstrate the diversity of radiation patterns in the 5G communication system in [28]. In [29], a deep learning technique is presented for the efficient wireless configuration of RISs in indoor environments. In [30], over Weibull fading channels RIS-SSK/SM systems are proposed for the perfect and imperfect channel phase knowledge states at the receiver. As a result, there is an abundance of research in the literature focused on exploring the potential of IM-based RIS systems for various wireless communication applications [31], [32], [33], [34], [35]. With the ongoing research efforts, it is expected that IM-based RIS systems will play a critical role in enabling the next generation of wireless communication networks.

A. Contributions

In this article, a novel wireless communication system called RIS-SMBM is proposed. In the proposed system, the data

bits are mapped to antenna indices, and the indices of different channels are formed according to the on-off state of the RF mirrors in addition to conventional constellation symbols. Based on our theoretical derivations, performance analyses, and simulation results, the contributions of our article are given item by item as follows:

- 1) We proposed a combined system consisting of the SM and MBM schemes based RIS system, called RIS-SMBM, to improve the data rate, spectral efficiency, error performance, and energy efficiency by exploiting the multiple RF chains in the SMBM system.
- 2) Theoretical expressions for the average bit error rate (ABER), complexity, energy efficiency, throughput, and data rate analysis of the RIS-SMBM scheme are derived.
- 3) We propose an optimal maximum-likelihood detector (ML) and an enhanced low-complexity (ELC) detector for the RIS-SMBM system. The ELC detector achieves near ML performance while reducing the complexity of the optimal ML detector for the proposed RIS-SMBM system.
- 4) The ABER performance results of the RIS-SMBM system are compared with the RIS-SM, RIS-aided QSM (RIS-QSM), and RIS-empowered MBM (RIS-MBM) techniques. Simulation results prove that the RIS-SMBM system provides better error performance and high spectral efficiency than these benchmark systems while consuming less transmission energy.
- 5) The theoretical, analytical, and simulation results of the RIS-SMBM system are obtained and it is observed that the results are very close to each other.
- 6) We investigate how the imperfect channel state information (CSI) affects the error performance of the proposed RIS-SMBM system.

B. Organization and Notation

The rest of this article is organized as follows. In Section II, the proposed RIS-SMBM system model is introduced. The performance analysis of the proposed system is given in Section III. In Section IV, energy efficiency, throughput, data rate, and complexity analysis are presented. In Section V, simulation results, performance comparisons, and discussions are proposed. Finally, Section VI concludes the article.

Notation: The following notation is considered for this work. $i)$ $(\cdot)^T$, $(\cdot)^H$, $\|\cdot\|_F$, $E[\cdot]$, and $|\cdot|$ express transpose, Hermitian, Frobenius norm, expectation, and Euclidean norm operators, respectively. $i)$ Bold lower/upper case symbols represent vectors/matrices; $\Re(\cdot)$ and $\Im(\cdot)$ are the real and imaginary elements of a complex number.

II. SYSTEM MODEL

The signal model, channel model, ML detector, ELC detector, and impact of imperfect channel state information for the proposed RIS-SMBM system are presented in this section.

A. RIS-SMBM Signal Model

This paper presents a novel high-performance wireless communication system called RIS-SMBM. Fig. 1 shows the

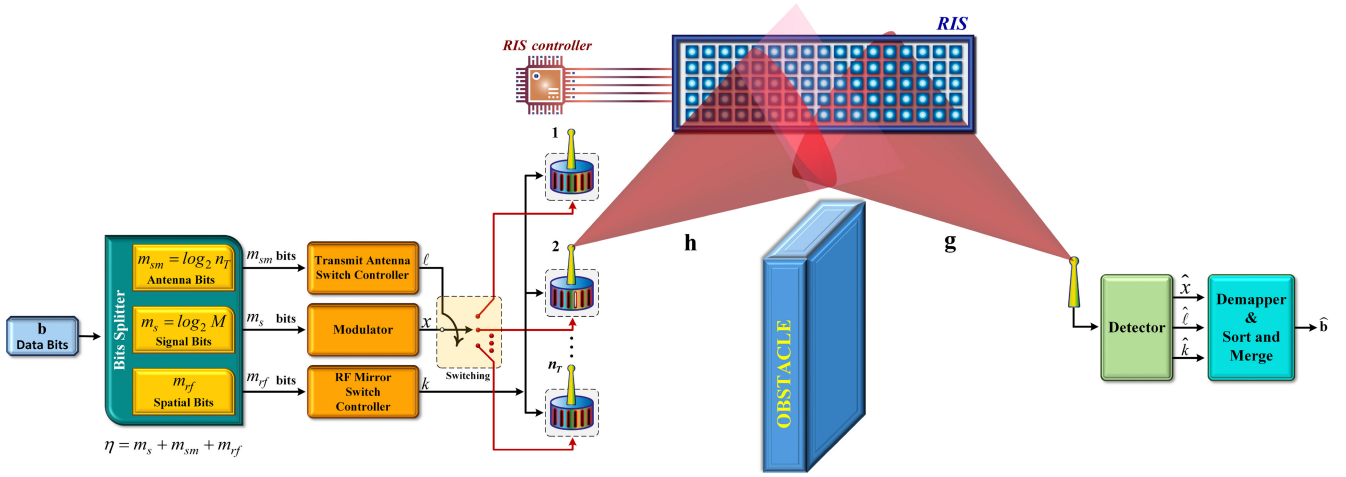


Fig. 1. The proposed RIS-SMBM scheme.

