

Near-Field MIMO RIS Channel Capacity

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Abstract—The rapid evolution of wireless communication systems has ushered in an era of unprecedented connectivity and data transmission capabilities. Among the key technologies driving these advancements are Multiple-Input Multiple-Output (MIMO) systems and Reflecting Intelligent Surfaces (RIS). On the one hand, MIMO harnesses the power of multiple antennas at both transmitter and receiver ends to exploit spatial diversity and multiplexing gains, enhancing data rates and signal reliability. On the other hand, RIS promise to enable precise manipulation of electromagnetic waves through intelligent reflecting elements. In this work we evaluate the Shannon point-to-point capacity of MIMO RIS systems, when all terminals have multiple antennas and have no limitation on the type of processing performed; in addition, our model includes near-field propagation effects.

I. INTRODUCTION

The evolution of wireless communication technologies has led to unprecedented enhancements in data rates, coverage, and spectral efficiency. A key enabler of these improvements is the implementation of MIMO systems, which employ multiple antennas at both the transmitter and receiver ends to exploit spatial diversity and multiplexing gains [1], [2]. Concurrently, RIS, a novel concept in wireless communication, has gained significant attention for its potential to manipulate electromagnetic waves, thereby enabling better control and optimization of signal propagation in various environments [3]. The combination of these two technologies has opened up new horizons for wireless communications, promising improved performance, energy efficiency, and coverage extension.

The concept of channel capacity stands as a fundamental metric because it represents the maximum data rate attainable in the presence of noise. Understanding the ultimate channel performance has become of paramount importance in the design and deployment of wireless systems. MIMO RIS systems are the new cutting edge technology that promises a larger channel capacity due to *multiplexing and diversity gains*.

The multiplexing gain in a MIMO system arises from the ability to break down a MIMO channel into multiple parallel and separate channels, typically denoted as R channels. By transmitting distinct data streams independently on these individual channels, we achieve a data rate increase of R times compared to a system equipped with only one antenna at both the transmitter and receiver [4].

A key novelty of our study lies in using a near-field channel model to understand the attainable multiplexing gain as a function of the system geometry. In the context of MIMO RIS systems, the reflection and scattering capabilities of the RIS introduce new degrees of freedom. These degrees of freedom give rise to the possibility of achieving a multiplexing gain exceeding the traditional limits without RIS. Understanding

and quantifying this newfound potential is an essential aspect of our investigation.

The findings in [5] reveal that wireless links using large intelligent surfaces have degrees of freedom (DoF) and gain that depend on normalized geometric factors and enabling spatial multiplexing even in line of sight (LOS) conditions.

The limits of using a large number of antennas, which is central to massive MIMO (mMIMO), are investigated in [6] and point out that previous analyses often relied on far-field channel models, whereas the asymptotic limit is reached in the near-field. The recurring theme in the research done on MIMO RIS systems [7], [8], [9] is the recognition that accurate assessments of system performance, such as spectral efficiency and SNR, depend on the incorporation of precise near-field channel models, whether it applies to multi-user OFDMA systems enhanced by RIS [10] or mMIMO technology. The work that has been done on deriving the channel capacity [8], [9] has not taken this into account. In addition, while other work has focused on single-stream transmission, we take the case of multi-stream transmission which involves sending multiple independent data streams concurrently. The channel capacity analysis becomes more intricate when dealing with multi-stream scenarios, as it must consider the interactions and spatial aspects of the communication system. Therefore, based on these findings, we illustrate the importance of accurately characterizing the MIMO RIS channel capacity through sending multiple streams of data, and based on the near-field channel model.

II. PROPOSED WORK

We consider a wireless RIS-assisted MIMO system where the transmitter and the receiver are both uniform planar arrays (UPA) made of patch antennas and the planes of the arrays are oriented parallel to each other and located in the xz plane. We assume there are N_T transmit antennas and N_R receive antennas, where $N_T = N_T^x \times N_T^z$ and $N_R = N_R^x \times N_R^z$ are the number of elements of the transmitter and receiver arrays, respectively. The spacings between consecutive antenna elements are denoted by d_T^x, d_T^z and d_R^x, d_R^z for the transmitter and receiver array, respectively. The antenna element indices are represented by (m, n) and (p, q) for transmitter and receiver, respectively. We assume that an obstacle is placed between the transmitter and receiver, so that the line of sight (LOS) between them is blocked (non-LOS communication channel), however the RIS is positioned so that a communication link can be established between the transmitter array and the receiver array, as shown in Fig. 1.

