Reconfigurable Intelligent Surfaces: Channel Estimation and Applications in Future Wireless Networks

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TIMELINE

2019

Channel Estimation

RIS-assisted MU-MIMO using Maximum Margin Matrix Factorization (M3F)

2020

Channel Estimation

RIS-assisted mmWave MU-MIMO using CNN.

2021

RIS-assisted RCC systems

RIS to eliminate mutual interference between radar and communication systems using local search and ZF methods.

2022

RIS-assisted ISAC

Exploit the geometrical properties of the constraints and adopt an alternating manifold-based optimization.

2023

Channel Estimation

RIS-assisted MU-MIMO systems with Channel Hardening effects

2

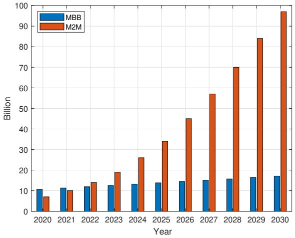
Outline

3

Introduction

- A set of physical objects defines the wireless environment.
  1. Controlled by nature.
  2. Cannot be modified.
- Electromagnetic waves alternations due to path loss, reflections, refraction, diffraction, and absorption.
- Affects the performance of the wireless communication systems.
- Most commercial communication systems have pushed towards higher operating frequencies.
- Attenuation limits the connectivity radius of nodes.

- Cisco estimates billions of devices connected by 2030.
- Existing techniques focus on the system design at the transmitter/receiver sides.
- Unfavorable wireless propagation environment.

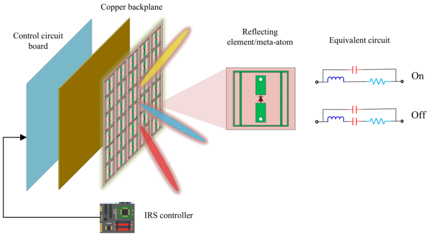


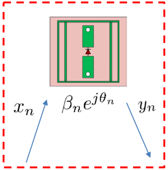
Introduction

- Fortunately, Reconfigurable intelligent surface (RIS) provides a groundbreaking technology to enhance overall performance.
- Advantages of RIS:
  1. Spectral Efficiency enhancement.
  2. Energy efficiency improvement.
  3. Improving the quality of existing paths.
  4. High passive beamforming is used to cancel undesired signals and interference mitigation.
- Compatibility and environment friendly.

What is The Reconfigurable Intelligent Surface?

- LIS, IRS, digitally controllable scatters, and software controllable surface.
- Two-dimensional array with a large number of reflective elements. Reflect signals to a desired direction.
- The RIS is neither part of the transmitter nor the receiver.
- **Random and uncontrollable** propagation environment into Smart radio environment **(controllable and programmable)**.
- A digitally-controlled metasurface with massive low-cost passive reflecting.





Motivation of Research

- Passive reflection improves the signal propagation. To apply this, the channel state information (CSI) is needed, however, the process is challenging due to passive nature at the same time.
- Channel estimation schemes that reduce the overhead and consider LOS path.
- The new wireless systems has pushed up to frequencies utilized by radar. Literature works on Interference mitigation require complex designs.
- The passive beamforming of the RIS makes it a promising technology to reduce the mutual interference.

Outline

Motivation for the 1$^{\mathrm{st}}$ Work

- Estimating the channels in RIS-aided systems is challenging.
- RIS provides energy and spectrum efficient communication.
- Improve SINR and enhance QoS.
- **To benefit from RIS, accurate channel state information (CSI) is required.**
- RISs have limited capability and cannot perform active Tx/Rx operations.

Related Works

Semi-passive RIS

- The channels for passive elements are estimated from active ones.
- Compression sensing and Deep learning.
- Needs huge training overhead.
- Capable of reflecting and sensing.
- Extension to massive MIMO.
- NO LOS channel.

Passive RIS

- The channels are estimated sequentially, one-by-one.
- Each element has two states: ON and OFF.
- Not practical; it requires perfect absorption and loss of power reflection.
- High training overhead.
- Accuracy degradation.

Our Approach

- All RIS elements are passive and cannot be switched OFF.
- RIS cannot send pilot signals.
- We estimate the LOS channel by controlling the phase shifts.
- Reduced training overhead compared to the Binary pattern.

LOS = Direct path between the BS and UEs.

System Model - Scenario Description

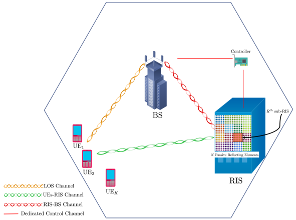
We consider a RIS-assisted Multi-User MIMO (MU-MIMO).

The BS:

- Uniform linear array (ULA).
- M elements.
- Serves K users; $\mathcal{K} = \{1, 2, ..., K\}$.
- Uncorrelated channels.
- Time division duplex (TDD) protocol.
- Uplink communication channel.

The RIS:

- Uniform planar array (UPA).
- N elements.
- Controller attached to RIS.
- Scattering matrix of discrete phase shifts.
- $\boldsymbol{\Omega} = \mathrm{diag}(\Omega_1, \Omega_2, \ldots, \Omega_N)$, where $\Omega_i = A_i e^{j\omega_i}$.



