

# Space-Time Block Coded Reconfigurable Intelligent Surface-Based Received Spatial Modulation

Ferhat Bayar , *Graduate Student Member, IEEE*, Onur Salan , Hacı İlhan , *Senior Member, IEEE*, and Erdogan Aydin 

**Abstract**—Reconfigurable intelligent surface (RIS) structures reflect incident signals by adjusting phase adaptively according to the channel condition during transmission to increase signal quality at the receiver. Spatial modulation (SM) technique is a potential candidate for future energy-efficient wireless communications due to its ability to provide better throughput, low-cost implementation, and good error performance. Also, Alamouti's space-time block coding (ASBC) is an important space and time coding technique for the diversity gain and simplified maximum likelihood (ML) detection. In this paper, we propose the RIS-assisted received spatial modulation (RSM) scheme with ASBC, namely RIS-RSM-ASBC, for next-generation wireless networks. The RIS in the proposed system model is separated into two parts, each used as an access point (AP) to transmit its Alamouti coded information while reflecting passive signals to the selected receive antenna. We design the optimal ML detector for the proposed RIS-RSM-ASBC scheme. Furthermore, we present the greedy detector (GD) to reduce the complexity of the ML detector. Extensive computer simulations are performed to corroborate theoretical derivations. The results show that the RIS-RSM-ASBC system is highly reliable and provides data rate enhancement compared to traditional RIS-assisted transmit SM (RIS-TSM), RIS-assisted transmit quadrature SM (RIS-TQSM), RIS-assisted received SM (RIS-RSM), RIS-assisted transmit space shift keying with ASBC (RIS-TSSK-ASBC), and RIS-assisted TSSK with Vertical-Bell Laboratories Layered Space-Time (RIS-TSSK-VBLAST) schemes.

**Index Terms**—Space time block coding, Alamouti's scheme, performance analysis, reconfigurable intelligent surface, spatial modulation, maximum likelihood, greedy detector.

## I. INTRODUCTION

ACCORDING to Cisco, all mobile traffic worldwide will reach 77 exabytes per month by the end of 2022. In

this context, 5G, which provides enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine-type communications were completed in June 2018. 5G technology was developed in June 2018 to provide enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine-type communications. However, it has been recognized that no single technology can fully support all 5G application requirements [1], leading researchers to investigate new technologies such as non-orthogonal multiple access (NOMA), multiple-input and multiple-output (MIMO), and terahertz communication [2], which will serve as the foundation for 6G technology. The key performance metrics for 6G aim to improve spectrum and energy efficiency, coverage, and mobility, while also providing intelligent and dynamic systems that can quickly adapt to changing environmental conditions and application types [3]. To achieve these goals, reconfigurable antenna-based techniques such as media-based modulation (MBM) [4], [5], [6], spatial modulation (SM) [7] and space shift keying (SSK) [8] have been proposed to create rich scattering environments. The NOMA-based SM scheme provides increased spectral efficiency without adding complexity, while the generalized code index modulation (GCIM)-aided SM (GCIM-SM) scheme is proposed to increase energy efficiency and data rate while reducing energy consumption [9]. Additionally, there are works in the literature on cooperative protocol [10] and physical layer security system [11] that utilize index modulation techniques to improve overall system error performance.

The researchers have focused on controlling the propagation environment to improve the quality of service (QoS) using intelligent reflecting surfaces (IRSs). The reconfigurable intelligent surface (RIS) scheme utilizes a large number of small, low-cost, and passive reflecting elements. The RIS adjusts the phase of the incident coming signal and reflects it to the destination without requiring any energy source [12]. To fully utilize the potential of RIS, exact channel state information (CSI) is required for passive and active beamforming. In this context, researchers focus on various channel estimation techniques in RIS-assisted systems to come up with the solution of its practical implementations [13], [14], [15], [16], [17], [18].

In [19], the researcher proposed RIS aided SSK (RIS-SSK) and RIS based SM (RIS-SM) schemes in collaboration with IM systems on the RIS scheme. In [20], the authors proposed an innovated RIS-based modulation scheme. In this model, the RIS is partitioned virtually into two halves, and each section of the RIS selects a receive antenna to beam-form the signal, which is controlled by the data stream. The theoretical derivations of the proposed system are represented over Rician fading channels. Also, [19], [21] and [22] provide error performance analyses

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Ferhat Bayar is with the Scientific and Technological Research Council of Turkey (TUBITAK), 41470 Kocaeli, Türkiye (e-mail: ferhat.bayar@tubitak.gov.tr).

Onur Salan is with the Communications and Signal Processing Research (HISAR) Laboratory, TUBITAK BILGEM, 41470 Kocaeli, Türkiye (e-mail: onur.salan@tubitak.gov.tr).

Hacı İlhan is with the Department of Electronics and Communications Engineering, Yildiz Technical University, 34220 Istanbul, Türkiye (e-mail: ilhanh@yildiz.edu.tr).

Erdogan Aydin is with the Department of Electrical and Electronics Engineering, Istanbul Medeniyet University, 34857 Istanbul, Türkiye (e-mail: erdogan.aydin@medeniyet.edu.tr).

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of RIS-based IM over Rayleigh and Weibull fading channels, respectively. In study [23], the authors propose the large intelligent surface-SM (LIS-SM) as a bridge between received SM (RSM) and transmit SM (TSM) schemes. At the transmitter, modulation symbol and selected transmitter antenna information are transmitted to the LIS, which reflects the incoming signals to the selected receive antenna. The LIS knows the transmit and receive antenna indexes in order to maximize the instantaneous signal-to-noise ratio (SNR) at the receiver. In [24], the implementation of single radio frequency (RF) MIMO with metasurface-based modulation is first introduced. The authors develop some implementations for metasurface-based single-RF MIMO in harmony variants of SM.

Ref. [25] presents a novel technique for open-loop massive MIMO downlink communication systems called generalized space time block coded spatial modulation (GSTBC-SM). GSTBC-SM combines the advantages of STBC and SM to improve system performance. Simulation results show that GSTBC-SM outperforms both STBC and SM in terms of spectral efficiency, energy efficiency, and error rate. A low-complexity maximum likelihood detector for GSTBC-SM is also proposed and is shown to achieve near-optimal performance. Alamouti scheme was used with the RIS schemes in [26], [27], [28]. The RIS-based Alamouti scheme provides improved error performance compared to the classical Alamouti schemes. STBC aided RIS based RSM (STBC-RIS-RSM) is a form of MIMO wireless communication system that employs a RIS to reflect the transmitted signals, with the aim of improving the system's performance and reducing its complexity. In contrast, a conventional MIMO system employs multiple antennas at both the transmitter and receiver to increase the system's capacity and enhance its performance. The key difference between these two systems lies in the approach they use to achieve improved performance. STBC-RIS-RSM leverages an RIS to reflect transmitted signals, while a conventional MIMO system employs multiple antennas at both ends of the communication link to achieve enhanced performance. Ref. [27] proposes RIS based Alamouti scheme which enables the RIS to transmit coded information while reflecting the incident SSK signals. Two new deep neural networks (DNN) aided cooperative RIS techniques are proposed for cooperative communication systems in [29]. In one model of this study, DNN is embedded in the RIS unit; in the other model, DNN is deployed at the destination for symbol detection instead of a ML detector. RIS-assisted MBM scheme is introduced in [30]. In [31], the authors have presented the RIS-assisted beam-index modulation in millimeter wave communication.

In this paper, we propose a RIS-based received SM scheme with Alamouti space-time block coding to improve the error performance of conventional RIS-based systems. Also, the theoretical derivations of error performance are presented for the proposed scheme.

#### A. Motivation and Contributions

This paper combines Alamouti's space-time block code ASBC [32] with the RIS-based RSM scheme. We use the RIS as an access point (AP) and employ SM at the receiver. In order to send two Alamouti symbols simultaneously, two transmit antennas are required. The RIS is portioned into two parts to transmit the ASBC codeword, thereby providing two separate antennas. Dividing the RIS into two parts allows for more flexibility in controlling the reflected signals. Each part can be

configured independently, which can enable fine-tuning of the reflected signals for optimal performance. It can also increase the coverage area of the wireless communication system. Dividing RIS into independent parts, it enables to cover a larger area by reflecting signals in different directions.

Our proposed scheme differs from the RIS-RSM scheme [19] in incorporating ASBC. Our proposed method and that of [27] differ in terms of where the IM technique is applied. In [27], SSK is used at the transmitter to reflect the incident SSK signals on RIS and transmit its information via ASBC, while we utilize SM at the receiver. In [26], the authors also proposed an RIS-assisted Alamouti scheme with the RIS as an AP. However, in that model, the RIS is blind, meaning it has no CSI, and its intelligence is manifested by adjusting the unmodulated RF signal to imitate the PSK symbol phases. In contrast, we have provided the intelligence of the RIS by knowing the CSI and selecting the received antenna with SM.

We investigate the RIS-assisted RSM scheme with ASBC to achieve better error performance at low SNR compared to the RIS-RSM [19]. Also, we study RIS-RSM-ASBC for the potential data rate improvement using the SM scheme at the receiver while comparing with [26]. The novel contribution and important observations of our paper can be summarized as follows:

- For the first time in literature, we propose an Alamouti's coded RIS-assisted RSM using optimal ML detector.
- We present the proposed scheme's theoretical average bit error probability (ABEP) and provide useful insights. Moreover, the receiver complexity, energy efficiency and data rate analyses have been performed and compared with benchmark systems.
- Our proposed system provides better error performance when compared with traditional SSK, SM, and quadrature SM [33] schemes. Also, we get better error performance compared to other studies such as RIS-TSM, RIS-TQSM, RIS-RSM [19], RIS-TSSK-ASBC [27], and RIS-TSSK-VBLAST [26]. We demonstrated the use of the GD algorithm to simplify the signal detection process at the receiver, resulting in a practical model with lower complexity while maintaining a significant level of error performance efficiency, particularly for a large number of reflecting elements.
- Finally, we show that the proposed scheme provides performance enhancement and enables highly reliable transmission, especially at low SNR.