system model of the RIS-SMBM system, which consists of one source terminal (ST), one RIS, and one destination terminal (DT). In the considered system model, there is no direct line of sight (LOS) link between ST-DT. The reason for this can be presented as obstacles such as buildings, constructions, and natural structures shown in Fig. 1. Hence, the ST and the DT communicate with each other through the RIS. We consider the RIS to be connected to a microcontroller through a communication-oriented software and consists of N reconfigurable intelligent reflecting elements which are deployed to assist data transmission to the DT by reflecting an incident RF signal transmitted by an ST. In the proposed system, ST has n_T transmit antennas, and the RT adopts single-antenna reception for a simple receiver structure. Each transmit antenna is equipped with m_{rf} RF mirrors. In the RIS-SMBM system, the on/off status of the available m_{rf} RF mirrors are determined by the incoming m_{rf} bits. Since each mirror can be on or off, a total of $2^{m_{rf}}$ different mirror activation patterns (MAPs) occur. Thus, different channel realizations up to $\mathcal{F} \triangleq 2^{m_{rf}}$, which is also the size of the MBM channel alphabet, can be occurred for each transmit antenna. In Fig. 1, $h_{\ell,k}^n$ and g_n are the fading channels between the ST and the RIS, and between the RIS and DT for the ℓ th transmit antenna, k th MAP state and n th reflecting meta-surface respectively, where $\ell \in \{1, 2, \dots, n_T\}$, $k \in \{1, 2, \dots, \mathcal{F}\}$, and $n \in \{1, 2, \dots, N\}$. For the ℓ th transmit antenna and k th MAP state, channel vectors between the ST→RIS, and the RIS→DT can be expressed as $\mathbf{h}_{\ell,k} = [h_{\ell,k}^1, h_{\ell,k}^2, \dots, h_{\ell,k}^N]^T \in \mathbb{C}^{N \times 1}$ and $\mathbf{g} = [g_1, g_2, \dots, g_N]^T \in \mathbb{C}^{N \times 1}$. We have $h_{\ell,k}^n, g_n \sim \mathcal{CN}(0, 1)$, and here $\mathcal{CN}(0, \sigma^2)$ represents complex Gaussian distribution has zero mean and σ^2 variance. It is supposed to have perfect CSI in DT.

The RIS-SMBM scheme makes use of the MBM technique to increase the spectral efficiency of the SM scheme. Therefore, the RIS-SMBM system utilizes two indices which are the active transmit antenna index and the active MAP index to convey information bits stream. In Fig. 1, the incoming data bits expressed by the vector $\mathbf{b}$ have dimensions $1 \times \eta$ is the sequence of data bits to be conveyed during one symbol period

TABLE I
MAPPING PROCEDURE FOR THE PROPOSED RIS-SMBM SYSTEM

	Input bits (η)	Symbol bits (m_S)	Spatial bits (m_{rf})	Antenna bits (m_{SM})
$M = 4$ $m_{rf} = 2$ $n_T = 4$	[111001] $\eta = 6$	[11] $x_4 = 1 - j$	[10] $k = 3$	[01] $\ell = 2$
$M = 8$ $m_{rf} = 3$ $n_T = 16$	[0101010100] $\eta = 10$	[010] $x_3 = -1 + j$	[101] $k = 6$	[0100] $\ell = 5$

(T_s). In the proposed system, $\mathbf{b}$ is split into three subgroups, which consist of the following three parts:

- $m_S = \log_2(M)$ bits map to a M -QAM symbol x_p , here $p \in \{1, 2, \dots, M\}$,
- m_{rf} bits are used to select the k th MAP,
- the remaining $m_{SM} = \log_2(n_T)$ bits are mapped to select a transmit antenna with index ℓ .

For these subgroups, m_S bits are transmitted an M -QAM symbol, whereas m_{rf} bits are conveyed with MAPs state, and the m_{SM} bits are transmitted in the active antenna index of the SM system. Finally, as can be shown from the transmitter of the RIS-SMBM scheme, the selected symbol is conveyed over the MAP state, and the single transmit antenna is activated by the SM technique.

Eventually, the spectral efficiency of the RIS-SMBM system can be written as follows:

$$\eta = \log_2(M) + m_{rf} + \log_2(n_T) \text{ [bits/s/Hz]}. \quad (1)$$

A tabular representation of the bit mapping for the RIS-SMBM system is presented in Table I. Considering Table I, an example of the mapping procedure of RIS-SMBM can be given. Suppose that the bit stream $\mathbf{b} = [111001]$ will be transmitted by the ST using the following system parameters: $M = 4$, $m_{rf} = 2$, $n_T = 4$ and $\eta = 6$ bits. Assume that the data bits stream is grouped as follows:

$$\mathbf{b} = [\underbrace{11}_{m_S \text{ bits}} \underbrace{10}_{m_{rf} \text{ bits}} \underbrace{01}_{m_{SM} \text{ bits}}]. \quad (2)$$

E. Impact of Imperfect Channel State Information on RIS-SMBM Scheme

In the absence of perfect CSI in the receiver, the impact of the channel estimate errors on the RIS-SMBM system will be discussed in this section. $h_{\ell,k}^n$ and g_n may be stated as follows, assuming that there is orthogonality between the estimate of the channel coefficients ($\tilde{h}_{\ell,k}^n, \tilde{g}_n$) and the estimation errors ($\epsilon_{h_{\ell,k}^n}, \epsilon_{g_n}$) [37]:

$$h_{\ell,k}^n = \tilde{h}_{\ell,k}^n + \epsilon_{h_{\ell,k}^n}, \quad g_n = \tilde{g}_n + \epsilon_{g_n}. \quad (12)$$

It is assumed that $h_{\ell,k}^n$ and $\tilde{h}_{\ell,k}^n$ and also g_n and $\tilde{g}_n$ have a jointly ergodic and stationary Gaussian process. The channel estimation errors denoted as $\epsilon_{h_{\ell,k}^n}$ and ϵ_{g_n} are represented as a complex Gaussian variable with a zero mean and σ_ϵ^2 variance, that is, $CN(0, \sigma_\epsilon^2)$. The change in channel estimation performance in this model is represented by $\sigma_\epsilon^2 = 1/SNR$, which might have multiple definitions depending on the channel dynamics and the channel estimation techniques. When using orthogonal pilot channel estimation symbols, adding more pilot symbols results in a linear decrease in estimate error.

