RIS-aided Media Based Modulation

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***Abstract*—Reconfigurable intelligent surface (RIS) technology and media based modulation (MBM) are promising physical layer techniques in wireless communication. While RIS uses electronically tunable surfaces in the far field of the transmit antenna(s) for the purpose of beamforming towards the receiver of interest, MBM uses such surfaces in the near field for the purpose of modulation. Both RIS and MBM offer improved communication performance at low radio-frequency (RF) hardware complexity. In this paper, we investigate MBM aided by RIS and show interesting performance results. We develop the system model for an RIS-aided MBM (RIS-MBM) system and analyse its bit error performance through analysis and simulation. For this system, we propose two schemes for optimizing the phases at the RIS, one maximizing the Frobenius norm of the channel and the other maximizing a bound on the achievable rate. We also compare the performance of RIS-aided MBM with that of RIS-aided generalized spatial modulation (RIS-GSM). Our results show that *i)* the performance of MBM improves with the use of RIS, *ii)* RIS phase optimization using rate maximization is better compared to that using Frobenius norm maximization, and *iii)* for a given rate, RIS-aided MBM achieves better performance compared to RIS-aided GSM.**

***Index Terms*—Reconfigurable intelligent surface, media based modulation, RIS-aided MBM, RIS-aided GSM, RIS phase optimization.**

I. Introduction

In recent years, index modulation (IM) has gained considerable attention for its improved transmission rate and error performance [1], [2]. In spatial IM techniques such as spatial modulation (SM) and space shift keying (SSK), the information can be transmitted not only through the conventional quadrature amplitude modulation (QAM) or phase shift keying (PSK) but also on the active antennas. As there is a one-to-one mapping between information bits and antenna indices in SM and SSK, the transmitter typically activates only one antenna while the others remain silent. This eliminates interchannel interference, inter antenna synchronization requirements and reduces transceiver complexity. In contrast, media-based modulation (MBM) scheme utilizes multiple RF mirrors nearby the transmit antennas to create a variety of channel fade realizations [4], [5]. In MBM, switching between the ON/OFF states of RF mirrors enables the realization of unique mirror activation patterns (MAPs), channel fades, and the indices of unique MAPs convey information. The spectral efficiency of an MBM system can be increased by increasing the RF mirrors.

Several articles in recent literature have discussed various aspects of MBM. The performance of MBM with GSM, selection of MAP based on Euclidean distance (ED)-based metric, feedback based phase compensation and constellation rotation have been discussed in [5]. Cooperative communication with MBM has been discussed in [6], [7]. Low complexity detection of MBM in massive multiple input multiple output (MIMO) is presented in [8], [9].

RIS consisting of passive reflective elements has been considered promising candidate for attaining high power/spectral efficiency. RIS is a power-efficient form of communication, and through the use of tunable reflecting elements, it facilitates communication between the transmitter and receiver [10], [11]. By changing the reflection coefficients at RIS, the desired signal's parameters at the receiver can be optimized. Also, RIS can suppress the unintended user's signal, improving the privacy of the communication. In the recent literature combination of two technologies, namely RIS and IM, gained significant attention because of power efficiency (due to RIS) and spectral efficiency (due to IM) [12], [13]. For multiple input multiple output configuration, a low complexity-based algorithm for selecting phases at the RIS has been discussed in [15]. The work in [16] considers practical channel scenarios for RIS-aided MBM systems. However, it does not assess bit error rate (BER) performance. The work of [17] considers Differential space-time block code (DSTBC) MBM, and the phases at the RIS are chosen from finite discrete phase shift states which do not depend on the channel knowledge and are not optimized. In our work, we develop the system model for an RIS-aided MBM system and analyze its BER performance through simulation. We also consider optimized phases at the RIS using channel knowledge. The new and novel contribution of this paper as follows.

- We develop an end-to-end system model for RIS-aided MBM, considering multiple antennas at the transmitter and receiver and multiple RF mirrors at each transmit antenna.
- We propose two methods for selecting optimal phases, namely 1) the Frobenius norm maximization method and 2) the rate maximization method for improved performance.
- Our simulation results show that 1) the use of RIS improves the performance of MBM, 2) optimal phases at RIS using rate maximization is better than the Frobenius norm maximization, and 3) the performance of RIS-aided MBM is superior to that of RIS-aided GSM.