#### B. Notations

Matrices and vectors are shown in boldface uppercase and boldface lowercase letter, respectively.  $(\cdot)^*$ ,  $(\cdot)^T$ , and  $(\cdot)^H$  define complex conjugation, transpose, and Hermitian transpose, respectively.  $[\cdot]^{-1}$  and  $\mathbf{I}_{n \times n}$  stand the inverse of a matrix and the identity matrix with  $n \times n$ , respectively.  $M$  defines modulation order.  $X_{\mathbb{R}}$  and  $X_{\mathbb{I}}$  denote the real and imaginary part of  $X$ , respectively. The definitions of parameters/symbols and abbreviations used in this paper are also listed in the Tables I and II, respectively.

#### C. Paper Organization

The remainder of this paper is organized as follows. Section II introduces the principle of the Alamouti's coded RSM scheme and defines the received signal model. Section III presents the

TABLE I  
LIST OF PARAMETERS/SYMBOLS

| Parameters/Symbols           | Definition                                                                                                |
|------------------------------|-----------------------------------------------------------------------------------------------------------|
| $E[X] (\mu_X)$               | Mean of RV $X$                                                                                            |
| $\text{Var}[X] (\sigma_X^2)$ | Variance of RV $X$                                                                                        |
| $E[X^n] (m_{X(n)})$          | $n^{\text{th}}$ moments of RV $X$                                                                         |
| $f_X(\cdot)$                 | Probability density function (PDF) of RV $X$                                                              |
| $M_X(\cdot)$                 | Moment generating function (MGF) of RV $X$                                                                |
| $\det(\cdot)$                | Determinant operation                                                                                     |
| $P(\cdot)$                   | Probability of an event.                                                                                  |
| $N_0$                        | Variance of additive white Gaussian noise (AWGN)                                                          |
| $\gamma$                     | Instantaneous signal to noise ratio (SNR)                                                                 |
| $\mathcal{O}$                | Order of approximation                                                                                    |
| $\mathbf{C}$                 | The covariance matrix of a multivariate random variable for time slot 1                                   |
| $\tilde{\mathbf{C}}$         | The covariance matrix of a multivariate random variable for time slot 2                                   |
| $\mathbf{m}$                 | The mean vector of a multivariate random variable for time slot 1                                         |
| $\tilde{\mathbf{m}}$         | The mean vector of a multivariate random variable for time slot 2                                         |
| $\Theta_{l,i}$               | The channel phase induced by the $i^{\text{th}}$ reflector at the $l^{\text{th}}$ receive antenna         |
| $\beta_{l,i}$                | The channel fading coefficients followed Rayleigh distribution                                            |
| $h_{l,i}$                    | The wireless fading channel between the $i^{\text{th}}$ reflector and the $l^{\text{th}}$ receive antenna |
| $\mathbf{y}_1$               | Received signal at the $l^{\text{th}}$ receive antenna                                                    |
| $\mathbf{n}_1$               | The AWGN at the $l^{\text{th}}$ receive antenna, and $\mathbf{n}_1 \sim \mathcal{CN}(0, N_0)$             |

TABLE II  
LIST OF ABBREVIATIONS

| Abbreviation  | Definition                             |
|---------------|----------------------------------------|
| ASBC          | Alamouti's Space-Time Block Coding     |
| ABEP          | Average Bit Error Probability          |
| ABER          | Average Bit Error Rate                 |
| CPEP          | Conditional Pairwise Error Probability |
| DNN           | Deep Neural Networks                   |
| GCIM          | Generalized Code Index Modulation      |
| GCIM-SM       | GCIM aided SM                          |
| GSTBC-SM      | Generalized STBC Spatial Modulation    |
| GD            | Greedy Detector                        |
| IM            | Index Modulation                       |
| IRS           | Intelligent Reflecting Surfaces        |
| ML            | Maximum Likelihood                     |
| MBM           | Media-Based Modulation                 |
| PEP           | Pairwise Error Probability             |
| RSSK          | Received Space Shift Keying            |
| RSM           | Received Spatial Modulation            |
| RIS           | Reconfigurable Intelligent Surface     |
| RIS-SSK       | RIS aided SSK                          |
| RIS-RSM-ASBC  | RIS-assisted RSM scheme with ASBC      |
| RIS-RSM       | RIS-assisted Received SM               |
| RIS-RQSSK     | RIS-assisted Received Quadrature SSK   |
| RIS-TSSK-ASBC | RIS-assisted Transmit SSK with ASBC    |
| RIS-TSM       | RIS-assisted Transmit SM               |
| RIS-TQSM      | RIS-assisted Transmit Quadrature SM    |
| RIS-SM        | RIS based SM                           |
| SSK           | Space Shift Keying                     |
| STBC          | Space Time Block Coding                |
| SM            | Spatial Modulation                     |
| STBC-RIS-RSM  | STBC aided RIS based Received SM       |
| TSSK          | Transmit Space Shift Keying            |
| TSM           | Transmit Spatial Modulation            |

derivation of the proposed system's ABEP. The analytical and Monte Carlo simulation results, complexity analysis, spectral and energy efficiency evaluations are given in Section IV. Finally, Section V concludes the paper.

## II. SYSTEM MODEL

In this section, we present the working principle of the RIS-RSM-ASBC scheme depicted in Fig. 1. The concept of using RIS as an AP is introduced in [1]. We also utilize the RIS as an AP in our scheme, which reflects the signals generated by a nearby RF source [1]. This involves reflecting signals from a nearby RF source through a surface or wall composed of  $N$  passive and low-cost reflector elements to reach a destination equipped with  $N_r$  receive antennas. Thereby, transmission between the source and RIS is not affected by fading and facilitates enhancing the receiver's SNR. Notably, the destination is located in the far-field of the RIS and does not directly receive signals from the RF source in this concept.

In the proposed system, bits generated from the source are split into three groups, each of which has  $\log_2(N_r)$ ,  $\log_2(M)$  and  $\log_2(M)$  bits, respectively. The first  $\log_2(N_r)$  bits determine the receive antenna index to adjust the RIS phases. The other  $2 \times \log_2(M)$  bits are entered to  $M$ -ary modulation and Alamouti encoder block from where two symbols are selected. These symbols are transmitted from the RF chains to the RIS.

The spectral efficiency of RIS-RSM-ASBC system is

$$\eta_{\text{RIS-RSM-ASBC}} = (2 \times \log_2 M + \log_2 N_r) / 2 \quad (1)$$

whereas traditional SM systems are  $\log_2 M + \log_2 N_r$  bits per channel use (bpcu).

The RIS is equipped with  $N$  passive reflecting elements. In this concept, we divide the RIS into two sub-surfaces, RIS-1 and RIS-2, to transmit their Alamouti symbols<sup>1</sup>. Both RIS pairs contain  $N/2$  reflector elements. Each full transmission consists of two time slots, in which we assume that the wireless fading channel does not change. The wireless fading the channel between the  $i$ th reflector and the  $l$ th receive antenna in each sub-surface can be represented as follows :

$$h_{l,i} = \beta_{l,i} \times e^{-j\Theta_{l,i}} \quad l \in \{1, 2, \dots, N_r\}, \quad (2)$$

where  $\Theta_{l,i}$  is the channel phase induced by the  $i$ th reflector at the  $l$ th receive antenna, and  $\beta_{l,i}$  is the channel fading coefficients followed Rayleigh distribution.

The RIS-1 reflects the symbol  $s_1$  from the first RF chain and RIS-2 reflects the symbol  $s_2$  from the second RF chain. Also, the controller determines the selected receiver antenna index according to  $\log_2 N_r$  information bits. Hereby, the baseband signal at the  $l$ th receive antenna of the destination in the first time slot can be expressed as:

$$y_l^{(1)} = s_1 \sum_{i=1}^{N/2} h_{l,i} e^{j\Phi_i} + s_2 \sum_{i=\frac{N}{2}+1}^N h_{l,i} e^{j\Phi_i} + n_l^{(1)}, \quad (3)$$

<sup>1</sup>To articulate the process of reflecting symbols from distinct RIS parts various research has been drawn upon to achieve this realization. In [34] and [35] various approaches and experiments regarding the manipulation of electromagnetic waves using RIS with positive intrinsic-negative (PIN)-diodes are discussed. Similarly, the utilization of varactor-diode-based RIS is explored in [36]. These studies demonstrate the capabilities of RIS in controlling and manipulating electromagnetic waves for various applications. By using this techniques, EM rays can be manipulated and while one part of RIS transmitting symbol  $s_1$ , the other part can transmit  $s_2$  with on-off states PIN diodes.

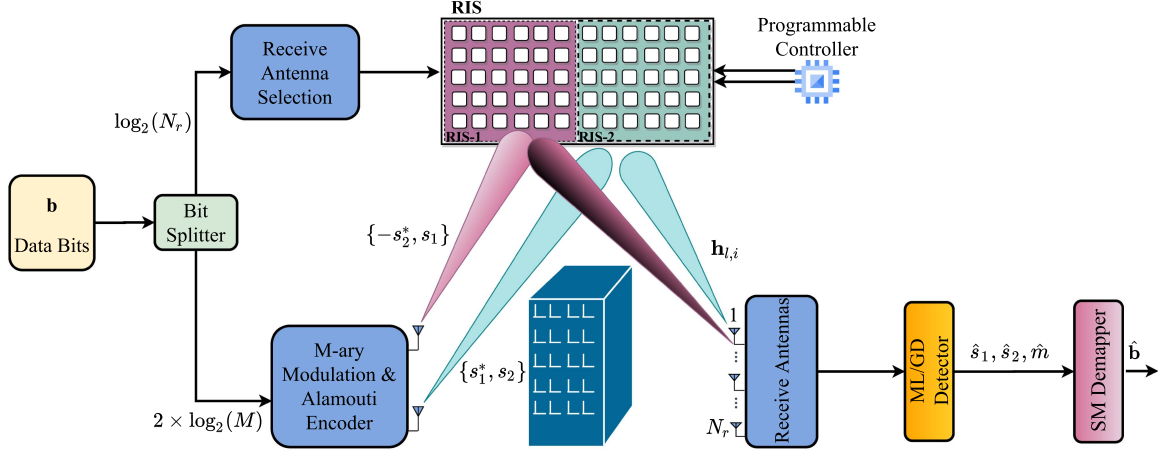


Fig. 1. System model of the RIS-RSM-ASBC scheme.