The ML detector in equation (10) may be reformulated for the RIS-SMBM system as follows in the case of absence of perfect CSI:

$$[\hat{x}, \hat{\ell}, \hat{k}] = \arg \min_{(\ell, k, p)} \left\| y - \sqrt{E_s} \tilde{\mathbb{H}} \mathbf{x} \right\|^2, \quad (13)$$

where, $\tilde{\mathbb{H}} = \left[\dots \left| \begin{matrix} \tilde{\mathbf{h}}_{k,1}^T & \tilde{\mathbf{g}} \\ \tilde{\mathbf{h}}_{k,2}^T & \tilde{\mathbf{g}} \\ \vdots & \vdots \\ \tilde{\mathbf{h}}_{k,n_T}^T & \tilde{\mathbf{g}} \end{matrix} \right| \dots \right]$, where $\tilde{\mathbf{h}}_{k,\ell} = [\tilde{h}_{\ell,k}^1, \tilde{h}_{\ell,k}^2, \dots, \tilde{h}_{\ell,k}^N]^T$, $\tilde{\mathbf{g}} = [\tilde{g}_1, \tilde{g}_2, \dots, \tilde{g}_N]^T$, and $\tilde{\Phi} = \text{diag}\{e^{j\tilde{\phi}_{\ell,k}^1}, e^{j\tilde{\phi}_{\ell,k}^2}, \dots, e^{j\tilde{\phi}_{\ell,k}^N}\}$.

III. PERFORMANCE ANALYSIS OF RIS-SMBM SYSTEM

In this section, the ABER of the RIS-SMBM technique is analyzed. The original bits of information transmitted from the transmitter may be obtained erroneously at the receiver side, due to the fading effect of the Rayleigh channel and the noise. Examining the pairwise error probability (PEP), which gives information about the probability of making an erroneous decision, is important for analytical error analysis. By using the well-known upper bounding technique, the ABER of the RIS-SMBM system is described as follows:

$$\mathbb{P}_{\text{RIS-SMBM}} \approx \frac{1}{\eta 2^\eta} \sum_{i=1}^{2^\eta} \sum_{j=1}^{2^\eta} \mathbb{P}(\mathbf{x}_i \rightarrow \hat{\mathbf{x}}_j) e_{i,j}, \quad (14)$$

where, $\mathbb{P}(\mathbf{x}_i \rightarrow \hat{\mathbf{x}}_j)$ represents the average PEP given in (14), and $e_{i,j}$ is defined as the number of bit errors associated with the corresponding pairwise error event.

When $\mathbf{x}_{i,p}$ is transmitted and it is erroneously detected as $\mathbf{x}_{\hat{i},\hat{p}}$, the conditional PEP (CPEP) of the proposed system is given as follows:

$$\begin{aligned} \mathbb{P}(\mathbf{x}_{i,p} \rightarrow \mathbf{x}_{\hat{i},\hat{p}} \mid \mathbb{H}) \\ = \mathbb{P}\left(\left|y - \mathbb{H}\mathbf{x}_{i,p}\right|^2 > \left|y - \mathbb{H}\mathbf{x}_{\hat{i},\hat{p}}\right|^2\right) \end{aligned}$$

$$\begin{aligned} &= \mathbb{P}\left(\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2 - 2\Re\left\{w^H \left(\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right)\right\} > 0\right) \\ &= \mathbb{P}(\mathcal{U} > 0), \end{aligned} \quad (15)$$

where $\mathcal{U} \sim \mathcal{N}(\mu_{\mathcal{U}}, \sigma_{\mathcal{U}}^2)$ is a Gaussian distributed random variable, where $\mu_{\mathcal{U}}$ and $\sigma_{\mathcal{U}}^2$ can be given as follows respectively:

$$\begin{aligned} \mu_{\mathcal{U}} &= E\left\{\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2 - 2\Re\left\{w^H \left(\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right)\right\}\right\} \\ &= E\left\{\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2\right\} - \left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2, \end{aligned} \quad (16)$$

$$\begin{aligned} \sigma_{\mathcal{U}}^2 &= \text{Var}\left\{\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2 - 2\Re\left\{w^H \left(\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right)\right\}\right\} \\ &= 4\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2 \text{Var}(w^H) = 2N_0 \left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2. \end{aligned} \quad (17)$$

Considering the proposed RIS-SMBM system model, depending on the correct and incorrect detection of the index i in (7), which includes the information of active MAP and active antenna indices, two cases occur.