The rest of the paper is organized as follows. The RIS-aided MBM system model and the methods to find the optimized phases at the RIS have been discussed in Sec. II.

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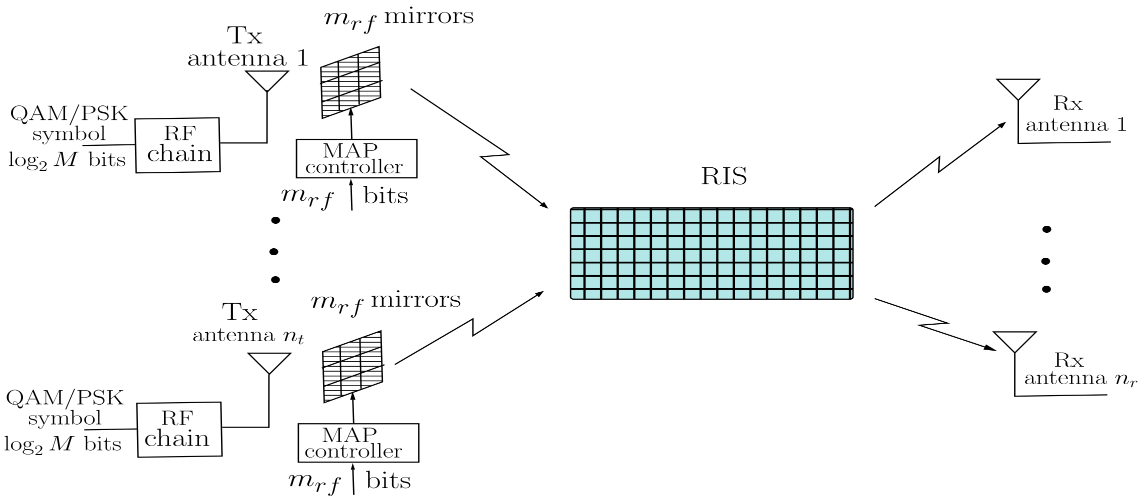


Fig. 1: RIS-aided MBM system.

The performance analysis of RIS-aided MBM is discussed in Sec. III. Simulation results and discussions are presented in Sec. IV. Conclusions are presented in Sec. V.

Notations: A matrix is represented by an uppercase boldface letter, a vector by a lowercase boldface letter, and a diagonal matrix by $\mathrm{diag}\{x_1, \cdots, x_n\}$. The determinant of a matrix is denoted by $\det(\cdot)$. An identity matrix of size K is denoted by $\mathbf{I}_K$. $(\cdot)^T$, $(\cdot)^H$, and $\mathbb{E}[\cdot]$ represent transposition, Hermitian and expectation operators, respectively. A complex Gaussian distribution with mean μ and variance σ^2 is denoted by $\mathcal{CN}(\mu, \sigma^2)$. $|.|$ denotes the magnitude of a complex number and $\mathbb{C}$ represents the set of complex-valued numbers.

II. System model

The RIS-aided MBM consists of an MBM transmitter, an MBM receiver, and an RIS, as shown in Fig. 1. The basic MBM transmits a tone using the complex channel fade realizations as modulation alphabets. In SSK multiple transmit antennas are used to create complex fade symbols. While in MBM, the complex fade symbols are generated by placing multiple RF mirrors near the transmit antennas. These RF mirrors are equivalent to scatterers placed near transmitters in propagation environments. The transmitter of RIS-aided MBM consists of n_t transmit antennas and M_{rf} mirrors at each transmit unit, out of which $1 \leq m_{rf} \leq M_{rf}$ mirrors are activated using mirror activation pattern (MAP). The receiver includes n_r receive antennas. An ON/OFF signal is used to change the radiation characteristics of each RF mirror. Every ON/OFF status combination of the mirrors creates a unique MAP that corresponds to an independent channel fade realization, and the total size of this channel fade alphabet is $2^{m_{rf}}$. In addition, we also have a RIS element array, which contains N passive reflective elements (sub-surfaces) to provide controlled transmission and improve the performance by having adjustable phase shifts. Let the reflection coefficient at the rth sub-surface of RIS be defined as $v_r = \alpha_r e^{j\theta_r}$, $r = 1, \cdots, N$ where $\alpha_r \in [0, 1]$ and $\theta_r \in [-\pi, \pi]$ are the reflection amplitude and phase of the rth sub-surface, respectively.