where  $n_l^{(1)}$  and  $\Phi_i$  stand for additive white Gaussian noise (AWGN) and reflector phases, respectively. Also,  $E[|s_1|^2] = E_s/2$  and  $E[|s_2|^2] = E_s/2$  where  $E_s$  is the average symbol energy,  $s_1$  and  $s_2$  are elements of  $M$ -QAM modulation. The reflector phases are adjusted related to the channel phases between RIS pairs and selected received antenna. We followed the same methods except transmitted symbols reflected from the RIS in the second time slot. We can represent the baseband signal at the  $l$ th receive antenna in the second time slot as below:

$$y_l^{(2)} = -s_2^* \sum_{i=1}^{N/2} h_{l,i} e^{j\Phi_i} + s_1^* \sum_{i=\frac{N}{2}+1}^N h_{l,i} e^{j\Phi_i} + n_l^{(2)} \quad (4)$$

After combining (3) and (4) into a matrix form, the obtained received signal can be given as:

$$\mathbf{y}_l = \mathbf{S} \mathbf{g}_l + \mathbf{n}_l \quad (5)$$

We can write (5) more clearly as follows:

$$\begin{aligned} \mathbf{y}_l &= \begin{bmatrix} y_l^{(1)} & y_l^{(2)} \end{bmatrix}^T \\ &= \underbrace{\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}}_{\mathbf{S}} \underbrace{\begin{bmatrix} \sum_{i=1}^{N/2} \beta_{l,i} e^{-j\Theta_{l,i}} e^{j\Phi_i} \\ \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} e^{-j\Theta_{l,i}} e^{j\Phi_i} \end{bmatrix}}_{\mathbf{g}_l} + \underbrace{\begin{bmatrix} n_l^{(1)} \\ n_l^{(2)} \end{bmatrix}}_{\mathbf{n}_l} \end{aligned} \quad (6)$$

It is important to note that we select the phase shifting  $\Phi_i = \Theta_{m,i}$  for  $i = 1, 2, \dots, N$  according to the information bits generated from the source to maximize the instantaneous SNR at the  $m$ th receive antenna. Therefore, we get instantaneous SNR at the  $m$ th selected receive antenna for the first time slot as follows:

$$\begin{aligned} \gamma_m &= \frac{E_s \left| \sum_{i=1}^{N/2} \beta_{m,i} e^{j(\Phi_i - \Theta_{m,i})} + \sum_{i=\frac{N}{2}+1}^N \beta_{m,i} e^{j(\Phi_i - \Theta_{m,i})} \right|^2}{N_0} \\ &= \frac{E_s \left| \sum_{i=1}^N \beta_{m,i} \right|^2}{N_0}. \end{aligned} \quad (7)$$

The receiver employs two detectors. Initially, the low complexity GD is utilized, followed by the ML detector. Each detector is presented in the next sections.

#### A. Greedy Detector

This section presents a low-complexity GD for the RIS-RSM-ASBC system. The GD facilitates the energy level of signals at the receiver by determining the receive antenna index. It does so by selecting the one with the highest instantaneous SNR at the receiver without requiring prior knowledge of the CSI. The selected antenna can be recovered with the following maximization method:

$$\hat{m} = \underset{l}{\operatorname{argmax}} (|y_l^{(1)}|^2 + |y_l^{(2)}|^2). \quad (8)$$

It is important to note that the instantaneous SNR at each received antenna should be combined with the time-slot information to improve the accuracy of antenna index estimation. Once the selected antenna is estimated, the symbols can be recovered as follows:

$$(\hat{s}_1, \hat{s}_2) = \underset{s_1, s_2}{\operatorname{argmin}} \left\| \mathbf{y}_{\hat{m}} - \mathbf{y}_{\text{ref}} \right\|^2, \quad (9)$$

where  $\mathbf{y}_{\hat{m}}$  refers base-band signals at the  $\hat{m}$ th estimated antenna for both time slots, and  $\mathbf{y}_{\text{ref}} = [s_1 + s_2 \quad -s_2^* + s_1^*]^T$ . For the proposed RIS-RSM-ASBC scheme pseudo-code of GD is presented in Algorithm 1.

#### B. Maximum Likelihood Detector

We have derived theoretical analysis considering the optimum ML detector for our proposed scheme. We have applied ML detector to (6) to recover the transmitted symbols and received antenna index as follows:

$$(\hat{s}_1, \hat{s}_2, \hat{m}) = \underset{s_1, s_2, m}{\operatorname{argmin}} \sum_{l=1}^{N_r} \left\| \mathbf{y}_l - \mathbf{S} \mathbf{g}_l \right\|^2, \quad (10)$$

where  $\hat{s}_1, \hat{s}_2, \hat{m}$  are estimation of  $s_1, s_2, m$  respectively.

### III. PERFORMANCE ANALYSIS

In this section, theoretical ABEP expression of the Alamouti coded RIS-based RSM scheme are obtained by evaluating pairwise error probability (PEP) and utilizing optimal ML detector.

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**Algorithm 1:** Greedy Detector for RIS-RSM-ASBC System.

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**Input:**  $\mathbf{y}$  refers received signal with  $2 \times N_r$  dimension,  $M$  refers modulation order,  $\mathbf{s}$  indicates symbol space with  $2^M \times 1$  dimension which includes  $M$ -QAM symbols

**Output:**  $\hat{m}, \hat{s}_1, \hat{s}_2$

- 1:  $receivedSnr \leftarrow |\mathbf{y}|^2$   $\triangleright$  SNRs at each antenna
- 2:  $\hat{m} \leftarrow \text{argmax}(\sum(receivedSnr, 1))$   $\triangleright$  Estimated antenna
- 3: Initialization :  $distances \leftarrow \text{zeros}(M, M)$   $\triangleright$  Set of Euclidian distance
- 4: **for** each  $r$  from 1 to  $M$  **do**
- 5:   **for** each  $c$  from 1 to  $M$  **do**
- 6:      $s_1 \leftarrow \mathbf{s}(r), s_2 \leftarrow \mathbf{s}(c)$   $\triangleright$  Current symbols
- 7:      $\mathbf{y}_{ref} \leftarrow \begin{bmatrix} s_1 + s_2 \\ -s_2^* + s_1^* \end{bmatrix}$   $\triangleright$  Reference signal
- 8:     Update  $distances(r, c) \leftarrow \|\mathbf{y}(:, \hat{m}) - \mathbf{y}_{ref}\|^2$   
 $\triangleright$  Distance for each symbols
- 9:   **end for**
- 10: **end for**
- 11:  $minDistance \leftarrow \min(distances(:))$   $\triangleright$  Minimum distance
- 12:  $[\hat{s}_1, \hat{s}_2] \leftarrow \text{find}(distances == minDistance)$   $\triangleright$  Row and column indices of the minimum distance corresponding  $\hat{s}_1$  and  $\hat{s}_2$

**Note:** The CSI is not known at the receiver, and the symbol detection is simplified.

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The conditional PEP (CPEP) expression of proposed system can be expressed as following:

$$P(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}} | \mathbf{g}) = P\left(\sum_{l=1}^{N_r} \|\mathbf{y}_l - \mathbf{S}\mathbf{g}_l\|^2 > \sum_{l=1}^{N_r} \|\mathbf{y}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2\right), \quad (11)$$

where

$$\hat{\mathbf{g}}_l = \begin{bmatrix} \sum_{i=1}^{N/2} \beta_{l,i} e^{j(\Theta_{\hat{m},i} - \Theta_{l,i})} & \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} e^{j(\Theta_{\hat{m},i} - \Theta_{l,i})} \end{bmatrix}^T$$

and  $\hat{\mathbf{S}} = \begin{bmatrix} \hat{s}_1 & \hat{s}_2 \\ -\hat{s}_2^* & \hat{s}_1^* \end{bmatrix}$ . Re-arranging (11) gives us the following:

$$\begin{aligned} P(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}} | \mathbf{g}) &= P\left(\sum_{l=1}^{N_r} \|\mathbf{n}_l\|^2 > \sum_{l=1}^{N_r} \|\mathbf{S}\mathbf{g}_l + \mathbf{n}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2\right) \\ &= P\left(\underbrace{\sum_{l=1}^{N_r} -\|\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2}_{\mathcal{K}} - 2\Re\left(\mathbf{n}_l^H (\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l)\right) > 0\right) \end{aligned} \quad (12)$$

where  $\mathcal{K}$  is Gaussian random variable with mean  $\mu_{\mathcal{K}} = -\sum_{l=1}^{N_r} \|\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2$  and variance  $\sigma_{\mathcal{K}}^2 = \sum_{l=1}^{N_r} 2N_o \|\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2$ .

As known,  $Q(\cdot)$  function can be defined as [37]:

$$P(X > x) = Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) du, \quad (13)$$

where  $X \sim \mathcal{N}(0, 1)$ . So when we go back to our (12), statistical values of  $\mathcal{K}$  is re-arranged doing by normalization of the its standard deviation and shifting its mean to zero. Therefore the following expression is obtained:

$$\begin{aligned} P(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}} | \mathbf{g}) &= Q\left(\frac{-\mu_{\mathcal{K}}}{\sigma_{\mathcal{K}}}\right) \\ &= Q\left(\sqrt{\frac{\sum_{l=1}^{N_r} \|\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2}{2N_o}}\right). \end{aligned} \quad (14)$$

Then, the unconditional PEP (UPEP) expression can be obtained by taking the expectation of (14) over the channel parameter:

$$\begin{aligned} \bar{P}_e(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}}) &= \int_0^\infty Q\left(\sqrt{\frac{\Gamma}{2N_o}}\right) f_\Gamma(\Gamma) d\Gamma, \\ &= \frac{1}{\pi} \int_0^\infty \int_0^{\pi/2} \exp\left(-\frac{\Gamma}{4\sin^2 \lambda N_o}\right) f_\Gamma(\Gamma) d\lambda d\Gamma, \\ &= \frac{1}{\pi} \int_0^{\pi/2} M_\Gamma\left(-\frac{1}{4\sin^2 \lambda N_o}\right) d\lambda, \end{aligned} \quad (15)$$

where  $\Gamma = \sum_{l=1}^{N_r} \|\mathbf{S}\mathbf{g}_l - \hat{\mathbf{S}}\hat{\mathbf{g}}_l\|^2$ .