Case 1: Incorrect detection of the index i , $i \neq \hat{i}$. In the first case, when the index i is detected incorrectly, the CPEP function can be written in terms of $Q(\cdot)$ as follows:

$$\mathbb{P}(\mathbf{x}_{i,p} \rightarrow \mathbf{x}_{\hat{i},\hat{p}} \mid \mathbb{H}) = Q\left(\sqrt{\frac{\left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2}{2N_0}}\right). \quad (18)$$

To calculate the total ABER performance, one can define as $\Gamma = |\gamma|^2 = \left|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})\right|^2$ and make use of the alternative form of the Q -function. With this approach, the unconditional PEP (UPEP) can be determined through the following expressions:

$$\begin{aligned} \mathbb{P}(\mathbf{x}_i \rightarrow \hat{\mathbf{x}}_j) &= \int_0^\infty Q\left(\sqrt{\frac{\Gamma}{2N_0}}\right) f_\Gamma(\Gamma) d\Gamma \\ &= \frac{1}{\pi} \int_0^\infty \int_0^{\pi/2} \exp\left(-\frac{\Gamma}{4\sin^2(\omega N_0)}\right) f_\Gamma(\Gamma) d\omega d\Gamma \\ &= \frac{1}{\pi} \int_0^{\pi/2} M_\Gamma\left(-\frac{1}{4\sin^2(\omega N_0)}\right) d\omega, \end{aligned} \quad (19)$$

where $f(\cdot)$ is the probability density function (PDF). As seen in (19), the $M_\Gamma(\cdot)$ which is the moment generating function (MGF) of the Γ , is needed to calculate the UPEP expression. It is possible to express as $|\gamma|^2 = \gamma_{\Re}^2 + \gamma_{\Im}^2$. Then Γ can be re-expressed as follows:

$$\Gamma = \gamma_{\Re}^2 + \gamma_{\Im}^2 = \left| \sum_{n=1}^N \mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}}) e^{-j(\phi_{n,i} - \phi_{n,\hat{i}})} \right|^2. \quad (20)$$

Considering (20), according to the central limit theorem (CLT), it is clear that for increasing values of N , $\gamma_{\Re}^2$, and $\gamma_{\Im}^2$ follow a complex Gaussian distribution. Then, the MGF of Γ can be derived according to the general quadratic form of correlated Gaussian random variables.

It can be expressed as $\Gamma = \mathbf{z}^T \mathbf{K} \mathbf{z}$ when $\mathbf{z} = [\gamma_{\Re}^2 \gamma_{\Im}^2]^T$ and $\mathbf{K} = \mathbf{I}_2$. Also, the covariance matrix and the mean vector of $\mathbf{z}$ are derived as follows, respectively:

$$\mathbf{C} = \begin{bmatrix} \sigma_1^2 & \sigma_{1,2} \\ \sigma_{2,1} & \sigma_2^2 \end{bmatrix}, \quad \mathbf{m} = \begin{bmatrix} \frac{N}{4} \pi(x_p)_{\Re} & \frac{N}{4} \pi(x_p)_{\Im} \end{bmatrix}, \quad (21)$$

where σ_1^2 , $\sigma_{1,2} = \sigma_{2,1}$, and σ_2^2 are defined as follows:

$$\begin{aligned} \sigma_1^2 &= \frac{N}{16} \left((16 - \pi^2) (x_p)_{\Re}^2 \right) + \frac{N}{2} |x_{\hat{p}}|^2 \\ \sigma_{1,2} &= \frac{N}{16} \left((16 - \pi^2) (x_p)_{\Re} (x_p)_{\Im} \right) \\ \sigma_2^2 &= \frac{N}{16} \left((16 - \pi^2) (x_p)_{\Im}^2 \right) + \frac{N}{2} |x_{\hat{p}}|^2. \end{aligned} \quad (22)$$

Based on these pieces of information, the MGF of Γ can be expressed as follows:

$$\begin{aligned} M_{\Gamma}(s) &= \left[\det(\mathbf{I} - 2s\mathbf{K}\mathbf{C}) \right]^{-1/2} \\ &\times \exp \left\{ \frac{1}{2} \mathbf{m} \{ \mathbf{I} - (\mathbf{I} - 2s\mathbf{K}\mathbf{C})^{-1} \} \mathbf{C}^{-1} \mathbf{m} \right\} \end{aligned} \quad (23)$$

Finally, substituting (23) into (19) provides the desired UPEP which includes the incorrect detection of index i .

Case 2: Correct detection of the index i , $i = \hat{i}$. In the second case, when the index i is correctly estimated, the CPEP function is expressed as follows:

$$\mathbb{P}(\mathbf{x}_{i,p} \rightarrow \mathbf{x}_{\hat{i},\hat{p}} \mid \mathbb{H}) = Q \left(\sqrt{\frac{|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})|^2}{2N_0}} \right). \quad (24)$$

Considering that $\Gamma = |\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})|^2$ and the MGF of Γ is expressed as follows:

$$\begin{aligned} M_{\Gamma}(s) &= \left(\frac{1}{1 - \frac{sN(16-\pi^2)|x_{i,p} - x_{\hat{i},\hat{p}}|^2}{8}} \right)^{1/2} \\ &\times \exp \left\{ \frac{\frac{sN^2\pi|x_{i,p} - x_{\hat{i},\hat{p}}|^2}{16}}{1 - \frac{sN(16-\pi^2)|x_{i,p} - x_{\hat{i},\hat{p}}|^2}{8}} \right\}. \end{aligned} \quad (25)$$

Substituting (25) into (19) gives the desired UPEP, which includes the correct detection of index i . Consequently, by substituting (19) into (14), we obtain the average total probability of the error for the RIS-SMBM system.