The Received Signal at the BS:

$$\mathbf{Y} = \mathbf{H}_1 \boldsymbol{\Omega} \mathbf{H}_2 \mathbf{X} + \mathbf{H}_{LOS} \mathbf{X} + \mathbf{W}. \tag{1}$$

$\mathbf{H}_{LOS} \in \mathcal{C}^{M \times K}$: LOS channel between UEs and the BS.
$\mathbf{H}_1 \in \mathcal{C}^{M \times N}$ and $\mathbf{H}_2 \in \mathcal{C}^{N \times K}$ the channel matrices between the RIS and the BS and between all K UEs and the RIS, respectively.
$\mathbf{X} \in \mathcal{C}^{K \times M}$ is the discrete-time transmitted signal collected from the K UTs.

System Model

The Received Signal at the BS:

$$\mathbf{Y} = \mathbf{H}_1 \mathbf{\Omega} \mathbf{H}_2 \mathbf{X} + \mathbf{H}_{LOS} \mathbf{X} + \mathbf{W}. \tag{2}$$

$\mathbf{H}_{LOS} \in \mathcal{C}^{M \times K}$: LOS channel between UEs and the BS.
$\mathbf{H}_1 \in \mathcal{C}^{M \times N}$ and $\mathbf{H}_2 \in \mathcal{C}^{N \times K}$ the channel matrices between the RIS and the BS and between all K UEs and the RIS, respectively.
$\mathbf{X} \in \mathcal{C}^{K \times M}$ is the discrete-time transmitted signal collected from the K UTs.

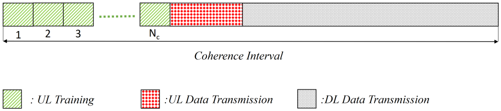
Our Goal

To estimate the composite channel $\mathbf{H_1 \Omega H_2}$, the RIS-based channels $\mathbf{H_1}$, $\mathbf{H_2}$, and the direct channel H_{LOS}.

Training Process with RIS splitting

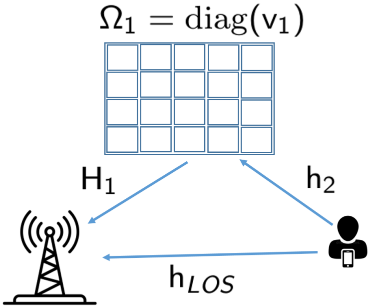
- Block fading.
- $\mathbf{H}_{LOS}$, $\mathbf{H}_1$, and $\mathbf{H}_2$ are assumed to be independent and identical (i.i.d.) distributed complex Gaussian.
- Predefined $\mathbf{X}_p\mathbf{X}_p^H = \mathbf{I}$.
- TDD transmission protocol.
  1. Zadoff-Chu.

  1. Uplink training. $\frac{N}{r} + 1$ frames.
  2. Channel estimation Processing.
  3. Downlink transmission.
- To avoid under- and over- determined system $r \leq \min(M, K)$



Proposed Approach for LOS Channel

Eliminate the reflected path by controlling the phase shifts.

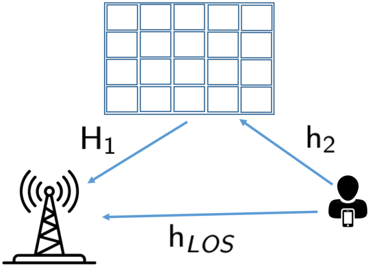


$$\mathrm{H}_1 \mathrm{diag}(\mathrm{v}_1)\mathrm{h}_2\mathrm{x}_1 + \mathrm{h}_{LOS}\mathrm{x}_1 + \mathrm{w}_1$$

Proposed Approach for LOS Channel

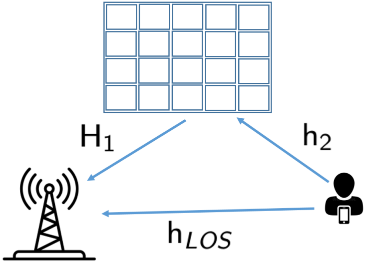
Eliminate the reflected path by controlling the phase shifts.

$$\Omega_1 = \mathrm{diag}(\mathrm{v}_1)$$



$$H_1 \mathrm{diag}(\mathrm{v}_1) h_2 x_1 + h_{LOS} x_1 + w_1$$

$$\Omega_2 = \mathrm{diag}(-\mathrm{v}1)$$



$$H_1 \mathrm{diag}(-\mathrm{v}_1) h_2 x_1 + h_{LOS} x_1 + w_2$$

Proposed Approach for LOS Channel

- Fletcher-Reeves (FR) method.
- Converges in a finite number of iterations
- Steepest descent (SDM) and Newton's method.
- Eliminate the reflected path by controlling the phase shifts.
- The vectorized received signal

$$\mathbf{y} = \underbrace{(\mathbf{I}_M \otimes \mathbf{X}_p)}_{\hookrightarrow\, \mathbf{\Phi} = \mathbf{\Phi}^T}\mathbf{h} + \mathbf{n} \tag{3}$$

$$\boxed{\hat{\mathbf{h}} = \min_{\mathbf{h}} \mathbf{\Phi}\mathbf{h} - \mathbf{y}} \tag{4}$$

Equivalently,

$$\hat{\mathbf{h}} = \min_{\mathbf{h}} \frac{1}{2}\mathbf{h}^T\mathbf{\Phi}\mathbf{h} - \mathbf{y}^T\mathbf{h}. \tag{5}$$