We need the MGF of  $\Gamma$  ( $M_\Gamma(s)$ ) to perform this integration. So we will divide the random variable  $\Gamma$  into two parts. From this point of view, we can re-write the  $\Gamma$  more precisely as follows:

$$\Gamma = \Gamma_{Ts_1} + \Gamma_{Ts_2}, \quad (16)$$

where

$$\begin{aligned} \Gamma_{Ts_1} &= \sum_{l=1}^{N_r} \left| \sum_{i=1}^{N/2} \beta_{l,i} e^{-j\Theta_{l,i}} (e^{j\Theta_{m,i}} s_1 - e^{j\Theta_{\hat{m},i}} \hat{s}_1) \right. \\ &\quad \left. + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} e^{-j\Theta_{l,i}} (e^{j\Theta_{m,i}} s_2 - e^{j\Theta_{\hat{m},i}} \hat{s}_2) \right|^2, \\ \Gamma_{Ts_2} &= \sum_{l=1}^{N_r} \left| -\sum_{i=1}^{N/2} \beta_{l,i} e^{-j\Theta_{l,i}} (e^{j\Theta_{m,i}} s_2^* - e^{j\Theta_{\hat{m},i}} \hat{s}_2^*) \right. \\ &\quad \left. + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} e^{-j\Theta_{l,i}} (e^{j\Theta_{m,i}} s_1^* - e^{j\Theta_{\hat{m},i}} \hat{s}_1^*) \right|^2. \end{aligned} \quad (17)$$

It is crucial to note that the  $\Gamma_{Ts_1}$  and  $\Gamma_{Ts_2}$  are independent of each other. This independence arises because the signals are experienced during distinct time slots. In the next statements,  $\Gamma_{Ts_1} \Gamma_1$  and  $\Gamma_{Ts_2} \triangleq \Gamma_2$  will be expressed as for the simplicity. Therefore, separate MGF derivations will be made for two time slots.

TABLE III  
THE EXPRESSIONS OF  $\Gamma_{11}$ ,  $\Gamma_{12}$ ,  $\Gamma_{13}$ ,  $\Gamma_{21}$ ,  $\Gamma_{22}$ , AND  $\Gamma_{23}$

| Time Slot-1                                                                                                                                                                                                                                                                         |  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| $\Gamma_{11} = \left  \sum_{i=1}^{N/2} \beta_{m,i} (s_1 - e^{-j\Psi_i} \hat{s}_1) + \sum_{i=\frac{N}{2}+1}^N \beta_{m,i} (s_2 - e^{-j\Psi_i} \hat{s}_2) \right ^2$                                                                                                                  |  |
| $\Gamma_{12} = \left  \sum_{i=1}^{N/2} \beta_{\hat{m},i} (s_1 e^{-j\Psi_i} - \hat{s}_1) + \sum_{i=\frac{N}{2}+1}^N \beta_{\hat{m},i} (s_2 e^{-j\Psi_i} - \hat{s}_2) \right ^2$                                                                                                      |  |
| $\Gamma_{13} = \sum_{l=1(l \neq m, l \neq \hat{m})}^{N_r} \left  \sum_{i=1}^{N/2} \beta_{l,i} (s_1 e^{-j\Theta_{l,i}} - \hat{s}_1 e^{-j\Theta_{\hat{m},i}}) + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} (s_2 e^{-j\Theta_{l,i}} - \hat{s}_2 e^{-j\Theta_{\hat{m},i}}) \right ^2$         |  |
| Time Slot-2                                                                                                                                                                                                                                                                         |  |
| $\Gamma_{21} = \left  \sum_{i=1}^{N/2} \beta_{m,i} (-s_2^* + e^{-j\Psi_i} \hat{s}_2^*) + \sum_{i=\frac{N}{2}+1}^N \beta_{m,i} (s_1^* - e^{-j\Psi_i} \hat{s}_1^*) \right ^2$                                                                                                         |  |
| $\Gamma_{22} = \left  \sum_{i=1}^{N/2} \beta_{\hat{m},i} (\hat{s}_2^* - s_2^* e^{-j\Psi_i}) + \sum_{i=\frac{N}{2}+1}^N \beta_{\hat{m},i} (s_1^* e^{-j\Psi_i} - \hat{s}_1^*) \right ^2$                                                                                              |  |
| $\Gamma_{23} = \sum_{l=1(l \neq m, l \neq \hat{m})}^{N_r} \left  \sum_{i=1}^{N/2} \beta_{l,i} (s_1^* e^{-j\Theta_{l,i}} - \hat{s}_1^* e^{-j\Theta_{\hat{m},i}}) + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} (\hat{s}_2^* e^{-j\Theta_{l,i}} - s_2^* e^{-j\Theta_{\hat{m},i}}) \right ^2$ |  |

#### A. The MGFs Derivation for the First Time Slot

This MGF can be derived by considering the general quadratic form of correlated Gaussian RVs and depends on erroneous or correct detection of the receive selected antenna index  $m$ .

1) *Under the wrong antenna decision,  $m \neq \hat{m}$ :*  $\Gamma_1$  can be divided into parts as  $\Gamma_1 = \Gamma_{11} + \Gamma_{12} + \Gamma_{13}$  and these random variables are defined in Table III. In this manner,  $\Gamma_{11}$ ,  $\Gamma_{12}$  and  $\Gamma_{13}$  stand for  $l = m$ ,  $l = \hat{m}$  and  $l \neq \hat{m}$ ,  $l \neq m$ . Also,  $\Psi_i = \Theta_{m,i} - \Theta_{\hat{m},i}$  has triangular distribution [38]:

$$f_{\Psi}(x) = \begin{cases} 2\pi \left(1 + \frac{x}{2\pi}\right); & -2\pi < x < 0 \\ 2\pi \left(1 - \frac{x}{2\pi}\right); & 0 < x < 2\pi \end{cases} \quad (18)$$

Here, we will firstly derive the MGF expression of  $\Gamma_{11} + \Gamma_{12}$ . After that, the MGF of  $\Gamma_{13}$  will be presented. It is known that MGF of the sum of two independent R.Vs is equal to the product of their MGFs. Hence, we will obtain the MGF of  $\Gamma_1$  as  $M_{\Gamma_1} = M_{(\Gamma_{11} + \Gamma_{12})} \times M_{\Gamma_{13}}$ .

Keeping in mind,  $\Gamma_{11} = |\Delta_{11}|^2 = (\Delta_{11})_{\Re}^2 + (\Delta_{11})_{\Im}^2$ ,  $\Gamma_{12} = |\Delta_{12}|^2 = (\Delta_{12})_{\Re}^2 + (\Delta_{12})_{\Im}^2$  and  $\Gamma_{11} + \Gamma_{12} = \mathbf{x}^T \mathbf{A} \mathbf{x}$  where  $\mathbf{x} = [(\Gamma_{11})_{\Re} \ (\Gamma_{11})_{\Im} \ (\Gamma_{12})_{\Re} \ (\Gamma_{12})_{\Im}]^T$ ,  $\mathbf{A}$  is diagonal matrix and  $\mathbf{x}^T \mathbf{A} \mathbf{x} = (\Delta_{11})_{\Re}^2 + (\Delta_{11})_{\Im}^2 + (\Delta_{12})_{\Re}^2 + (\Delta_{12})_{\Im}^2$ .

Let  $\mathcal{G} = \Gamma_{11} + \Gamma_{12}$ , then MGF of  $\mathcal{G}$  can be obtained as follows [39, Eq. (3.2a.1)]:

$$M_{\mathcal{G}}(s) = \left( \sqrt{\det(\mathbf{I} - 2s\mathbf{A}\mathbf{C})} \right)^{-1} \times \exp \left( -\frac{1}{2} \mathbf{m}^T \left[ \mathbf{I} - (\mathbf{I} - 2s\mathbf{A}\mathbf{C})^{-1} \right] \mathbf{C}^{-1} \right), \quad (19)$$

where  $\mathbf{m}$  and  $\mathbf{C}$  are the mean vector and the covariance matrix of  $\mathbf{x}$ , respectively. Also,  $\mathbf{I}$  is identity matrix. We can define mean vector of  $\mathbf{x}$  by  $\mathbf{m} = [\mu_{(\Delta_{11})_{\Re}} \ \mu_{(\Delta_{11})_{\Im}} \ \mu_{(\Delta_{12})_{\Re}} \ \mu_{(\Delta_{12})_{\Im}}]^T$ . The entities of  $\mathbf{m}$  can be represented in Table IV.