Also, the UPEP is achieved analytically via computer simulations by averaging the PEP values over a large number of channel realizations for each SNR value for case 2 (it can also be simply written for case 1) as follows:

$$\begin{aligned} \mathbb{P}(\mathbf{x}_{i,p} \rightarrow \mathbf{x}_{\hat{i},\hat{p}}) &= E_{\mathbb{H}} \left\{ \mathbb{P}(\mathbf{x}_{i,p} \rightarrow \mathbf{x}_{\hat{i},\hat{p}} \mid \mathbb{H}) \right\} \\ &= E_{\mathbb{H}} \left\{ Q \left(\sqrt{\frac{|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{\hat{i},\hat{p}})|^2}{2N_0}} \right) \right\}, \end{aligned} \quad (26)$$

where $E_{\mathbb{H}}\{\cdot\}$ is the expectation with respect to the channel vector $\mathbb{H}$.

TABLE II
ENERGY-SAVING COMPARISONS OF RIS-SMBM SYSTEM IN
PERCENTAGE COMPARED TO RIS-SM, RIS-MBM,
AND RIS-QSM SYSTEMS ($\mathcal{E}_{\text{sav}}$ %)

M	n_T	m_{rf}	RIS-SM	RIS-MBM	RIS-QSM
8	4	5	50.00%	20.00%	30.00%
16	16	10	55.56%	22.22%	33.33%
32	64	15	57.69%	23.08%	34.62%

Finally, the analytical ABER of the RIS-SMBM system is described as follows:

$$\begin{aligned} \mathbb{P}_{\text{RIS-SMBM}} &\approx \frac{1}{\eta 2^\eta} \sum_{i=1}^{2^\eta} \sum_{j=1}^{2^\eta} E_{\mathbb{H}} \left\{ Q \left(\sqrt{\frac{|\mathbb{H}(\mathbf{x}_{i,p} - \mathbf{x}_{j,\hat{p}})|^2}{2N_0}} \right) \right\} e_{i,j}. \end{aligned} \quad (27)$$

IV. THE ENERGY EFFICIENCY, THROUGHPUT, DATA RATE, AND COMPLEXITY ANALYSIS FOR RIS-SMBM SYSTEM

In this section, energy efficiency, throughput, data rate, and complexity analyses, which are important performance criteria, are obtained. Also, the energy efficiency, throughput, data rate, and complexity analyses of the RIS-SMBM scheme are compared with the RIS-SM, RIS-MBM, and RIS-QSM systems.

A. The Energy Efficiency Analysis

In the proposed RIS-SMBM system, most of the information bits are carried in the active transmit antenna index and the active MAP index. When information bits are transmitted in indices, little or no energy is consumed. Therefore, the RIS-SMBM system provides high energy efficiency. The percentage of energy-saving ($\mathcal{E}_{\text{sav}}$) per η bits of the RIS-SMBM system compared to other benchmark systems is defined as follows:

$$\mathcal{E}_{\text{sav}} = \left(1 - \frac{n_b}{\eta} \right) E_b \%, \quad (28)$$

where E_b is the bit energy and n_b is the spectral efficiency of benchmark systems. The percentage of energy efficiency provided by the RIS-SMBM system compared to the RIS-SM, RIS-MBM, and RIS-QSM benchmark systems is presented in Table II. Three different cases are considered for different M , n_T , and m_{rf} values, and the percentage of energy efficiency provided by the RIS-SMBM system is calculated for all cases. It is seen that the RIS-SMBM system provides higher energy efficiency than all the benchmark systems. For example, for the first case $M = 8$, $n_T = 4$ and $m_{rf} = 5$ in Table II, the RIS-SMBM system provides 50%, 20%, and 30% higher energy efficiency than RIS-SM, RIS-MBM, and RIS-QSM systems, respectively.

B. The Throughput and Data Rate Analysis

The throughput for the considered system is defined as the number of bits that can be correctly obtained at the

TABLE III
DATA RATE COMPARISONS IN [BITS/S/Hz] FOR RIS-SM,
RIS-MBM, RIS-QSM, AND RIS-SMBM SCHEMES

n_T	m_{rf}	M	RIS-SM	RIS-MBM	RIS-QSM	RIS-SMBM
2	8	16	5	12	6	13
8	5	4	5	7	8	10
32	10	8	8	13	13	18

TABLE IV
A COMPARATIVE EVALUATION OF THE COMPUTATIONAL COMPLEXITY

Systems	Real Multiplications (RMs)
$\mathcal{O}_{\text{RIS-SMBM (ML)}}$	$(N + 4M)n_T 2^{m_{rf}}$
$\mathcal{O}_{\text{RIS-SMBM (ELC)}}$	$3(1 + \frac{M+N}{4})n_T 2^{m_{rf}}$
$\mathcal{O}_{\text{RIS-SM}}$	$(N + 4M)n_T \left(1 + \frac{m_{rf}}{n_S + n_{SM}}\right)$
$\mathcal{O}_{\text{RIS-QSM}}$	$(N + 4M)n_T \left(1 + \frac{m_{rf}}{n_S + 2n_{SM}}\right)$
$\mathcal{O}_{\text{RIS-MBM}}$	$(N + 4M)2^{m_{rf}} \left(1 + \frac{n_{SM}}{n_S + m_{rf}}\right)$

receiver. According to this definition, the throughput for the RIS-SMBM system is expressed as [38]:

$$\mathcal{T} = \frac{(1 - \mathbb{P}_{\text{RIS-SMBM}})}{T_s} \eta, \quad (29)$$

where $(1 - \mathbb{P}_{\text{RIS-SMBM}})$ is defined as the probability of correct bits obtained by the receiver of the RIS-SMBM system during the symbol transmission period T_s . Considering Table III, it is seen that the amount of information bits transmitted during a symbol period of the RIS-SMBM system is higher than the RIS-SM, RIS-MBM, and RIS-QSM systems. Therefore, it is clear that the proposed RIS-SMBM system provides high throughput.