The information bits in RIS-aided MBM are transmitted using RF mirror indexing and quadrature amplitude modulation (QAM)/(PSK) symbols in each channel use as follows.

1) Each transmitter unit sends m_{rf} bits based on MAP, and the total bits transmitted through n_t antennas are $n_t m_{rf}$.
2) Each antenna transmits a M-ary QAM/PSK symbol, and the total transmitted bits through the n_t antennas are $n_t \log_2 M$ bits. Therefore the achieved rate in RIS-aided MBM in bits per channel use (bpcu) is

$$\Gamma_{RIS-MBM} = n_t m_{rf} + n_t \log_2 M \ \text{ bpcu}. \tag{1}$$

The input-output relation of an RIS-aided MBM is described as follows. Let $\mathbf{G} \triangleq [\mathbf{g}^1, \mathbf{g}^2, \ldots, \mathbf{g}^N] \in \mathbb{C}^{n_r \times N}$ be the channel matrix between RIS and the receiver where $\mathbf{g}^i = [g_1^i, g_2^i, \ldots, g_{n_r}^i]^T \in \mathbb{C}^{n_r \times 1}$ with $g_j^i \sim \mathcal{CN}(0, 1)$ being the channel fade coefficient between ith RIS element and jth receive antenna. Let $\mathbf{h}^k \triangleq [\mathbf{h}_1^k, \mathbf{h}_2^k, \ldots, \mathbf{h}_{n_t}^k]$ be the $1 \times n_t 2^{m_{rf}}$ channel vector between the transmitter and k^{th} RIS element, with $\mathbf{h}_i^k \in \mathbb{C}^{1 \times 2^{m_{rf}}}$ being the channel vector between kth RIS element and ith transmit antenna. Further each $\mathbf{h}_i^k$ can be written as $\mathbf{h}_i^k = [h_{i,1}^k, h_{i,2}^k, \ldots, h_{i,2^{m_{rf}}}^k]$, where $h_{i,j}^k \sim \mathcal{CN}(0, 1)$ is the channel fade coefficient corresponding to the j^{th} MAP. The received signal vector $\mathbf{y}$ at the receiver is given by

$$\mathbf{y} = \left[\sum_{i=1}^{N} \mathbf{g}^i v_i \mathbf{h}^i \right] \mathbf{x} + \mathbf{n}, \tag{2}$$

where $\mathbf{y}$, $\mathbf{n} \in \mathbb{C}^{n_r \times 1}$ are the received signal vector and additive noise vector at the receiver, respectively. Further (2) can be written as

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

where $\mathbf{H} \triangleq [(\mathbf{h}^1)^T, (\mathbf{h}^2)^T, \ldots, (\mathbf{h}^N)^T]^T \in \mathbb{C}^{N \times n_t 2^{m_{rf}}}$, $\mathbf{\Phi} = \mathrm{diag}\{v_1, \cdots, v_N\}$ is the phase matrix. The transmitted signal vector $\mathbf{x}$ is generated from the set $\mathbb{S}_{RIS-MBM}$ given by

$$\mathbb{S}_{RIS-MBM} = \{\mathbf{s};\ s_i \in \mathbb{A} \cup 0, ||\mathbf{s}||_0 = n_t\}, \tag{4}$$

where $\mathbf{s}$ is a $n_t 2^{m_{rf}} \times 1$ vector and s_i is the i^{th} element of $\mathbf{s}$, $|| \cdot ||_0$ denotes the 0-norm of a vector and $\mathbb{A}$ is the modulation alphabet. The maximum likelihood (ML) detection is given by

$$\hat{\mathbf{x}} = \min_{\mathbf{x} \in \mathbb{S}_{RIS-MBM}} ||\mathbf{y} - \mathbf{P}\mathbf{x}||_F, \tag{5}$$

where $\hat{\mathbf{x}}$ is the decoded signal vector used to estimate the MAP and the modulation symbols, $\mathbf{P} \triangleq \mathbf{G}\Phi\mathbf{H}$ is the end-to-end channel matrix and $||.||_2$ is the Euclidean norm for vectors.