TABLE IV  
THE DERIVATION OF ENTITIES OF  $\mathbf{m}$  AND  $\hat{\mathbf{m}}$

| Time Slot-1                                                                                  | Time Slot-2                                                                                      |
|----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| $\mu_{(\Delta_{11})_{\Re}} = \frac{N\sqrt{\pi}}{4} ((s_1)_{\Re} + (s_2)_{\Re})$              | $\mu_{(\Delta_{21})_{\Re}} = \frac{N\sqrt{\pi}}{4} ((s_1^*)_{\Re} - (s_2^*)_{\Re})$              |
| $\mu_{(\Delta_{11})_{\Im}} = \frac{N\sqrt{\pi}}{4} ((s_1)_{\Im} + (s_2)_{\Im})$              | $\mu_{(\Delta_{21})_{\Im}} = \frac{N\sqrt{\pi}}{4} ((s_1^*)_{\Im} - (s_2^*)_{\Im})$              |
| $\mu_{(\Delta_{12})_{\Re}} = -\frac{N\sqrt{\pi}}{4} ((\hat{s}_1)_{\Re} + (\hat{s}_2)_{\Re})$ | $\mu_{(\Delta_{22})_{\Re}} = -\frac{N\sqrt{\pi}}{4} ((\hat{s}_1^*)_{\Re} - (\hat{s}_2^*)_{\Re})$ |
| $\mu_{(\Delta_{12})_{\Im}} = -\frac{N\sqrt{\pi}}{4} ((\hat{s}_1)_{\Im} + (\hat{s}_2)_{\Im})$ | $\mu_{(\Delta_{22})_{\Im}} = -\frac{N\sqrt{\pi}}{4} ((\hat{s}_1^*)_{\Im} - (\hat{s}_2^*)_{\Im})$ |

Likewise, we can give the covariance matrix of  $\mathbf{x}$  as below:

$$\mathbf{C} = \begin{bmatrix} \sigma_{1,1}^2 & \sigma_{1,2} & \sigma_{1,3} & \sigma_{1,4} \\ \sigma_{1,2} & \sigma_{2,2}^2 & \sigma_{2,3} & \sigma_{2,4} \\ \sigma_{1,3} & \sigma_{2,3} & \sigma_{3,3}^2 & \sigma_{3,4} \\ \sigma_{1,4} & \sigma_{2,4} & \sigma_{3,4} & \sigma_{4,4}^2 \end{bmatrix}. \quad (20)$$

The entities of covariance matrix are obtained as in Tables V and VI where  $\Upsilon = \frac{N}{8}(4 - \pi)$ ,  $\Lambda = \frac{N}{4}$ ,  $\Xi = \frac{-N\pi}{16}$  for time slot 1 and time slot 2, respectively. On the other hand, the MGF of the  $\Gamma_{13}$  is found, which can be rewritten from Table III as follows:

$$\Gamma_{13} = \sum_{l=1(l \neq m, l \neq \hat{m})}^{N_r} \left| \sum_{i=1}^{N/2} \beta_{l,i} s_{i,1} + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} s_{i,2} \right|^2, \quad (21)$$

where  $s_{i,1} = (s_1 e^{-j\Theta_{l,i}} - \hat{s}_1 e^{-j\Theta_{\hat{m},i}})$  and  $s_{i,2} = (s_2 e^{-j\Theta_{l,i}} - \hat{s}_2 e^{-j\Theta_{\hat{m},i}})$ . Thanks to the variables  $s_{i,1}$  and  $s_{i,2}$  are independent and due to the central limit theorem (CLT) for the large  $N$  ( $N \gg 1$ ), the  $\Gamma_{13}$  expression have a central zero mean Chi-Squared distribution with order  $(N_r - 2)$ . Keep in mind that  $X = \sum_{i=1}^n Z_i$  where  $Z_i \sim \mathcal{N}(0, \sigma_Z^2)$ , the MGF of  $X$  with a central zero-mean Chi-Square distribution can be written as [40]:

$$M_X(s) = \left( \frac{1}{1 - 2s\sigma_X^2} \right)^{n/2}, \quad (22)$$

where  $n$  stands for degree of freedom. Therefore, we can write the MGF of  $\Gamma_{13}$  by appropriately changing the parameters in

TABLE V  
STATISTICAL PROPERTIES OF THE COVARIANCE ENTITIES OF  $\mathbf{C}$  FOR TIME SLOT-1

|                                                                                                                       |                                                                                                                                                                  |
|-----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_1^2 = \Upsilon\left((s_1)_{\Re}^2 + (s_2)_{\Re}^2\right) + \Lambda\left( \hat{s}_1 ^2 +  \hat{s}_2 ^2\right)$ | $\sigma_{1,3} = \Xi\left((s_1)_{\Re}(\hat{s}_1)_{\Re} + (s_1)_{\Im}(\hat{s}_1)_{\Im} + (s_2)_{\Re}(\hat{s}_2)_{\Re} + (s_2)_{\Im}(\hat{s}_2)_{\Im}\right)$       |
| $\sigma_2^2 = \Upsilon\left((s_1)_{\Im}^2 + (s_2)_{\Im}^2\right) + \Lambda\left( \hat{s}_1 ^2 +  \hat{s}_2 ^2\right)$ | $\sigma_{1,4} = \Xi\left((s_1)_{\Im}(\hat{s}_1)_{\Re} + (s_1)_{\Re}(\hat{s}_1)_{\Im} + (s_2)_{\Im}(\hat{s}_2)_{\Re} + (s_2)_{\Re}(\hat{s}_2)_{\Im}\right)$       |
| $\sigma_3^2 = \Upsilon\left((\hat{s}_1)_{\Re}^2 + (\hat{s}_2)_{\Re}^2\right) + \Lambda\left( s_1 ^2 +  s_2 ^2\right)$ | $\sigma_{2,4} = \Xi\left((s_1)_{\Re}(\hat{s}_1)_{\Re} + (s_1)_{\Im}(\hat{s}_1)_{\Im} + (s_2)_{\Re}(\hat{s}_2)_{\Re} + (s_2)_{\Im}(\hat{s}_2)_{\Im}\right)$       |
| $\sigma_4^2 = \Upsilon\left((s_1)_{\Im}^2 + (s_2)_{\Im}^2\right) + \Lambda\left( s_1 ^2 +  s_2 ^2\right)$             | $\sigma_{2,3} = \Xi\left((\hat{s}_1)_{\Re}(s_1)_{\Im} + (\hat{s}_1)_{\Re}(\hat{s}_1)_{\Im} + (\hat{s}_2)_{\Im}(s_2)_{\Re} + (\hat{s}_2)_{\Re}(s_2)_{\Im}\right)$ |
| $\sigma_{1,2} = \Upsilon\left((s_1)_{\Re}(s_1)_{\Im} + (s_2)_{\Re}(s_2)_{\Im}\right)$                                 | $\sigma_{3,4} = \Upsilon\left((\hat{s}_1)_{\Re}(\hat{s}_1)_{\Im} + (\hat{s}_2)_{\Re}(\hat{s}_2)_{\Im}\right)$                                                    |

TABLE VI  
STATISTICAL PROPERTIES OF THE COVARIANCE ENTITIES OF  $\tilde{\mathbf{C}}$  FOR TIME SLOT-2

|                                                                                                                               |                                                                                                                                                                            |
|-------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\sigma_1^2 = \Upsilon\left((s_1^*)_{\Re}^2 + (s_2^*)_{\Re}^2\right) + \Lambda\left( \hat{s}_1^* ^2 +  \hat{s}_2^* ^2\right)$ | $\sigma_{1,3} = \Xi\left((s_1^*)_{\Im}(\hat{s}_1^*)_{\Im} - (s_1^*)_{\Re}(\hat{s}_1^*)_{\Re} - (s_2^*)_{\Re}(\hat{s}_2^*)_{\Re} + (s_2^*)_{\Im}(\hat{s}_2^*)_{\Im}\right)$ |
| $\sigma_2^2 = \Upsilon\left((s_1^*)_{\Im}^2 + (s_2^*)_{\Im}^2\right) + \Lambda\left( \hat{s}_1^* ^2 +  \hat{s}_2^* ^2\right)$ | $\sigma_{1,4} = \Xi\left((s_1^*)_{\Im}(\hat{s}_1^*)_{\Re} + (s_1^*)_{\Re}(\hat{s}_1^*)_{\Im} + (s_2^*)_{\Im}(\hat{s}_2^*)_{\Re} + (s_2^*)_{\Re}(\hat{s}_2^*)_{\Im}\right)$ |
| $\sigma_3^2 = \Upsilon\left((\hat{s}_1^*)_{\Re}^2 + (\hat{s}_2^*)_{\Re}^2\right) + \Lambda\left( s_1^* ^2 +  s_2^* ^2\right)$ | $\sigma_{2,4} = \Xi\left((s_1^*)_{\Re}(\hat{s}_1^*)_{\Re} - (s_1^*)_{\Im}(\hat{s}_1^*)_{\Im} + (s_2^*)_{\Re}(\hat{s}_2^*)_{\Re} - (s_2^*)_{\Im}(\hat{s}_2^*)_{\Im}\right)$ |
| $\sigma_4^2 = \Upsilon\left((s_1^*)_{\Im}^2 + (s_2^*)_{\Im}^2\right) + \Lambda\left( s_1^* ^2 +  s_2^* ^2\right)$             | $\sigma_{2,3} = \Xi\left((\hat{s}_1^*)_{\Re}(s_1^*)_{\Im} + (s_1^*)_{\Re}(\hat{s}_1^*)_{\Im} + (s_2^*)_{\Im}(\hat{s}_2^*)_{\Re} + (s_2^*)_{\Re}(\hat{s}_2^*)_{\Im}\right)$ |
| $\sigma_{1,2} = \Upsilon\left((s_1^*)_{\Re}(s_1^*)_{\Im} + (s_2^*)_{\Re}(s_2^*)_{\Im}\right)$                                 | $\sigma_{3,4} = \Upsilon\left((\hat{s}_1^*)_{\Re}(\hat{s}_1^*)_{\Im} + (\hat{s}_2^*)_{\Re}(\hat{s}_2^*)_{\Im}\right)$                                                      |

(22):

$$M_{\Gamma_{13}}(s) = \left( \frac{1}{1 - \frac{Ns}{2} (|s_1|^2 + |\hat{s}_1|^2 + |s_2|^2 + |\hat{s}_2|^2)} \right)^{N_r - 2} \quad (23)$$

Eventually, the MGF of  $\Gamma_{T_{s_1}} \triangleq \Gamma_1$  in (16) is yielded by the product of MGFs of  $\Gamma_{11} + \Gamma_{12}$  and  $\Gamma_{13}$ .