Proposed Approach for LOS Channel

1. **Initialization:** We start with $\mathbf{h}^0 \in \mathcal{C}^{MK}$.
2. **Iterative Update:**

$$\boxed{\mathbf{h}^i = \mathbf{h}^{i-1} + \alpha_i \mathbf{u}^i}, \tag{6}$$

where

$$\mathbf{u}^{i+1} = -\nabla g(\mathbf{h^i}) + \upsilon_i \mathbf{u}^i, \tag{7}$$

3. **Convergence Criteria:**

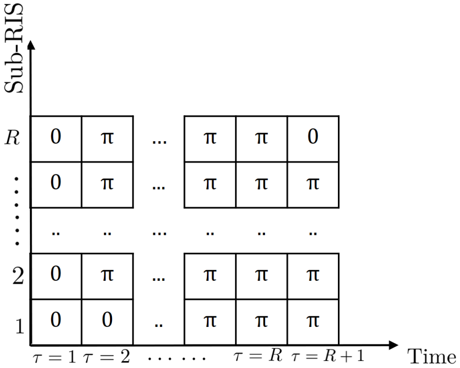
$$||\nabla g(\mathbf{h^i})|| = 0 \text{ or NMSE} = ||\mathbf{h^i} - \mathbf{h^{i-1}}||_\mathbf{2}^\mathbf{2} ||\mathbf{h^i}||_2^{-2} \leq \epsilon.$$

- $\mathbf{u}^{i+1}$: The FR direction and $\mathbf{u}^1 = -\nabla g(\mathbf{h^0})$.
- $\alpha_i = \frac{\left(u^i, \Phi \mathbf{h}^{i-1}\right)}{\left(u^i, \mathbf{\Phi} u^i\right)}$: The step-size.
- ϵ: Stopping threshold.
- NMSE: Normalized mean-squared error.
- Converges at most MK iterations.

Proposed Approach For RIS-based Channels

we assume the UL training period is divided up into $\tau = \frac{N}{r} + 1 = N_S + 1$ frames. And to obtain $\mathbf{H}_1^{(v)}\mathbf{\Omega}^{(v)}\mathbf{H}_2^{(v)}$ we apply the following steps,

- Divide the RIS into $N_S = \frac{N}{r}$ sub-RISs.
  1. Channel matrices into smaller propagation matrices.
- At instant $\tau = 1$, set phase shifts for each single element on the RIS to $0^\circ \rightarrow (\mathbf{Y}_{\tau_1})$.
- At $\tau = v + 1 \ \forall v = 1, 2, ..., \frac{N}{r}$, set phase shifts for the v^{th} sub-RIS to 0° while the other to 180°. we have $(\mathbf{Y})$ at $\tau = v + 1$ denoted by $(\mathbf{Y}_{\tau_{v+1}})$.
- To obtain $\mathbf{Y}^{(\mathbf{v})} = \mathbf{H}_1^{(v)}\mathbf{\Omega}^{(v)}\mathbf{H}_2^{(v)}$, we add $\mathbf{Y}_{\tau_1}$ to $\mathbf{Y}_{\tau_{v+1}}$.



Proposed Approach

- Let $\mathbf{H}_2^{(v)} = \mathbf{U}^{(v)}\mathbf{\Sigma}^{(v)}{\mathbf{V}^{(v)}}^H$ be the SVD-decomposition of $\mathbf{H}_2^{(v)}$.
- The covariance of the received signal can be expressed as

$$\boxed{\Xi^{(v)} = \mathbf{Q}^{(v)}{\mathbf{Q}^{(v)}}^H} \tag{8}$$

- $\mathbf{Q}$ is triangular matrix.
- Uniqueness of Cholesky Factorization iff positive semi-definite (respectively, positive definite)

- $\Xi^{(v)}$ is a Hermitian matrix.
- Does it have positive eigenvalues?
- Central Wishart has positive eigenvalues.
- The Characteristic polynomial $p\left(\mathbf{H}_1^{(v)}\mathbf{\Omega}^{(v)}\mathbf{H}_2^{(v)}{\mathbf{H}_2^{(v)}}^H\mathbf{\Omega}^{(v)}{\mathbf{H}_1^{(v)}}^H\right) = p\left({\mathbf{H}_1^{(v)}}^H\mathbf{H}_1^{(v)}\mathbf{\Omega}^{(v)}\mathbf{H}_2^{(v)}{\mathbf{H}_2^{(v)}}^H\mathbf{\Omega}^{(v)}\right)$

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 RIS CE

Proposed Approach

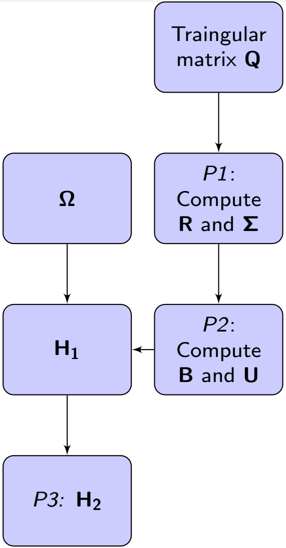
Divide the original problem into three sub-problems

$$\left(\hat{\mathbf{H}}_1,\hat{\mathbf{H}}_2\right) = \min_{\hat{\mathbf{H}}_1,\hat{\mathbf{H}}_2} ||\widehat{\mathbf{Y}} - \mathbf{H}_1\mathbf{\Omega}\mathbf{H}_2||^2. \tag{9}$$

Step 1: Obtain the $\mathbf{Q}$ from the Cholesky decomposition of the covariance matrix.