A. Reflection phase design for RIS-aided MBM system

In this subsection, we discuss the selection of optimal phases at the RIS to improve the system's performance. A key feature of an RIS is that it can adjust reflection coefficients according to the channel conditions. For the purpose of the analysis, we select $\alpha_r = 1$, $r = 1, \cdots, N$. We propose two methods for finding the optimal phases at the RIS as follows.

1) Frobenius norm maximization: The received signal-to-noise ratio (SNR) can be maximized by maximizing the Frobenius norm of the end-to-end $n_r \times n_t 2^{m_{rf}}$ channel matrix $\mathbf{P}$, which contains the phase matrix $\mathbf{\Phi}$. Therefore optimal value of $\mathbf{\Phi}$ is obtained by solving the following optimization problem,

$$\begin{aligned} \mathbf{\Phi} = & \max_{\theta_i} ||\mathbf{P}||_F, \\ \text{s.t. } & |v_i| = 1, \ \forall i = 1 \dots N, \end{aligned} \tag{6}$$

where $||\cdot||_F$ denotes the Frobenius norm of a matrix. Finding optimal $\mathbf{\Phi}$ is a non-convex problem due to unit modulus constraints. Instead, the above optimization problem is solved using numerical methods.

2) Rate maximization: The capacity of a $n_r \times n_t 2^{m_{rf}}$ RIS-aided MBM system can be lower bounded as

$$C^{n_r \times n_t} \leq C_{RIS-MBM}, \tag{7}$$

where $C^{n_r \times n_t}$ denotes the capacity of an $n_r \times n_t$ RIS-aided MIMO system given by

$$C^{n_r \times n_t} = \mathbb{E}_{\mathbf{P}} \left[\log_2 \left(\Re \left(\det \left[\mathbf{I}_{n_r} + \rho \mathbf{P}\mathbf{P}^H \right] \right) \right) \right], \tag{8}$$

where $\rho = \frac{E_s}{\sigma^2}$, E_s is the transmit signal power, $\Re(.)$ denotes the real part, $\mathbf{P} \triangleq \mathbf{G}\Phi\mathbf{H}$ is the $n_r \times n_t$ RIS-aided MIMO end-to-end channel matrix with $\mathbf{H} \in \mathbb{C}^{N \times n_t}$ being the channel matrix between the RIS and the transmitter, $\mathbf{G} \in \mathbb{C}^{n_r \times N}$ being the channel matrix between the RIS and the receiver, and $\mathbf{\Phi} = \text{diag}\{v_1, \cdots, v_N\}$ represents the phase matrix for the RIS. In this method, RIS has the knowledge of MAP selection being made at each transmitting antenna, so it uses the effective $n_r \times n_t$ RIS-MIMO channel matrix for phase optimization. The optimal phases at the RIS can be obtained such that this lower bound on the capacity is maximized, which maximizes the capacity of the RIS-aided MBM system. Thus the optimal phase $\mathbf{\Phi}$ is obtained by solving the following optimization problem given as

$$\begin{aligned} \mathbf{\Phi} \ = & \max_{\theta_i} \left\{ \log_2 \left(\Re \left(\det \left[\mathbf{I}_{n_r} + \rho \mathbf{P}\mathbf{P}^H \right] \right) \right) \right\}, \\ \text{s.t. } & |v_i| = 1, \ \forall i = 1 \dots N. \end{aligned} \tag{9}$$

Since $\log(.)$ function is a monotone increasing function, the above problem can be equivalently formulated as

$$\begin{aligned} \mathbf{\Phi} \ = & \max_{\theta_i} \left\{ \det \left[\mathbf{I}_{n_r} + \rho \mathbf{P}\mathbf{P}^H \right] \right\}, \\ \text{s.t. } & |v_i| = 1, \ \forall i = 1 \dots N. \end{aligned} \tag{10}$$

The problem in (10) is non-convex problem and solved numerically.

III. Performance Analysis

In this section, we investigate the performance of RIS-aided MBM system using union bound based on pairwise error probability (PEP) and capacity bounds.