2) *Under the correct antenna decision,  $\hat{m} = m$ :* In this case, we will calculate the PEP for correct antenna detection. We can write  $\Gamma_1$  for  $\hat{m} = m$  as follows:

$$\begin{aligned} \Gamma_1^{(\hat{m}=m)} &= \sum_{l=1}^{Nr} \left| \sum_{i=1}^{N/2} \beta_{l,i} e^{j(\Theta_{l,i} - \Theta_{m,i})} (s_1 - \hat{s}_1) \right. \\ &\quad \left. + \sum_{i=\frac{N}{2}+1}^N \beta_{l,i} e^{j(\Theta_{l,i} - \Theta_{m,i})} (s_2 - \hat{s}_2) \right|^2 \\ \Gamma_1^{(\hat{m}=m)} &= \sum_{l=1}^{Nr} |H_{l,i} (s_1 - \hat{s}_1) + H_{l,i} (s_2 - \hat{s}_2)|^2 \\ &\leq \sum_{l=1}^{Nr} |H_{l,i} (s_1 - \hat{s}_1)|^2 + \sum_{l=1}^{Nr} |H_{l,i} (s_2 - \hat{s}_2)|^2, \end{aligned} \quad (24)$$

where  $H_{l,i} = \sum_{i=1}^{N/2} \beta_{l,i} e^{j(\Theta_{l,i} - \Theta_{m,i})}$ . It is worth mentioning that we utilize the upper bound approach in (24). Let's suppose that  $A = \sum_{l=1}^{Nr} |H_{l,i} (s_1 - \hat{s}_1)|^2$  and  $B = \sum_{l=1}^{Nr} |H_{l,i} (s_2 - \hat{s}_2)|^2$ , the MGF of  $M_{\Gamma_1}(s) = M_A(s) \times M_B(s)$ . We can rewrite clearly  $A_1$  and  $B_1$  as follows:

$$\begin{aligned} A_1 &= (s_1 - \hat{s}_1) \left( |H_{m,i}|^2 + \sum_{l \neq m}^{Nr} |H_{l,i}|^2 \right), \\ B_1 &= (s_2 - \hat{s}_2) \left( |H_{m,i}|^2 + \sum_{l \neq m}^{Nr} |H_{l,i}|^2 \right), \end{aligned} \quad (25)$$

where  $H_{m,i} = \sum_{i=1}^{N/2} \beta_{m,i}$  and distributed as  $H_{m,i} \sim \mathcal{N}(\frac{\sqrt{\pi}N}{4}, \frac{(4-\pi)N}{8})$  for large  $N$  values (due to the CLT). Similarly,  $H_{l,i} \sim \mathcal{CN}(0, \frac{N}{2})$ . Therefore, the MGFs of  $A$  and  $B$  can be obtained product of two  $\chi^2$  variables respectively as follows [40]:

$$\begin{aligned} M_{A_1}(s) &= \left( \frac{1}{1 - \frac{sN(4-\pi)|s_1 - \hat{s}_1|^2}{4}} \right)^{1/2} \\ &\quad \times \exp \left( \frac{\frac{sN^2\pi|s_1 - \hat{s}_1|^2}{16}}{1 - \frac{sN(4-\pi)|s_1 - \hat{s}_1|^2}{4}} \right) \left( \frac{1}{1 - \frac{sN|s_1 - \hat{s}_1|^2}{2}} \right)^{N_r - 1} \\ M_{B_1}(s) &= \left( \frac{1}{1 - \frac{sN(4-\pi)|s_2 - \hat{s}_2|^2}{4}} \right)^{1/2} \\ &\quad \times \exp \left( \frac{\frac{sN^2\pi|s_2 - \hat{s}_2|^2}{16}}{1 - \frac{sN(4-\pi)|s_2 - \hat{s}_2|^2}{4}} \right) \left( \frac{1}{1 - \frac{sN|s_2 - \hat{s}_2|^2}{2}} \right)^{N_r - 1}. \end{aligned} \quad (26)$$

Finally, the MGF of  $\Gamma_1^{(\hat{m}=m)}$  is yielded from the product of MGFs of  $A_1$  and  $B_1$  for correct antenna detection.

### B. The MGFs Derivation for the Second Time Slot

In light of information given previous section, the analyses in Section III-A (for the case of both  $m \neq \hat{m}$  and  $m = \hat{m}$ ) is also valid for Second Time Slot. Therefore same procedures are applied in this section.

1) *Under the wrong antenna decision,  $\hat{m} \neq m$ :* The MGF of  $\Gamma_{21}$ ,  $\Gamma_{22}$  and  $\Gamma_{23}$  derived from Table III with suitable modifications in (19) and (23). Covariance ( $\tilde{\mathbf{C}}$ ) and mean ( $\tilde{\mathbf{x}}$ ) entites are given for MGF of  $(\Gamma_{21} + \Gamma_{22})$  in Tables IV and VI, respectively. Also, the MGF of  $\Gamma_{23}$  can be given by doing proper

modifications in (23) as following :

$$M_{\Gamma_{23}}(s) = \left( \frac{1}{1 - \frac{Ns}{2} (|\hat{s}_1^*|^2 + |\hat{s}_1^*|^2 + |\hat{s}_2^*|^2 + |\hat{s}_2^*|^2)} \right)^{N_r-2} \quad (27)$$

2) Under the correct antenna decision,  $\hat{m} = m$ : The analyses in Section III-A2 is also applicable for this case. Firstly, we can write MGF of  $A_2$  and  $B_2$  as below:

$$\begin{aligned} M_{A_2}(s) &= \left( \frac{1}{1 - \frac{sN(4-\pi)|\hat{s}_2^* - s_2^*|^2}{4}} \right)^{1/2} \\ &\times \exp \left( \frac{\frac{sN^2\pi|\hat{s}_2^* - s_2^*|^2}{16}}{1 - \frac{sN(4-\pi)|\hat{s}_2^* - s_2^*|^2}{4}} \right) \left( \frac{1}{1 - \frac{sN|\hat{s}_2^* - s_2^*|^2}{2}} \right)^{N_r-1}, \\ M_{B_2}(s) &= \left( \frac{1}{1 - \frac{sN(4-\pi)|\hat{s}_1^* - s_1^*|^2}{4}} \right)^{1/2} \\ &\times \exp \left( \frac{\frac{sN^2\pi|\hat{s}_1^* - s_1^*|^2}{16}}{1 - \frac{sN(4-\pi)|\hat{s}_1^* - s_1^*|^2}{4}} \right) \left( \frac{1}{1 - \frac{sN|\hat{s}_1^* - s_1^*|^2}{2}} \right)^{N_r-1}. \end{aligned} \quad (28)$$

In this manner, MGF of  $\Gamma_{23}^{(\hat{m}=m)}$  can be obtained as  $M_{\Gamma_{23}^{(\hat{m}=m)}} = M_{A_2}(s) \times M_{B_2}(s)$ .

Thus, separate MGF derivations have been made for two time slots containing wrong and correct antenna detection cases. The PEP values for each case are obtained by substituting and integrating the corresponding MGF expression in (15).

Finally, the upper bound of ABER for RIS-RSM-ASBC system can be expressed as follows:

$$P_b \leq \frac{1}{2^{2\eta}} \sum_{\mathbf{S}, \hat{\mathbf{S}}} \sum_{m, \hat{m}} \frac{P(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}}) e(m, \mathbf{S}, \hat{m}, \hat{\mathbf{S}})}{2\eta}, \quad (29)$$

where  $P(m, \mathbf{S} \rightarrow \hat{m}, \hat{\mathbf{S}})$  and  $e(m, \mathbf{S}, \hat{m}, \hat{\mathbf{S}})$  stand for the UPEP and the number of bit errors associated with the corresponding UPEP events, respectively.

#### IV. RESULTS

In this section, Monte-Carlo simulations, complexity analysis, energy and spectral efficiencies of proposed system are presented.

##### A. Numerical Results

Here, we provide Monte-Carlo simulations for the proposed RIS-RSM-ASBC and compare them with the theoretical results obtained. ML detector is utilized to detect the transmitted symbols and indices on the receiving side. We assume that all fading channels are uncorrelated Rayleigh fading distribution. The SNR parameter used in the simulations is expressed as:  $\text{SNR(dB)} = 10 \log_{10}(E_s/N_0)$ , where  $E_s$  is the average symbol energy. We have conducted our Monte-Carlo simulations in MATLAB with a precision of  $10^7$  bits which are generated by uniformly distributed. The RF sources and the IRS are close enough that the transmission is not affected by fading [1], [19]. The complex Gaussian noise have generated with a mean of 0 and a variance of  $N_0$ .

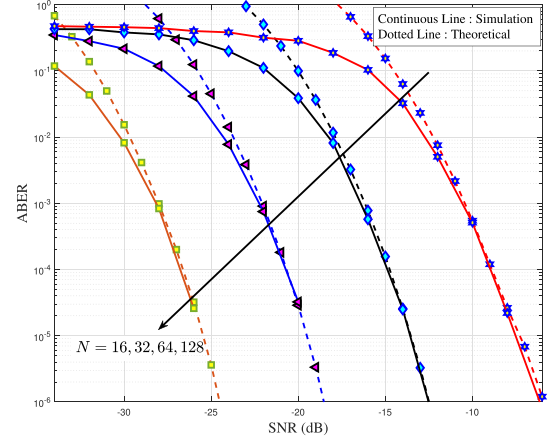


Fig. 2. Simulation and theoretical BER performance of the proposed RIS-RSM-ASBC with  $(M = 4, N_r = 4)$  for varying  $N$ .

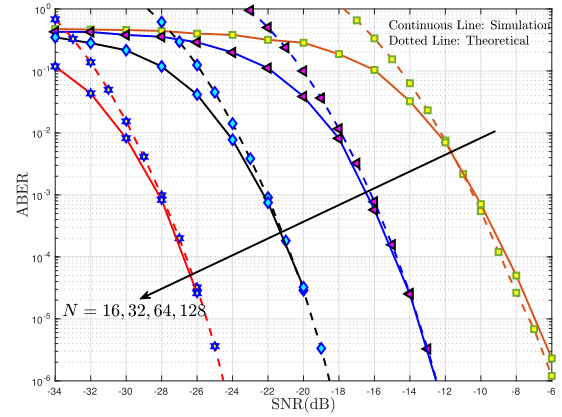


Fig. 3. Simulation and theoretical BER performance of the proposed RIS-RSM-ASBC scheme with  $(M = 4, N_r = 2)$  for varying  $N$ .