Step 2: Compute the SVD components of H_1.

Step 3: $\mathbf{\Omega}$ and $\mathbf{H_1}$ are known, (9) becomes convex.
$\min_{\mathbf{H}_2^{(v)}} \left(||\widehat{\mathbf{Y}^{(\mathbf{v})}} - \mathbf{H}_1^{(v)}\mathbf{\Omega}^{(v)}\mathbf{H}_2^{(v)}||_2^2 + \lambda_3||\mathbf{H}_2^{(v)}||_F^2 \right).$



Simulation Results

- We study the NMSE performance using channel realizations generated randomly and independently.

$$NMSE = \mathbb{E}\left\{ \frac{||\boldsymbol{\Delta} - \hat{\boldsymbol{\Delta}}||_2^2}{||\boldsymbol{\Delta}||_2^2} \right\}, \tag{10}$$

- We consider the following schemes:
  - LS estimator, where $\left(\mathbf{Y}_k\mathbf{X}^H\left(\mathbf{X}\mathbf{X}^H\right)^{-1}\right)^H$ represents the cascaded channel for the k^{th} user.
  - Binary Reflection scheme, where the channels are obtained one by one through keeping only one RIS element and turning off the rest elements.

Simulation Results

We evaluate the performance of the LOS Channel estimation method with $M = 12$, and $K = 12$ vs. different SNR values.

- Proposed algorithm based on the FR method to estimate the LOS channel outperforms the binary reflection RIS pattern CE.
- Does not require to turn off some of the RIS elements to compute the channels.
- The degradation in the binary reflection CE approach is due to that the RIS surface will lose some reflection gain.

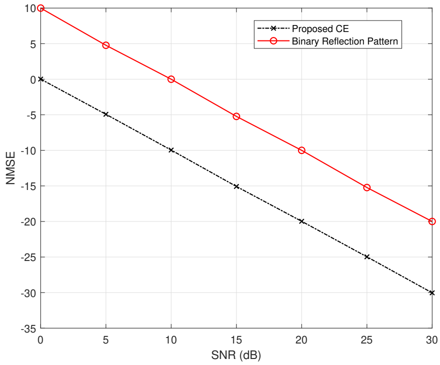


Figure: The performance of FR method on estimating the LOS channel vs different SNR values.

Simulation Results

We evaluate the performance of the RIS-based channel estimation method with $M = 12$, and $K = 12$ vs. different SNR values.

- Proposed algorithm based on the FR method to estimate the channel outperforms the binary reflection RIS pattern CE.
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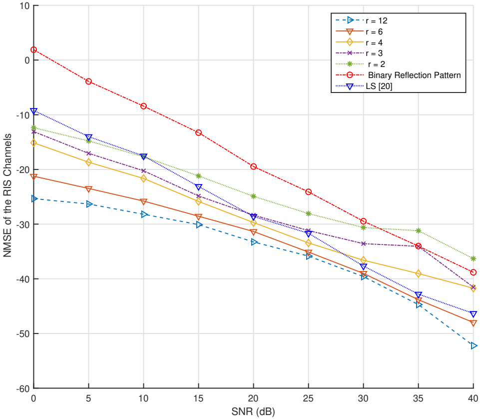

Figure: The Effect of Sub-RIS size on the NMSE performance vs SNR.

Summary of the 1st Work

- We propose an estimation method for a RIS-assisted multi-user UL MIMO communication system where all elements on the RIS unit are entirely passive.
- We introduce an iterative scheme based on the Fletcher-Reeves method to estimate the channel between the user terminals (UTs) and the BS.
- We introduce our new proposed approach based on the M3F method to estimate the RIS-based channels.
- We prove the efficiency and performance of our approaches through numerical simulation results.

Outline

Motivation for the 2$^{\mathrm{nd}}$ Work

- In TDD scheme, the uplink and downlink channels are separated in time. While FDD scheme separates the channels in frequency.
- The training overhead increases with number of antennas and users.
- Channel state information (CSI) dimenstions increase drastically with the number of antenna elements N and/or M.
- Deep-Learning (DL) has many applications in wireless communication systems. The Channel matrix is regarded as an image.

Our Goal

Reduce the training overhead by reducing the number of users involved during sounding period.

Contributions

- We propose a CE approach that reduces the number of active users during the training period.
- We develop a two-stage CE algorithm that combines an analytical part and Deep-learning approach.
- We adopt CNNs approach to estimate the missing channel coefficients based on the partial information collected in the first stage.

System Model

The channel between the BS and the RIS is defined as

$$\mathbf{H} = \sum_{k=0}^{N_{B,R}} \alpha_{B,R}^{(k)} \mathbf{a}_{B,R}\left(\phi_{B,R}^{(k)}\right) \mathbf{a}_{B,R}^{H}\left(\theta_{B,R}^{(k)}\right), \quad (1)$$

- $\alpha_{B,R}^{(k)}$: path gain of the k^{th} path between the BS and the RIS.
- $\theta_{B,R}^{(k)}$, $\phi_{B,R}^{(k)}$ represent the angle-of-departure (AoD) and angle-of-arrival (AoA).
- $N_{B,R}$ denotes the number of resolvable paths.