A. Upper bound on BER

Assuming perfect channel knowledge at the receiver, the conditional pairwise error probability (PEP) between transmitted signal vectors $\mathbf{x}$ and $\tilde{\mathbf{x}}$ is given by

$$P(\mathbf{x} \rightarrow \tilde{\mathbf{x}} | \mathbf{P}) = Q \left(\sqrt{\frac{||\mathbf{P}(\mathbf{x} - \tilde{\mathbf{x}})||_2^2}{2\sigma^2}} \right), \tag{11}$$

where σ^2 is the noise power and $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{u^2}{2}} du$ is the Q function. The distribution of $\mathbf{P}$ needs to be found to get the unconditional PEP. The exact distribution of the end-to-end channel matrix $\mathbf{P}$ could not be determined analytically. Instead, we use the Monte Carlo sampling approach to find the average PEP. A large number of samples of $P(\mathbf{x} \rightarrow \tilde{\mathbf{x}} | \mathbf{P})$s are generated and averaged to get the unconditional PEP. Therefore the upper bound on the bit error rate P_e for RIS-aided MBM system is given by

$$P_e \leq \frac{1}{2^{\Gamma_{RIS-MBM}}} \sum_{\mathbf{x}} \sum_{\mathbf{x} \neq \tilde{\mathbf{x}}} \left\{ P(\mathbf{x} \rightarrow \tilde{\mathbf{x}}) \frac{\delta(\mathbf{x}, \tilde{\mathbf{x}})}{\Gamma_{RIS-MBM}} \right\}, \tag{12}$$

where $P(\mathbf{x} \rightarrow \tilde{\mathbf{x}})$ is the unconditional PEP, $\delta(\mathbf{x}, \tilde{\mathbf{x}})$ represents the difference in the bit patterns of the transmitted signal vectors $\mathbf{x}$ and $\tilde{\mathbf{x}}$.

B. RIS-aided MBM capacity

It has been shown in the recent literature that the capacity bounds of index modulation are independent of transmit signal constellations [18]. Extending the capacity bounds to the RIS-aided MBM system, we can write

$$C^{n_r \times n_t} \leq C_{RIS-MBM} \leq C^{n_r \times n_t} + n_t m_{rf}, \tag{13}$$

where $C^{n_r \times n_t}$ is the capacity of an $n_r \times n_t$ RIS-aided MIMO system given in (8). Similarly, the above bound can also be defined for the RIS-aided GSM system.

IV. Results and discussions

This section discusses numerical results on the bit error rate (BER) of the considered RIS-aided MBM system. In all the simulations, perfect knowledge of the channel is assumed at the receiver, and ML detection is used.

BER performance of MBM without RIS and with RIS: Fig. 2 shows the BER performance of MBM modulation without RIS and with RIS for $N = 8$, $n_r = 16$, $n_t = 1, 2$ and $m_{rf} = 2, 6$, and 4-QAM modulation. As expected, the performance of MBM improves significantly with the use of RIS. For example,

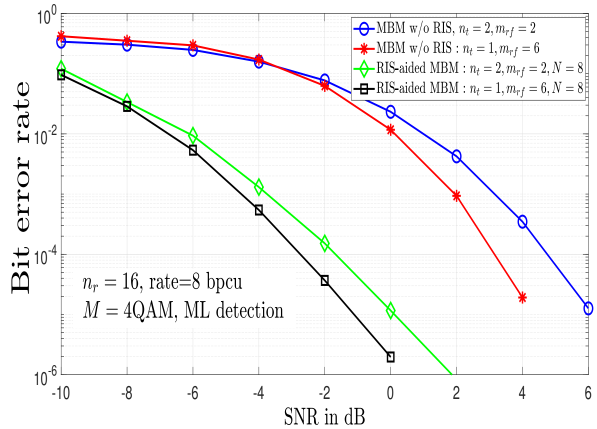


Fig. 2: BER performance of MBM without RIS and with RIS for $N = 8$.

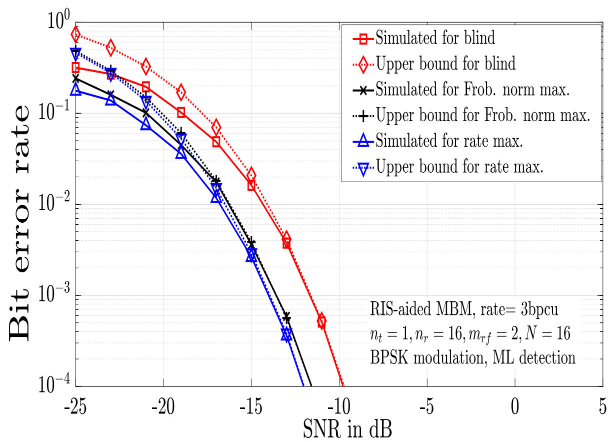


Fig. 3: BER performance of RIS-aided MBM and upper bounds for different phase selections.

at a BER of 10^{-4}, there is an SNR advantage of 6.5 dB in favor of RIS-aided MBM compared to MBM without RIS.