C. Complexity Analysis

This section offers the receiver computational complexities of the proposed RIS-SMBM system and benchmark systems. Computational complexity expressions of RIS-SMBM, RIS-SM, RIS-QSM, and RIS-MBM systems are given in Table IV. The computational complexity of the systems is calculated in terms of real multiplications (RMs). The computational complexity of the proposed RIS-SMBM system is higher than benchmark systems, since both the transmit antenna index and the MAP index are used in information transmission. However, despite its high complexity, the RIS-SMBM system provides higher spectral efficiency and better performance than benchmark systems. Also, numerical examples of spectral efficiency and computational complexity of RIS-SM, RIS-QSM, RIS-MBM, and RIS-SMBM systems are given in Fig. 2. As can be easily seen from Fig. 2, the RIS-SMBM system has higher spectral efficiency than other systems. However, the RIS-SMBM (ML) system has considerably higher computational complexity than other systems. Therefore, an ELC detector is proposed to reduce the complexity of the RIS-SMBM system. It can be seen in Fig. 2 that the ELC detector reduces the complexity of the RIS-SMBM system.

The hardware cost of a RIS-based system depends on the number of surface elements, with more surface elements

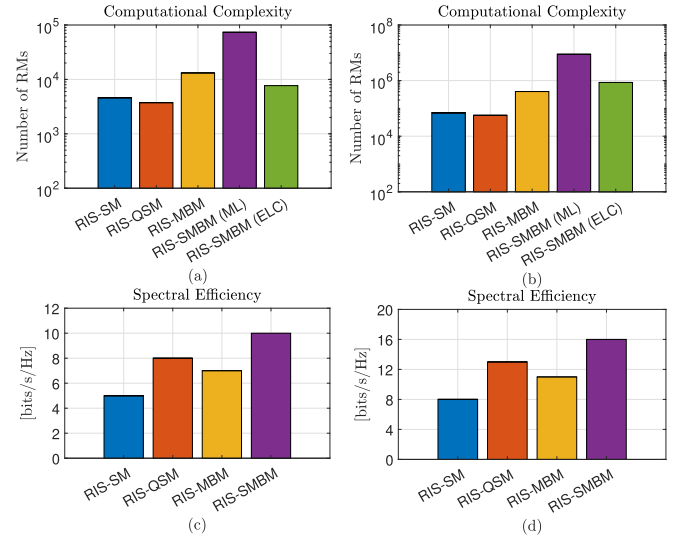


Fig. 2. Computational Complexity and Spectral Efficiency Comparisons while $M = 4$, $N_T = 8$, $m_{rf} = 5$, $N = 32$ for (a), (c); and $M = 8$, $N_T = 32$, $m_{rf} = 8$, $N = 128$ for (b), (d).

resulting in higher costs. However, increasing the number of surface elements brings benefits such as improved control of the transmitted signal, higher performance, and increased achievable throughput. Also, it is important to carefully consider the specific use case, performance requirements, and associated costs when evaluating the impact of increasing the number of surface elements [39], [40].

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, simulation results for the proposed RIS-SMBM system are presented. The proposed system is compared with its counterparts and the results are discussed. Comparison curves of the analytical and BER performances of the proposed system are given and performance changes are investigated in varying parameters. The SNR expression in the simulations is defined as $\text{SNR(dB)} = 10 \log_{10}(E_s/N_0)$. The optimal ML detector and ELC detector for the RIS-SMBM system are used for the estimation of the transmitted symbol and active indices at the receiver. All simulation results are obtained under the assumption that fading channels are uncorrelated Rayleigh distributions. Also, for all systems, the receiver antenna is selected as one.

In Fig. 3 (a), the BER performance curves including simulation, analytical and theoretical results of the RIS-SMBM system are presented for varying m_{rf} values while $M = 4$, $n_T = 64$, $N = 64$. The spectral efficiency of the RIS-SMBM system is $\eta = 4, 6, 8$ while $m_{rf} = 1, 3, 5$, respectively. When the obtained results are examined, as the m_{rf} number decreases by 2, an improvement of approximately 13 dB is observed in the BER results. As can be observed from Fig. 3 (a), when the number of m_{rf} decreases, the number of transmitted information decreases, but the BER performance improves. The BER performances of the proposed RIS-SMBM system in Fig. 3 (b) are given and compared with theoretical and analytical results for $M = 4$, $n_T = 4$, and $m_{rf} = 2$ at varying N values. The simulation, theoretical, and analytical

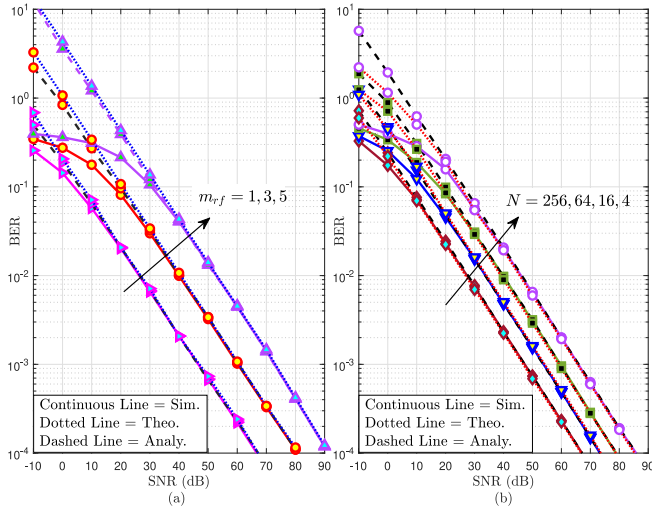


Fig. 3. Performance comparisons of the RIS-SMBM system (a) for $M = 4$, $n_T = 4$, $N = 64$ while $m_{rf} = 1, 3, 5$, (b) for $M = 4$, $n_T = 4$, and $m_{rf} = 2$ while $N = 4, 16, 64, 256$.