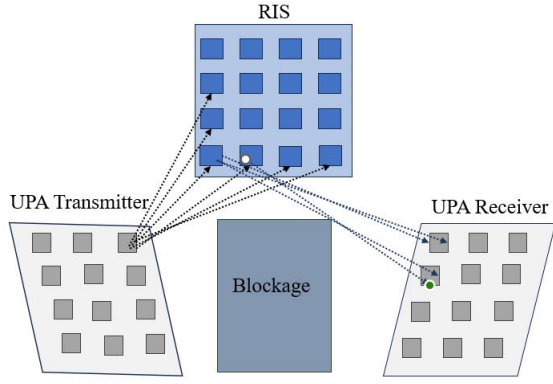


Fig. 1: Problem geometry.

The RIS is positioned in a plane perpendicular to the UPAs with N_{ris} RIS elements directed along the y-z axis where $N_{\text{ris}} = N_{\text{ris}}^y \times N_{\text{ris}}^z$. We are assuming that the antennas are isotropic and that each RIS element can be tuned to optimize the phase shift.

The received signal is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \quad (1)$$

where $\mathbf{y} \in \mathbb{C}^{N_R \times 1}$ represents the received signal vector, with each entry representing a received symbol at one of the receive antennas. $\mathbf{H} \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix defined as

$$\mathbf{H} = \mathbf{H}_{T_{m,n} \rightarrow \text{ris}} \boldsymbol{\theta}_{\text{ris}} \mathbf{H}_{\text{ris} \rightarrow R_{p,q}}. \quad (2)$$

$\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ is the transmit signal vector where each entry represents the symbols transmitted from one of the transmit antennas. $\mathbf{z} \in \mathbb{C}^{N_R \times 1}$ represents the noise vector which we model as additive white gaussian Noise (AWGN) with normalized unit variance.

Each element in the channel matrix $\mathbf{H}_{T_{m,n} \rightarrow \text{ris}} \in \mathbb{C}^{N_T \times N_{\text{ris}}}$ and $\mathbf{H}_{\text{ris} \rightarrow R_{p,q}} \in \mathbb{C}^{N_{\text{ris}} \times N_R}$ in (2) is derived with the general NLOS near-field channel model given by

$$h_{(s_{m,n}, r_{p,q})} = \sqrt{\frac{1}{4\pi \|\mathbf{r}_{p,q} - \mathbf{s}_{m,n}\|^2}} e^{-j\frac{2\pi}{\lambda} \|\mathbf{r}_{p,q} - \mathbf{s}_{m,n}\|} \quad (3)$$

where $s_{(m,n)}$ and $r_{(p,q)}$ are the transmit and receive antenna position, respectively, and $\|\cdot\|$ denotes the Euclidean distance. $\boldsymbol{\theta}_{\text{ris}} \in \mathbb{C}^{N_{\text{ris}} \times N_{\text{ris}}}$ represents the phase shifts introduced by each individual RIS element.

We would like to emphasize that we are using the near-field channel model since the far-field channel is a limiting case of the near-field channel. Therefore, by using the near-field channel we can analyze both the far-field and the near-field.

Next, for any matrix $\mathbf{H}$ in (2) we evaluate its singular value decomposition (SVD) [4], i.e., $\mathbf{H} \in \mathbb{C}^{N_R \times N_T}$ can be written as

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V} \quad (4)$$

where $\mathbf{U} \in \mathbb{C}^{N_R \times N_R}$ and $\mathbf{V} \in \mathbb{C}^{N_T \times N_T}$ are unitary matrices, and $\boldsymbol{\Sigma} \in \mathbb{C}^{N_R \times N_T}$ is a diagonal matrix composed of σ_i

singular values of $\mathbf{H}$ [4]. Note, we are assuming channel knowledge at both transmitter and receiver; therefore, we can use the waterfilling power allocation to evaluate the channel capacity given by

$$C = \sum_{i=1}^{R_{\mathbf{H}}} \log_2 \left(1 + \frac{\lambda_{X,i}}{\sigma^2} \lambda_{H,i}^2 \right) \quad (5)$$

$R_{\mathbf{H}}$ is the rank of $\mathbf{H}$ (DoF), where $\lambda_{X,i}$ are the eigenvalues of the transmit-symbols autocorrelation matrix [11], $\lambda_{H,i}$ are singular values of $\mathbf{H}$ matrix, and σ^2 is the variance (recall that the noise variance has been normalized to 1). This optimization is difficult to achieve since the reflecting elements in an RIS introduce complex phase shifts, modeling these elements accurately and accounting for their effects in the channel matrix will be challenging. In addition, the RIS elements may be reconfigured dynamically to adapt to changing channel conditions or user requirements which makes it difficult to obtain a single channel matrix for SVD, as the channel may vary over time.

Future steps include studying and analyzing the degrees of freedom once we fix the transmitter and RIS and vary the position of the receiver, i.e., analyzing how the position of the receiver with respect to the RIS will affect the channel capacity. In addition, we would like to visualize these results through a heat map. Extensions include the study of the sum-rate capacity of the multi user version of this point-to-point problem.

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