BER performance of RIS-aided MBM and upper bound: Fig. 3 shows the simulated BER performance of RIS-aided MBM system for $n_t = 1$, $n_r = 16$, $m_{rf} = 2$, $N = 16$ and BPSK modulation. The phases at the RIS are selected from the blind method and the proposed methods. In the blind phase selection, the values of θ_i s are taken to be zero. From the simulation, phase selection based on rate maximization performs better than the Frobenius norm maximization and blind method. Additionally, the upper bounds corresponding to each BER are also plotted. At high SNRs, the bounds are tight.

BER performance of RIS-aided MBM with different phase selections and varying modulation order: In Fig. 4, we compare the BER performance of RIS-aided MBM with RIS phases selected from blind, Frobenius norm, rate maximization method. Also, simulations are carried out for $M = 16, 64$, and 256, respectively. The simulation shows that the rate maximization method has the best performance, followed by the Frobenius norm maximization method. The blind method has the least performance as it does not exploit the knowledge of the channel at the RIS. The performance gap between the rate maximization method and the Frobenius norm maximization seen to be increasing as M varies from 16 to 256. In other words, the rate maximization has an SNR advantage of about 0.66 dB, 1.4 dB, and 1.96 dB over Frobenius norm maximization for $M = 16, 64$, and 256, respectively. The improvement in performance for the phase selection using rate optimization is due to the available knowledge of used MAP at the RIS.

Capacity bounds of RIS-aided MBM system: In Fig. 5, we plot the upper and lower bounds of capacity for the RIS-aided MBM system for $N = 4, 16$. The capacity bounds have been plotted for the blind method and proposed methods for selecting the RIS phases. The figure shows that phase selection based on the rate maximization technique can achieve a higher capacity in RIS-aided MBM compared to the blind phase and Frobenius norm maximization technique.

BER performance comparison of RIS-aided MBM, with RIS-aided SM and GSM: In Fig. 6, we compare the BER performance of RIS-aided MBM with that of RIS-aided SM and GSM. We use the following system model of an RIS-aided GSM,

$$\mathbf{y} = \mathbf{G\Phi Hx} + \mathbf{n}, \tag{14}$$

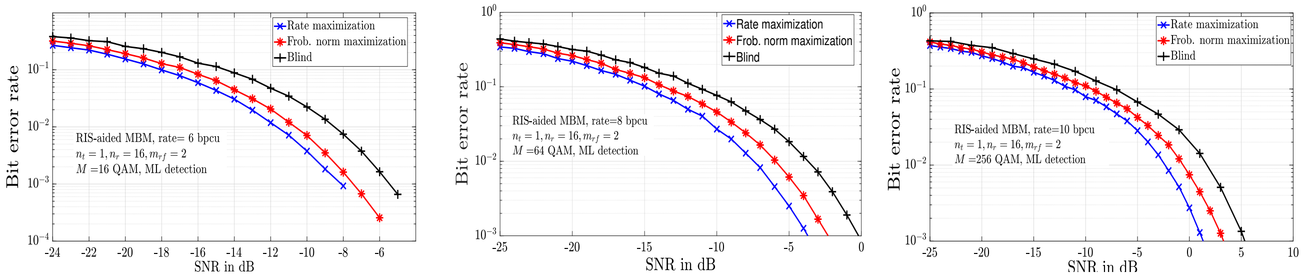
where $\mathbf{y} \triangleq [y_1, y_2, \ldots, y_{n_r}]^T$, and $\mathbf{n} = [n_1, n_2 \ldots n_{n_r}]^T$ are the received signal vectors and noise vectors, respectively and $\mathbf{G} \in \mathbb{C}^{n_r \times N}$, $\mathbf{H} \in \mathbb{C}^{N \times n_t}$, $\mathbf{\Phi}$ are as defined in (3) and $\mathbf{x}$ is the transmitted signal vector in GSM. In RIS-aided GSM, n_{rf} transmit RF chains, $1 \leq n_{rf} \leq n_t$ are used. The RIS-aided GSM system structure can be simplified into a RIS-aided SM system if $n_{rf} = 1$. The rate of an RIS-aided GSM is given by

$$\Gamma_{RIS-GSM} = \lfloor \log_2 \binom{n_t}{n_{rf}} \rfloor + n_{rf} \log_2 M \text{ bpcu}. \tag{15}$$