We focus on the simulation and theoretical ABER performance of the proposed RIS-RSM-ASBC scheme in Figs. 2 and 3. These figures show the effect of the number of reflecting elements on the error performance for  $N_r = 2$  and  $N_r = 4$ , respectively. The findings clearly show that the error performance linearly increases with the growth in  $N$  as expected. According to Fig. 2, the ABER of proposed scheme significantly improves by about 18 dB with the number of  $N$  increasing from 16 to 128. Likewise, Figs. 2 and 3 show that the effect of  $M$  decreases with the increase in  $N$ . As seen in these figures, there is a conformity between the simulation results and the theoretical findings obtained from Figs. 2 and 3.

In Fig. 4, we compare the ML and GD-based receivers in terms of BER performance. As shown in Fig. 4, the ML detector performs better than GD, which was expected. However, the greedy detector shows quite close performance, especially for high  $N$  values. In proposed GD, firstly we estimate the selected receive antenna and then recover the transmitted symbols according to the estimated antenna index. In this manner, the accuracy in estimation of the selected antenna is crucial and increases with the number of passive reflecting elements. As a result, using the sub-optimal GD for high  $N$  values provides an advantage considering the system complexity, despite the ML detector performing better overall.

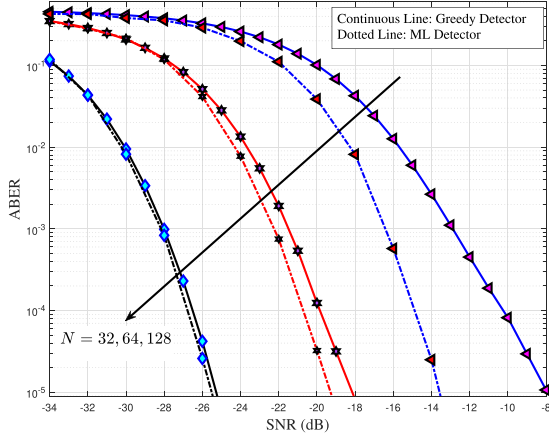


Fig. 4. BER performance comparison of GD and ML detector for proposed RIS-RSM-ASBC scheme with  $(M = 4, N_r = 4)$  for varying  $N$ .

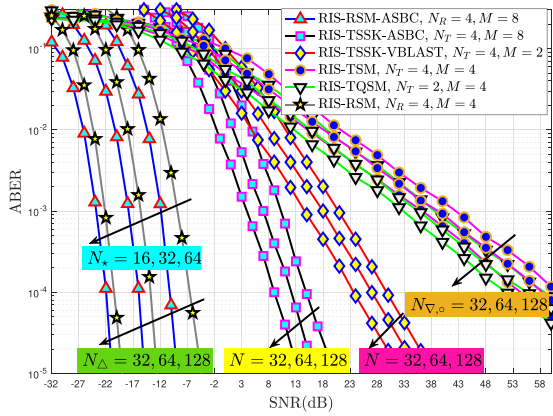


Fig. 5. BER performance of the RIS-RSM-ASBC ( $M = 8, N_r = 4$ ), RIS-TSSK-ASBC ( $M = 8, N_t = 4$ ), RIS-TSSK-VBLAST ( $M = 2, N_T = 4$ ), RIS-TSM ( $M = 4, N_T = 4$ ), RIS-TQSM ( $M = 4, N_T = 2$ ) and RIS-RSM ( $M = 4, N_r = 4$ ) for varying  $N$ .

Fig. 5 shows that RIS-RSM-ASBC provides better error performance compared to RIS-TSSK-ASBC, RIS-TSSK-VBLAST, RIS-TSM, RIS-TQSM, and RIS-RSM. It is worth noting that although there are fewer reflectors in the proposed scheme, it provides better performance than the conventional RIS-RSM system. As seen from Fig. 5, RIS-RSM-ASBC provides over 50 dB improvement in the required SNR to achieve a target BER value in comparison to both RIS-TSM and RIS-TQSM. Also, it is shown that the proposed RIS-RSM-ASBC scheme is significantly better than RIS-TSSK-VBLAST. While RIS-RSM-ASBC provides  $10^{-3}$  ABER performance at  $\text{SNR} = -17$  dB for  $N = 32$ , RIS-TSSK-VBLAST provides it with  $\text{SNR} = 15$  dB for  $N = 32$ .

The effect of RIS division is presented in Fig. 7. In this configuration, the effect of RIS on error performance is investigated when it is not portioned in half. The total number of passive reflectors is fixed to  $N = 128$  for each scheme, with  $N_r = 4, M = 4$ . In this figure following configurations are designed: two subspace surfaces with equal number of reflectors ( $N_{\text{RIS-1}} = 64, N_{\text{RIS-2}} = 64$ ), such that the difference in the number of reflectors between RIS-1 and RIS-2 is 1 ( $N_{\text{RIS-1}} = 65, N_{\text{RIS-2}} = 64$ ), the difference between them is 32 ( $N_{\text{RIS-1}} = 80, N_{\text{RIS-2}} = 48$ ) and the difference between them is as 64 ( $N_{\text{RIS-1}} = 96, N_{\text{RIS-2}} = 32$ ). We have found

that when the difference in the number of reflectors between the two RIS is only 1, there is almost no change on the error performance. However, as the difference in the number of reflectors increases, an improvement on performance is observed. Therefore, we suggest that further examination regarding the division of RIS can be made by considering the CLT for future studies.

Lastly, we can summarize the performance improvements provided by the proposed scheme as follows:

- RIS-RSM-ASBC scheme provides about 14 dB BER performance improvements over RIS-TSSK-ASBC scheme.
- Compared to the proposed RIS-RSM-ASBC scheme, a more than 30 dB difference in required SNR is observed for the RIS-TSSK-VBLAST.
- The proposed RIS-RSM-ASBC scheme provides over 50 dB better performance than both RIS-TSM and RIS-TQSM.
- We provide better error performance than conventional RIS-RSM schemes.

### B. Energy Efficiency

The RIS-RSM-ASBC scheme consumes transmission energy to send  $u_1 = 2 \log_2 M$  bits conveyed over directly by the modulated symbols. Also, the selected receive antenna information is transmitted without energy consumption. As a result, the percentage of energy-saving ( $E_{sav}$ ) per  $u$  bits for the proposed scheme can be obtained as following [9] :

$$E_{sav} = \% \left( 1 - \frac{u_1}{u} \right) E_b, \quad (30)$$

where  $E_b$  is the bit energy. Accordingly, energy saving ratio of RIS-RSM, RIS-QSM, RIS-TSSK-ASBC and RIS-RSM-ASBC schemes are presented in Table VII. In this table, all systems are evaluated in various scenarios using different  $N_r$ ,  $N_t$  and  $M$  settings. As  $N_r$  expands for constant  $M$ , it is clear that the energy saving ratio of our proposed scheme increases. However, it is clearly seen that an increase in  $M$  may decrease energy efficiency from where the transition of  $M = 8, N_r = 4$  into  $M = 8, N_r = 16$ . In the proposed system, Alamouti symbols are transmitted to the same selected receive antenna. It is significant to note that improvement in energy efficiency and data rate can be achieved by sending Alamouti symbols to different antennas.

### C. Spectral Efficiency

In this section, we compare RIS-VBLAST, RIS-RQSM, RIS-RSM, RIS-SM, RIS-RQSSK, RIS-RSSK, RIS-SSK, RIS-TSSK-ASBC and RIS-RSM-ASBC schemes in terms of their data rates, as presented in Table VIII. From this point of view, the spectral efficiency of these systems is analysed with respect to the number of receive or transmit antennas and modulation orders in Fig. 6. Firstly, the effect of the number of receive or transmit antennas on the spectral efficiency is illustrated in Fig. 6(a) when  $M = 16$ . It is clearly seen that the spectral efficiency of RIS-RQSM, RIS-RSM, RIS-RSSK and RIS-RQSSK, RIS-TSSK-ASBC and RIS-RSM-ASBC techniques improves exponentially as the number of transmit/receive antennas increases. On the other hand, it is shown that the spectral efficiency of RIS-VBLAST system enhances linearly with the number of transmit antennas, as we expected. It is seen that our proposed system provides the same performance as RIS-TSSK-ASBC and superiority to the RIS-SSK system for  $M > \sqrt{N_r}$ . Secondly, the effect of modulation order on spectral efficiency

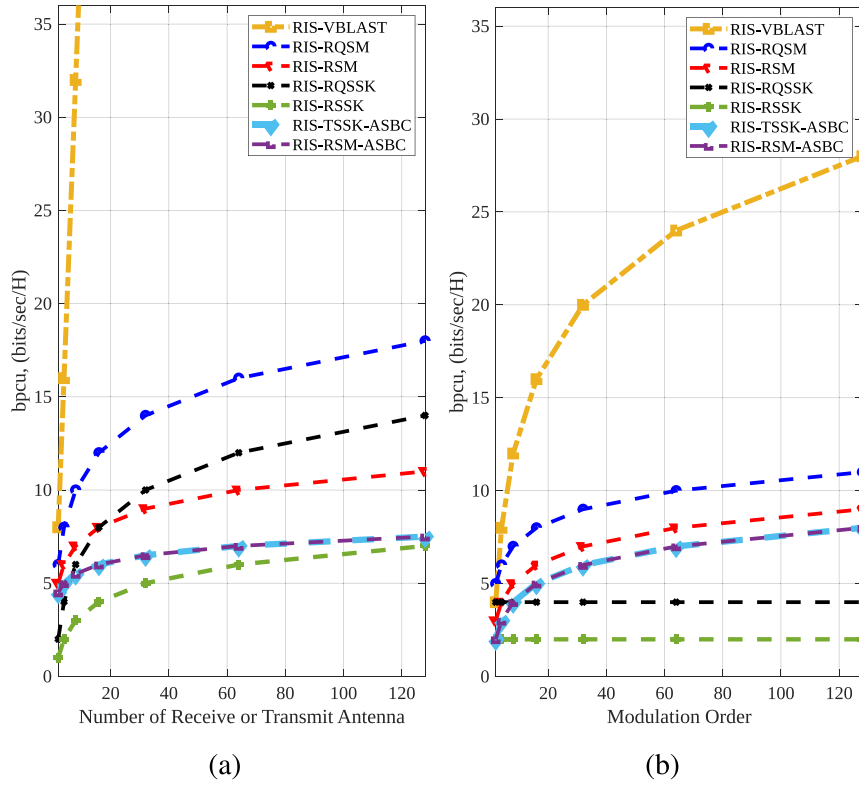


Fig. 6. Comparison of RIS-RQSM, RIS-RSM, RIS-RSSK, RIS-RQSSK, RIS-VBLAST, RIS-TSSK-ASBC and RIS-RSM-ASBC systems according to their spectral efficiencies (a) under the various transmit/receive antenna numbers for  $M = 16$  and (b) under the various modulation orders for  $N_r, N_t = 4$ .