Likewise, the channel between the RIS and the r^{th} user $\mathbf{G}$ is given by

$$\mathbf{G}_r = \sum_{k=0}^{N_{R,U}} \alpha_{R,M}^{(k)} \mathbf{a}_{R,M}\left(\theta_{R,M}^{(k)}\right), \quad (2)$$

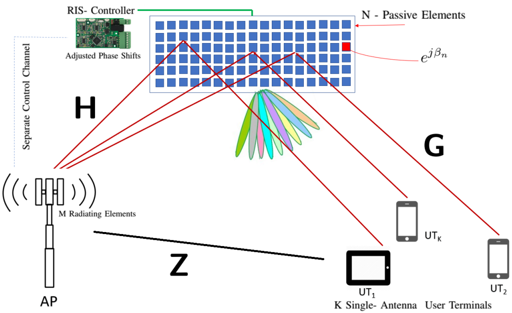

Figure: RIS- Assisted massive MIMO system

System Model

The composite channel between the BS and the r^{th} UT is

$$\mathbf{h}_r = \mathbf{H}\boldsymbol{\Omega}\mathbf{G}_r, \tag{3}$$

The received signal during the training period

$$\mathbf{Y} = \mathbf{H}_c\mathbf{X} + \mathbf{W}, \tag{4}$$

where

- $\mathbf{H}_c = [\mathbf{h}_1\mathbf{h}_2 \dots \mathbf{h}_K]$
- $\mathbf{X} \in \mathcal{C}^{K\times T}$ is the transmitted signal.
- $\mathbf{W} \in \mathcal{C}^{M\times T}$ is the additive white Gaussian noise.
- $\mathbf{H}_c$, $\mathbf{X}$, and $\mathbf{W}$ are independent.

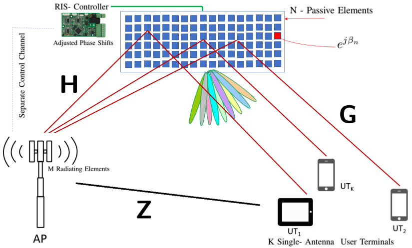

Figure: RIS- Assisted massive MIMO system

The Proposed Approach - First Stage

- Limited scattering environment, thus, there are $3-5$ resolvable paths.
- $\alpha_{B,R}^{(0)} >> \alpha_{B,R}^{(k)}, \forall k = 1, \ldots, N_{B,R}$.
- The mmWave channel is sparse in the angular domain

Therefore, we can neglect the NLOS paths, and the channel coefficients are

$$\mathbf{H} = \alpha_{B,R}^{(0)} \mathbf{a}_{B,R}\left(\phi_{B,R}^{(0)}\right) \mathbf{a}_{B,R}^{H}\left(\theta_{B,R}^{(0)}\right), \tag{5}$$

and

$$\mathbf{G}_r = \alpha_{R,M}^{(0)} \mathbf{a}_{R,M}\left(\theta_{R,M}^{(0)}\right). \tag{6}$$

Thus, the composite channel

$$\begin{aligned}\mathbf{H}_{r,c} =& \alpha_{B,R}^{(0)} \mathbf{a}_{B,R}\left(\phi_{B,R}^{(0)}\right) \mathbf{a}_{B,R}^{H}\left(\theta_{B,R}^{(0)}\right) \boldsymbol{\Omega} \alpha_{R,M}^{(0)} \mathbf{a}_{R,M}\left(\theta_{R,M}^{(0)}\right) \\ =& \alpha^{(0)} \mathbf{a}_{B,R}\left(\phi_{B,R}^{(0)}\right),\end{aligned} \tag{7}$$

where $\alpha^{(0)} = \alpha_{B,R}^{(0)} \alpha_{R,M}^{(0)} \mathbf{a}_{B,R}^{H}\left(\theta_{B,R}^{(0)}\right) \boldsymbol{\Omega} \mathbf{a}_{R,M}\left(\theta_{R,M}^{(0)}\right)$ is the effective propagation path gain.

Remarks

- The composite channel $\mathbf{H}_c$ includes unknown angular directions, AoAs and AoDs.
- Similar propagation gains, delays, AoDs, and AoAs for adjacent users.

The proposed approach consists of three steps as follows:

Step 1: Estimate the AoAs at the BS via **energy detection**. AoAs can be computed by determining the non-zero elements.

$$\hat{m} = \left\{ m \middle| \frac{1}{T} \sum_{n=1}^{T} |\tilde{\mathbf{Y}}_{m,n}|^2 > \eta, m = 1, \ldots, M \right\}. \tag{11}$$

Step 2: Effective propagation path gains estimation via the Least-square (LS) approach and AoDs via **correlation-based detector**.

$$\hat{n} = \underset{n=1,2,\ldots,K}{\arg\max} \, |\langle \tilde{\mathbf{Y}}_{i,.}, \tilde{\mathbf{X}}_{n,.} \rangle|. \tag{12}$$

Then, given the indices $(\hat{m}, \hat{n})$, the optimal $\tilde{\mathbf{H}}_{c,i,j}$ using LS can be computed as

$$\hat{\tilde{\mathbf{H}}}_{c,i,j} = \left(\tilde{\mathbf{X}}_{n,.} \tilde{\mathbf{X}}_{n,.}^H \right)^{-1} \tilde{\mathbf{X}}_{n,.} \tilde{\mathbf{Y}}_{m,.}^H, \forall (i,j) \in (\hat{m}, \hat{n}). \tag{13}$$

Step 3: The effective path gains are implicitly function of the RIS-based AoAs and AoDs, the RIS-UTs AoAs can be computed.