For the simulation, we consider $n_t = 2, 4$, $n_r = 16$, $n_{rf} = 1, 2$, $m_{rf} = 2$ and $N = 4, 8, 16$ and rate of 8 bpcu is considered. The phases at the RIS are selected from the blind method. The simulation shows that RIS-aided MBM has the best performance, followed by RIS-aided GSM, and RIS-aided SM has the least performance. For example, at a BER of 10^{-4} for $N = 16$, RIS-aided MBM has an SNR advantage of 4 dB and 8 dB compared to RIS-aided GSM and SM, respectively.

V. Conclusions

In this work, we investigated the performance benefits of using RIS in media based modulation systems. In this study, we proposed maximizing the Frobenius norm of the end-to-end channel matrix and maximizing the rate of the effective end-to-end system for selecting the phases at RIS. Our simulation results showed that the RIS phase using rate optimization performed better than Frobenius norm maximization. Also, our results showed that the RIS-aided MBM system performs better than the RIS-aided GSM system. Future topics can include efficient techniques to select the phases at RIS, investigation of transceiver techniques/algorithms, and implementations. Analysis of RIS-aided MBM for imperfect channel state information can also be explored.

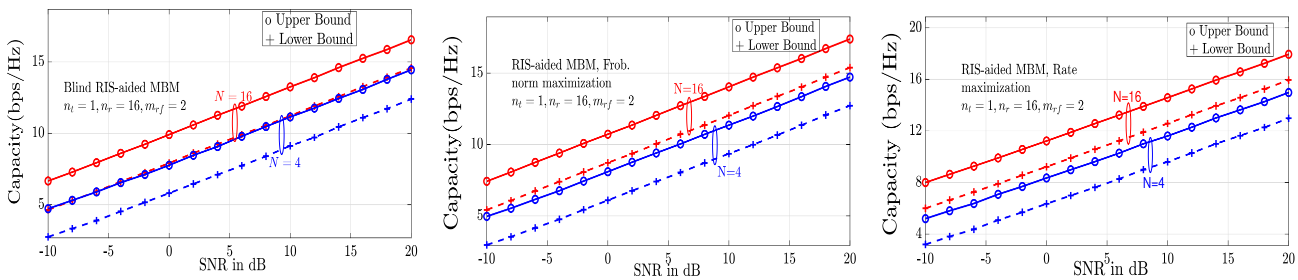


(a) 16 QAM modulation.

(b) 64 QAM modulation.

(c) 256 QAM modulation.

Fig. 4: BER performance of RIS-aided MBM with different phase selection and varying modulation order.



(a) blind phase selection.

(b) Frobenius norm maximization.

(c) rate maximization.

Fig. 5: Capacity bounds of RIS-aided MBM system for different phase selection.

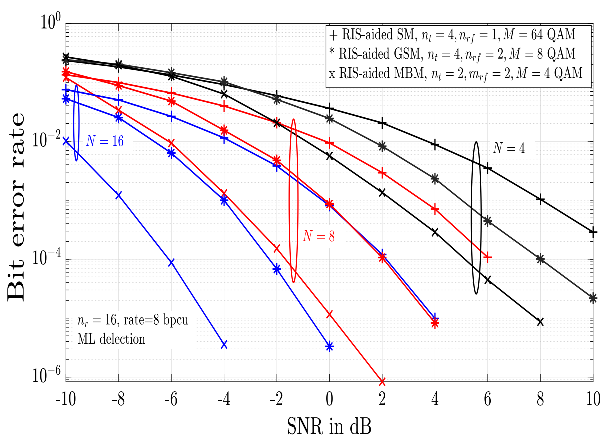


Fig. 6: BER performance comparisons of RIS-aided MBM with RIS-aided GSM and SM for N=4,8,16 and n_r = 16.

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