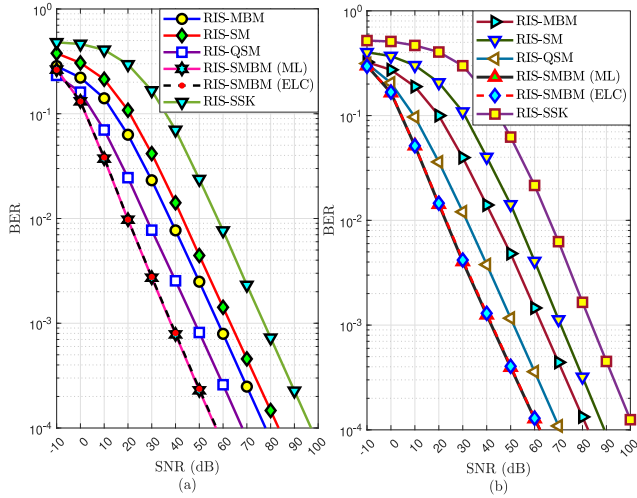


Fig. 4. Simulation performance comparisons of the RIS-SMBM, RIS-MBM, RIS-SM, RIS-QSM, and RIS-SSK systems (a) $N = 128$ and $\eta = 8$, (b) $N = 256$ and $\eta = 10$.

results are quite similar to each other. Also, as can be easily seen from the BER curves in Fig. 3 (b), it is clear that the performance of the system improves as the N parameter increases. Thus, using a reasonable number of reflecting surfaces N will enable the system to function at the desired error rates. Also, in Fig. 3 (a) and (b), the simulation and analytical curves overlap perfectly.

We present BER performance comparisons of RIS-SSK, RIS-SM, RIS-MBM, RIS-QSM, and RIS-SMBM systems for $\eta = 8$ bits/s/Hz and $N = 128$ in Fig. 4 (a). The system parameters selected for the RIS-SMBM, RIS-MBM, RIS-SM, RIS-QSM, and RIS-SSK systems are ($M = 64$, $n_T = 2$, $m_{rf} = 1$), ($M = 8$, $m_{rf} = 5$), ($M = 4$, $n_T = 64$), ($M = 4$, $n_T = 8$), and ($n_T = 256$), respectively. It is seen that the RIS-SMBM system provides better BER performance than RIS-SM, RIS-MBM, RIS-QSM, and RIS-SSK systems at the same spectral efficiency. RIS-SMBM system provides 11.10 dB, 20.86 dB, 26.35 dB, and 40.01 dB SNR gain

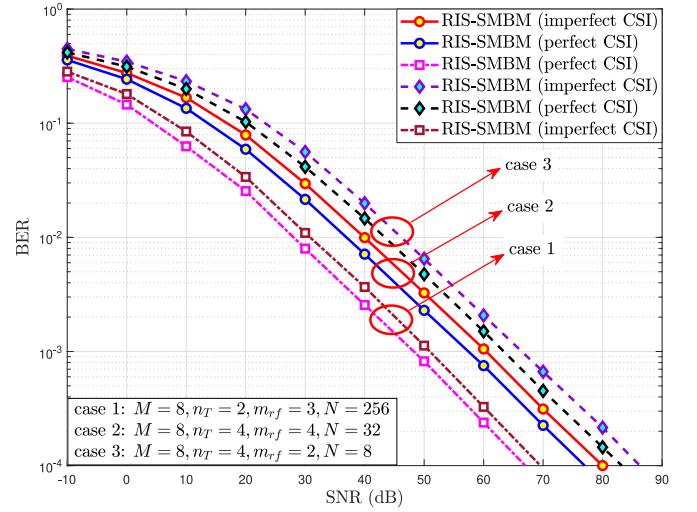


Fig. 5. Simulation performance comparisons of the proposed RIS-SMBM for perfect and imperfect CSI while $N = 8, 32, 256$ and $\eta = 7$.

according to RIS-QSM, RIS-MBM, RIS-SM, and RIS-SSK systems, respectively. It is also seen that the BER performances of the RIS-SMBM (ML) and RIS-SMBM (ELC) systems are almost the same.

Fig. 4 (b) presents the performance comparison of the RIS-SMBM system with RIS-QSM, RIS-MBM, RIS-SM, and RIS-SSK. Also, ($M = 128$, $n_T = 4$, $m_{rf} = 1$), ($M = 16$, $m_{rf} = 6$), ($M = 4$, $n_T = 256$), ($M = 4$, $n_T = 16$), and ($n_T = 1024$) are the values of the system parameters for RIS-SMBM, RIS-MBM, RIS-SM, RIS-QSM, and RIS-SSK systems, respectively. It is observed that the RIS-SMBM system provides better error performance than RIS-MBM, RIS-QSM, RIS-SM, and RIS-SSK systems when the spectral efficiency $\eta = 10$ bits/s/Hz and $N = 256$. RIS-SMBM system has 8.53 dB, 20.15 dB, 26.94 dB, and 39.67 dB SNR gain according to RIS-QSM, RIS-MBM, RIS-SM, and RIS-SSK systems, respectively. In addition, similar to the results in Fig. 4, the BER performances of the RIS-SMBM (ML) and RIS-SMBM (ELC) are pretty similar in Fig. 4 (b).