The Proposed Approach - Second Stage

- In the first stage, we collect partial CSI collected from ζK UTs.
- In the second stage, we present a DL-based approach to recover the entire CSI through a deep CNNs.
- The composite channel matrix can be seen as a image.
- We use the pre-trained *Caffe* model.

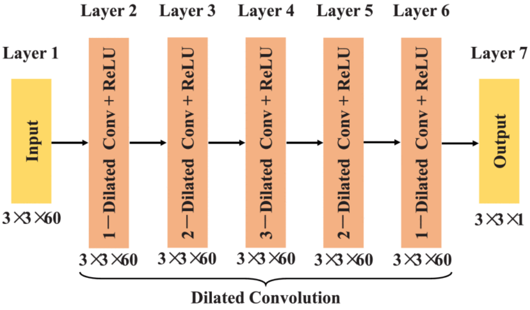

Figure: Stage Two: the proposed STS-CNN model

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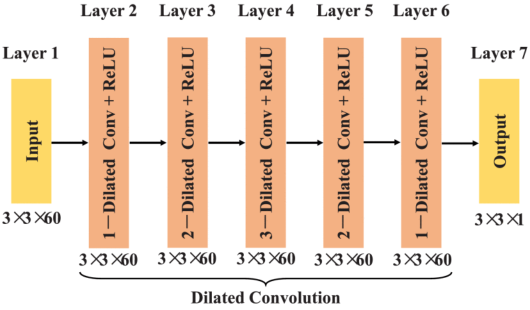


Figure: Stage Two: the proposed STS-CNN model

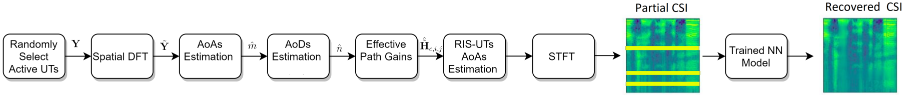


Figure: The two-stage proposed approach diagram.

Numerical Results

The simulation setup parameters are summarized in Table 2

Table: Simulation Parameters

Parameter	Value
Channel Type	Saleh-Valenzuel
Carrier Frequency	26 GHz
Number Of Main Paths	1
Number Of SubPaths Per Main Path	8
Number Of Antennas at BS	M
Number Of Antennas at RIS	N
Number Of UTs	K
Element spacing	$\frac{\lambda}{2}$
Active UTs ratio	ζ
Learning Rate	$\kappa = 0.01$
Stride size	S

Numerical Results

- Proposed approach outperforms the On-Off conventional scheme by 10 dB.
- The NMSE decreases as SNR value increase.
- Intensity increases with SNR.

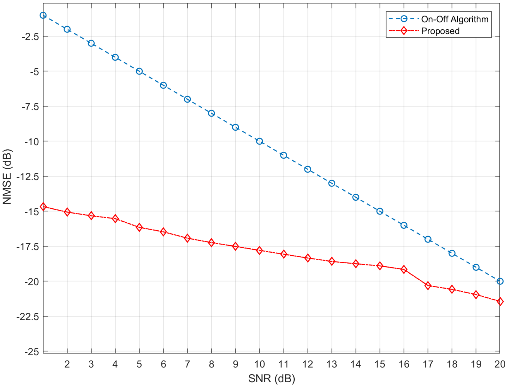


Figure: The NMSE vs SNR with $\zeta = 0.2$ and $\frac{d}{\lambda} = 0.1$.

Numerical Results

- The proposed approach depends on the elements' spacing. .
- The spatial correlation between channel coefficients depends on spacing.
- For uniform distribution, closed-form Bessel function solution given by $\rho(d) = J_o\left(\frac{2\pi d}{\lambda}\right)$.

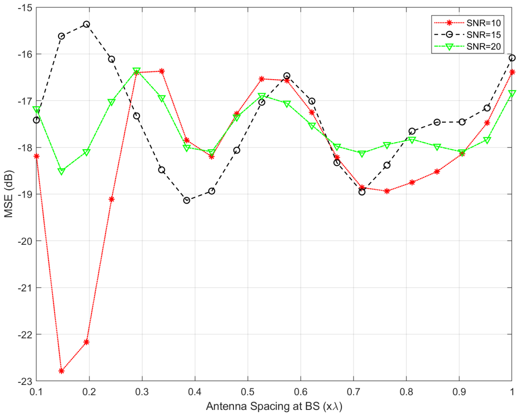


Figure: The effect of Antenna spacing at the BS on the NMSE performance of the proposed approach.