TABLE VII  
ENERGY SAVING RATIOS

| $N_r$ or $N_t$ | $M$ | RIS-RSM | RIS-RQSM | RIS-VBLAST | RIS-TSSK-ASBC | RIS-RSM-ASBC |
|----------------|-----|---------|----------|------------|---------------|--------------|
| 4              | 4   | 50%     | 66.6%    | 75%        | 33.3%         | 33.3%        |
| 8              | 4   | 60%     | 75%      | 87.5%      | 50%           | 50%          |
| 16             | 8   | 57.1%   | 72.72%   | 93.75%     | 40%           | 40%          |

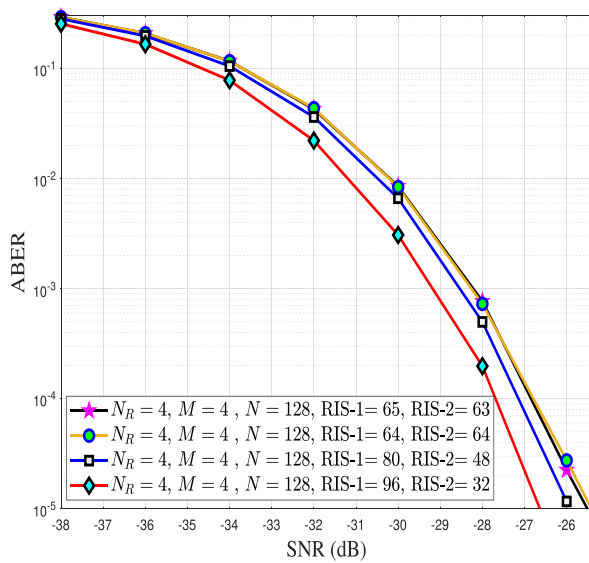


Fig. 7. Effect of RIS division providing different number of passive reflectors for each sub-space of RIS on error performance of RIS-RSM-ASBC schemes.

TABLE VIII  
SPECTRAL EFFICIENCY COMPARISONS

| Systems                        | Bits per Channel Usage (bpcu)        |
|--------------------------------|--------------------------------------|
| RIS-VBLAST                     | $N_t \log_2 M$                       |
| RIS-RQSM                       | $\log_2 M + \log_2 N_r + \log_2 N_t$ |
| RIS-RSM [19]                   | $\log_2 M + \log_2 N_r$              |
| RIS-SM                         | $\log_2 M + \log_2 N_t$              |
| RIS-RQSSK                      | $2 \log_2 N_r$                       |
| RIS-RSSK [19]                  | $\log_2 N_r$                         |
| RIS-SSK [41]                   | $\log_2 N_t$                         |
| RIS-TSSK-ASBC                  | $\log_2 M + (\log_2 N_t)/2$          |
| RIS-RSM-ASBC (Proposed System) | $\log_2 M + (\log_2 N_r)/2$          |

is presented under the fixed number of transmit/receive antenna  $N_r, N_t = 4$  in Fig. 6(b). As expected, the spectral efficiency remains stable for RIS-RQSSK and RIS-RSSK techniques. On the other hand, the performance of the RIS-RSM-ASBC approaches that of the RIS-RSM under a large number of antennas.

#### D. Complexity Analysis

This section presents the receiver complexity of the specified/referenced systems and our proposed model. The

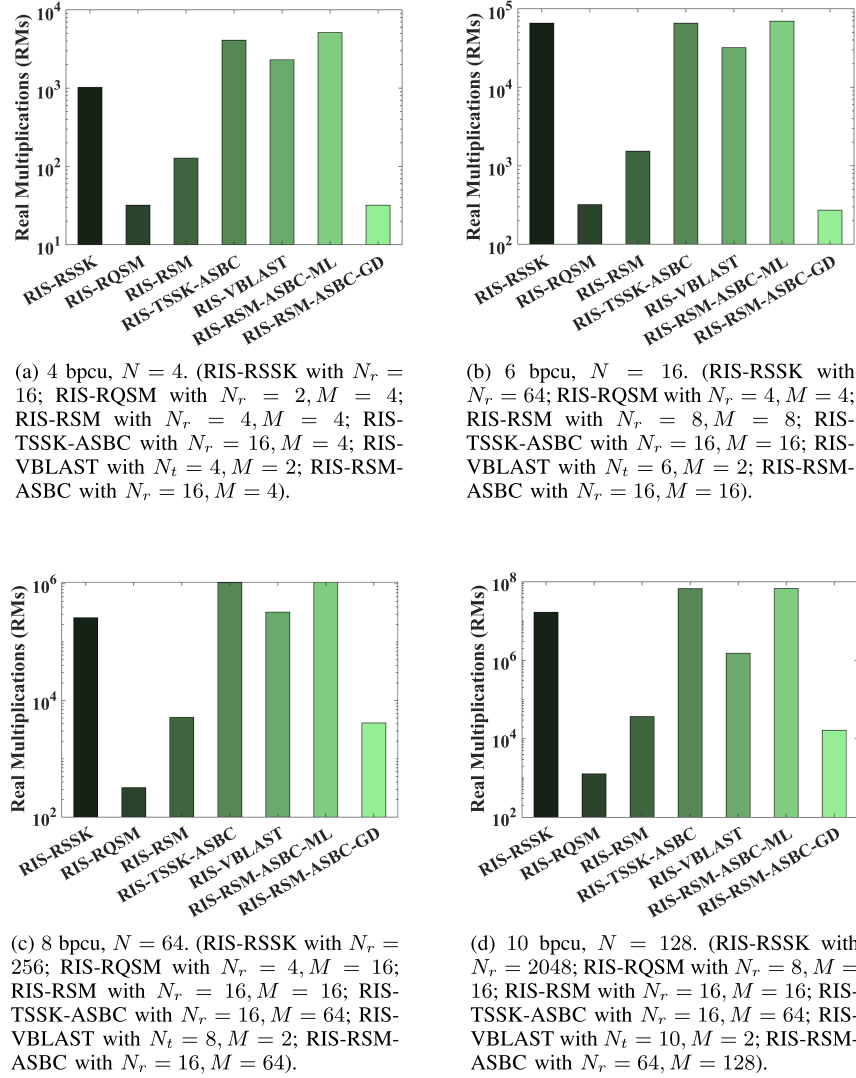


Fig. 8. The complexity comparison of RIS-RSSK, RIS-RQSM, RIS-RSM, RIS-VBLAST, RIS-TSSK-ASBC, and RIS-RSM-ASBC schemes for different configurations.

TABLE IX  
COMPUTATIONAL COMPLEXITY COMPARISONS

| Systems                           | Real Multiplications (RMs) |
|-----------------------------------|----------------------------|
| RIS-RSSK [19]                     | $NN_r^2$                   |
| RIS-RQSM                          | $(N + M)N_r^2$             |
| RIS-RSM [19]                      | $(N + M)N_r^2$             |
| RIS-VBLAST                        | $N_t^4$                    |
| RIS-TSSK-ASBC [27]                | $(N_t M)^2$                |
| RIS-RSM-ASBC-ML (Proposed System) | $(M^2 + N)N_r^2$           |
| RIS-RSM-ASBC-GD (Proposed System) | $N_r M^2$                  |

computational complexity of detection algorithms can be calculated by taking into account the real multiplications/divisions at the receiver.

The results of the complexity analysis are summarized in Table IX and also a comparison of the receiver complexity for different bench-mark schemes is presented under the various data rates in Fig. 8 in logarithmic domains. Note that systems are evaluated by their optimum detection algorithms. In addition, RIS-RSM-ASBC has evaluated both GD and ML detector. It is

clear evident that the uncoded RIS-assisted IM schemes have superior complexity performance than coded systems at whole data rates. Unfortunately, the complexity of ML in our proposed scheme increases as greater values of  $N$  and  $M$ . Therefore, we also proposed a simplified receiver, namely greedy detector, for the proposed system.

In ML detector, in order to make a joint decision for the proposed system,  $N_r(M^2 + N)$  complex operations evaluated  $N_r$  times that makes:

$$\mathcal{O}_{\text{RIS-RSM-ASBC-ML}} = N_r^2(M^2 + N). \quad (31)$$

On the other hand, we have  $N_r$  times complex operation at antenna detection and we have  $M^2 + N_r$  times complex operation at symbol detection according to (8) and (9), respectively and which yields  $N_r(1 + M^2)$ . Therefore, complexity of GD-based proposed system is obtained as follows:

$$\mathcal{O}_{\text{RIS-RSM-ASBC-GD}} = N_r M^2. \quad (32)$$

It is clearly seen that we reduce exponent of  $N_r$  and discard impact of the number of reflector elements.

## V. CONCLUSION

In this paper, we have proposed Alamouti space-time coded RIS-assisted RSM scheme and derived the ABER expressions of proposed scheme using ML detection. In addition, we verified our theoretical derivations with Monte-Carlo simulations for various system configurations. We have also presented useful insights such as complexity, data rate and spectral efficiency analysis of proposed scheme and compared with existing RIS-assisted techniques. We showed that our proposed scheme provides superior error performance than RIS-TSM, RIS-TQSM, RIS-RSM, RIS-TSSK-ASBC and RIS-TSSK-VBLAST systems at extremely low SNR values. Unfortunately, we showed that the proposed scheme compromises in terms of receiver complexity, energy efficiency and data rate. Therefore, we improved receiver complexity by proposing a greedy detector. It is worth mentioning that to enhance the spectral efficiency of the proposed system, the symbols intended for transmission through a single antenna can be transmitted through two separate antennas, thereby resulting in an additional increase in data rate.

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