Simulation performance comparisons of the proposed RIS-SMBM system for perfect and imperfect CSI are presented with different system parameters in Fig. 5. It is observed that the error performance of the proposed RIS-SMBM system deteriorates in the case of imperfect CSI.

Three-dimensional BER performance depending on $m_{rf} = 1, 3, 5, 7, 9$ and $n_T = 2, 4, 8, 16, 32$ parameters is given in Fig. 6. Where the number of MAP bits represents the number of bits carried in the MAP indices formed according to the on/off state of the RF mirrors. In the performance results, instead of the values of the m_{rf} and n_T parameters themselves, the number of bits carried depending on these parameters is considered. It is seen that BER results improve when m_{rf} and n_T values decrease. Therefore, the results show that the minimum BER value occurs for $m_{rf} = 1$ and $n_T = 2$ and the maximum BER value occurs for $m_{rf} = 9$ and $n_T = 32$.

Fig. 7 shows the BER performance of the RIS-SMBM that changes depending on the number of MAP bits and reflecting

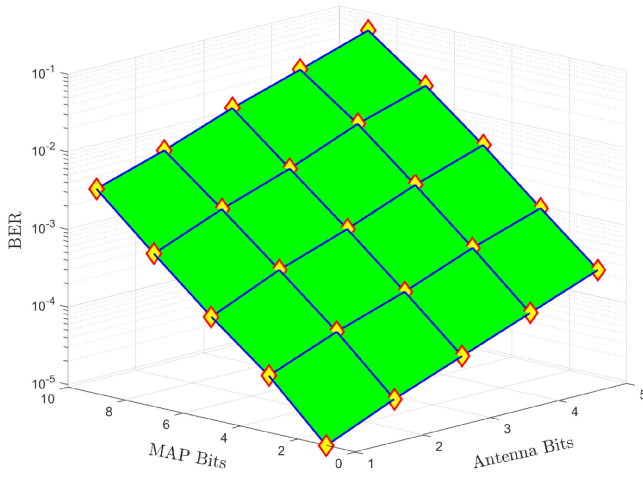


Fig. 6. BER performance of the RIS-SMBM system for $M = 4$, $N = 32$, and $\text{SNR} = 80$ dB.

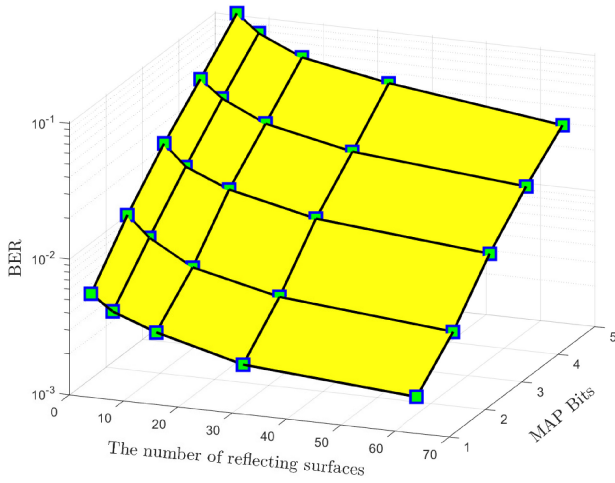


Fig. 7. BER performance of the RIS-SMBM system for $M = 4$, $n_T = 4$, and $\text{SNR} = 40$ dB.

surfaces. In the simulation in Fig. 7, $m_{rf} = 1, 2, 3, 4, 5$ and $N = 4, 8, 16, 32, 64$ values are selected, and the effect of these parameters over the error performance is questioned. It has been observed that the error performance gets better as the number of reflecting surfaces increases and the number of MAP bits decreases. As a result, while increasing the number of reflective surfaces improves the system performance, increasing the number of RF mirrors worsens it. However, it should be noted that increasing the number of RF used in the system increases the spectral efficiency of the system. Therefore, the number of RF mirrors and reflective surfaces should be determined in reasonable numbers according to the system's needs.

VI. CONCLUSION

In this article, a new system with high performance and high spectral efficiency called RIS-SMBM, which is a combination of RIS, SM, and MBM techniques, is proposed. In the proposed system, data bits are transmitted in the M -QAM symbol, active transmit antenna, and active MAP indices. Therefore, the proposed system provides much higher data

rates than traditional communication systems. It is shown that the proposed RIS-SMBM system has better BER performance for the same spectral efficiency than RIS-SSK, RIS-SM, RIS-QSM, and RIS-MBM systems. The error performance change of the RIS-SMBM scheme is observed depending on the RF number m_{rf} and reflecting surface number N parameters. It is observed and discussed that the performance of the proposed system improves as the N number increases and the m_{rf} number decreases. To further reduce the complexity of the RIS-SMBM system, an ELC detector that provides error performance close to the optimal ML detector is proposed. In addition, the computational complexity, energy efficiency, data rate, and throughput of the RIS-SMBM, RIS-SM, RIS-QSM, and RIS-MBM systems are calculated and the results are compared. Also, closed-form theoretical implications and analytical expressions are derived for the proposed system. Then, the theoretical and analytical results are then validated by comparing them with simulation results. Furthermore, the effect of imperfect CSI on the performance of the proposed RIS-SMBM system is investigated. As a result, the RIS-SMBM system provides a high data rate and high energy efficiency with reasonable complexity compared to counterpart communication systems and transmits data with less error.

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