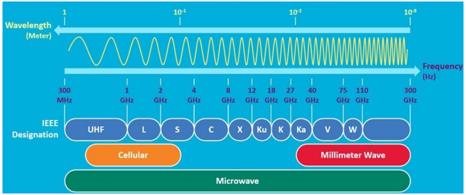
Summary of the 2^{rd} Work

- We have presented a channel estimation approach for RIS-assisted mmWave MIMO system.
- The proposed approach computes channel parameters, i.e., AoAs, AoDs, and the effective channel gains, for a certain ratio of UTs.
- The second stage we utilize the STS-CNN network to reconstruct the missing

Outline

Introduction

- FCC and NTIA notices underutilized spectrum.
- The concept of spectrum sharing gained a lot of interest.
- Both radar and communication systems occupy the the same frequency resources.
- Due to the existence, radar and communication systems will cause interference to each another.
  1. radar receiver are sensitive.
  2. saturate communication users
- To achieve harmonious coexistence.



Related Works

Previous works on radar and communication coexistence include:

- MIMO via Matrix completion (MIMO-MC).
- Interference Alignment (IA).
- Design BS TX covariance.
- MIMO radar and MIMO communication system.

Motivation for the 3^{rd} Work

- The use of radar has been widened to civilian applications, e.g., cruise control and traffic control.
- On parallel, the quest for ever-increasing rates in wireless communication pushed to operating frequency assigned to radar. mmWave Communication provides high bandwidth.
- Reconfigurable Intelligent surface (RIS) adds a new DoF. The RIS passive beamforming in interference mitigation.
- No previous work use the RIS to mitigate the mutual interference in the RCC systems.

Contributions

- We propose a new framework that enables the spectrum sharing between a MIMO radar and a communication system.
- Improve the performance of the Multi-User (MU)-MIMO RCC.
- We exploit the passive beamforming gain of the RIS.
- We formulate an optimization problem.

System Model

- A RIS-assisted multiple-input-multiple-output (MIMO) radar and communication coexisting (RCC).
- The BS is equipped with M antenna elements, RIS has N reflecting elements.
- The radar system is equipped with L_t and L_r, $L_t = L_r = L_R$.
- Multiple single-antenna UTs.

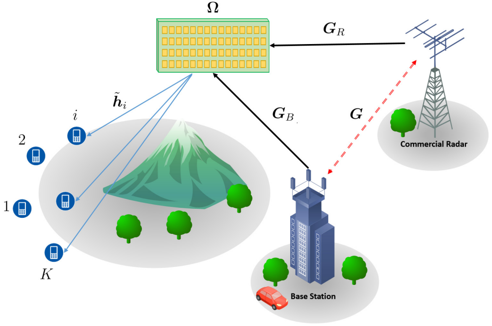


Figure: RIS-assisted MIMO RCC system

System Model

- $\mathbf{\Omega} = diag(\Omega_1, \Omega_2, \ldots, \Omega_N)$. where reflection coefficient $\Omega_i = A_i e^{j\omega_i}$.
- $\mathcal{W} = \{0, \Delta\omega, \cdots, (L_\omega - 1)\Delta\omega\}$, where $L_\omega = 2^{l_b}$ represents phase shifts quantization levels, and l_b represents the number of bits to represent the phase shift, and then $\Delta\omega = \frac{2\pi}{L_\omega}$.

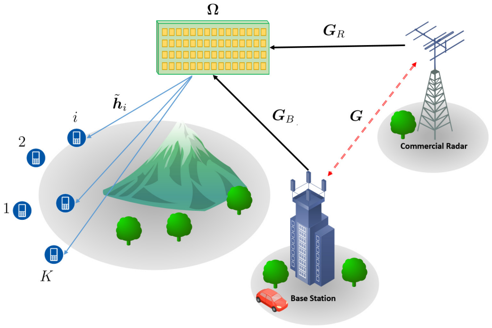


Figure: RIS-assisted MIMO RCC system

System Model

- *Channels between RIS-ComUTs:*

$$\mathbf{H}_t = \left[\tilde{\boldsymbol{h}}_1, \tilde{\boldsymbol{h}}_2, \cdots, \tilde{\boldsymbol{h}}_K\right]^T \in \mathcal{C}^{K\times N}.$$

- *Cascaded Channel between BS and i^{th} ComUT:*

$$\boldsymbol{h}_i = \tilde{\boldsymbol{h}}_i \boldsymbol{\Omega} \boldsymbol{G}_B \in \mathcal{C}^{1\times M}.$$

- *Cascaded Channel between RadTx and i^{th} ComUT:*

$$\tilde{\boldsymbol{f}}_i = \tilde{\boldsymbol{h}}_i \boldsymbol{\Omega} \boldsymbol{G}_R \in \mathcal{C}^{1\times L_R}.$$

- The interfering channel between the BS and Radar $\mathbf{G} = [\mathbf{g}_1, \mathbf{g}_2, \ldots, \mathbf{g}_M] \in \mathcal{C}^{M\times L_R}$.

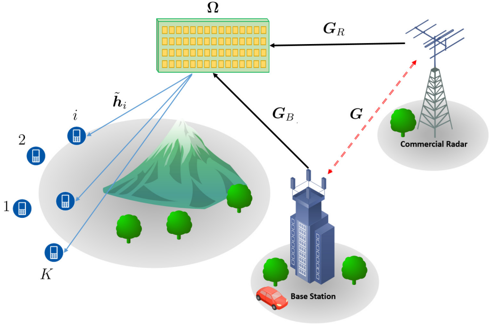


Figure: RIS-assisted MIMO RCC system

System Model

- At time l, the received signal at the i^{th} UE

$$y_i^c[l] = \mathbf{h}_i^H \sum_{k=1}^{K} \mathbf{w}_k s_k[l] + \sqrt{P_R}\mathbf{f}_i^H \mathbf{s}_l + n_i[l]. \quad (14)$$

- The received signal at the radar

$$\mathbf{y}_l^R = \alpha\sqrt{P_R}\mathbf{a}_R\mathbf{a}_T^T(\theta)s_l + \left(\boldsymbol{G}_B\boldsymbol{\Omega}\boldsymbol{G}_R^T + \mathbf{G}^T\right)\sum_{k=1}^{K}\mathbf{w}_k d_k[l] + \mathbf{n}_l, \quad (15)$$

where:

- Radar waveform $\frac{1}{L}\sum_{l=1}^{L}\mathbf{s}_l\mathbf{s}_l^H = \mathbf{I}$.
- $\mathbf{w}_k$ Precoding vectors.
- $\mathbf{a}_R$ and $\mathbf{a}_T$ the array responses.
- P_R Radar transmitted power.
- α Pathloss.

System Model

Without loss of generality, in this paper, we rely on the following assumptions:

1. The communication system is the only source for the interference in the radar system.
2. The channel state information is assumed to be known at the BS.
3. The duration for the communication system symbol is the same as the duration of the sub-pulse of the radar system.
4. The channels are assumed to be statistically independent, and the radar signals are statistically independent of the communication signals.

Problem Formulation

- The normalized achievable sum-rate for the UEs of the communication system

$$R = \sum_{i=1}^{K} \log_2(1+\rho_i), \tag{16}$$

where ρ_i represents the received (SINR) of the i^{th} UE

$$\rho_i = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum_{k=1,k\neq i}^{K} |\mathbf{h}_i^H \mathbf{w}_k|^2 + P_R \|\mathbf{f}_i\|^2 + \sigma_c^2}$$

Our Goal

Maximize the sum-rate for a RIS-assisted RCC system by jointly design the active and passive beamforming

Desing Criteria

- Maintaining the interfering power from the communication system within a certain threshold $\hat{p}_0$.
- Maintaining the transmit power within the budget for both the radar transmitter and the BS.

Problem Formulation

- The normalized achievable sum-rate for the UEs of the communication system

$$R = \sum_{i=1}^{K} \log_2(1+\rho_i), \tag{17}$$

where ρ_i represents the received (SINR) of the i^{th} UE

$$\rho_i = \frac{|\mathbf{h}_i^H \mathbf{w}_i|^2}{\sum\limits_{k=1,k\neq i}^{K} |\mathbf{h}_i^H \mathbf{w}_k|^2 + P_R \|\mathbf{f}_i\|^2 + \sigma_c^2}$$

$$(\mathrm{P1}): \max_{\{\mathbf{w}_k\},\boldsymbol{\Omega}} \sum_{i=1}^{K} \log_2(1+\rho_i) \tag{18}$$

$$s.t. P_{int} \leq \hat{p}_0, \tag{19}$$

$$\omega_n \in \mathcal{W}, \forall n \in \mathcal{N}, \tag{20}$$

$$||\mathbf{w}_k||^2 = 1, \tag{21}$$

$$p_k^c \leq \frac{P_C}{K}, \forall k. \tag{22}$$

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The Proposed Approach

- The optimization problem (P1) is a non-convex and requires a joint optimization over two variables $(\mathbf{\Omega}, \mathbf{w}_i)$.
- The successive convex approximation (SCA) method, and the Cross-Entropy (CE) algorithm.
- ω_i belongs to the discrete phase shifts set $\mathcal{W} = \{0, \frac{2\pi}{2^l}, \cdots, \frac{2\pi}{2^l}\left(2^l - 1\right)\}$.
- *Exhaustive Search (ES)*. The searching set N^{2^l}.
- Reduce the time complexity using *Local Search (LS)*.

The Proposed Approach

The LS approach:

1. Define the feasible solution set of the phase shift of each RIS elements based on the quantization level l_b, i.e., the discrete phase-shifts set $\mathcal{W}$.
2. The algorithm runs for N iterations, and the phase shifts are optimized sequentially one-by-one.
3. For the i^{th} element, the phase shifts for $(i+1)^{th}$ to N^{th} elements are fixed.
4. The phase shift for i^{th} element has L_w possibilities, and then we construct the corresponding phase shift matrices.
5. Compute the achievable sum-rate for each and every possible phase shift matrix. Let $\mathcal{R}^{(i)} = \left\{R_1^{(i)}, R_2^{(i),} \cdots, R_{L_w}^{(i)}\right\}$. The optimal phase shifts for the i^{th} element is denoted by ω_i^{j*}, where $j* = \max_j \mathcal{R}^{(i)}$.
6. The precoding matrix can be obtained as $\mathbf{W}^j = \frac{1}{\beta}(\kappa_j^* \kappa_j)^{-1}\kappa_j^*$, where $\kappa_j = \left(\mathbf{H}\boldsymbol{\Omega}^j \mathbf{G}_B\right)$ and $\beta = |(\kappa_j^* \kappa_j)^{-1}\kappa_j^*|$.

Numerical Results

In this section, we present numerical results to validate the effectiveness of the proposed MIMO Radar and MU-MIMO communication coexistence spectrum sharing system assisted by a RIS via Monte Carlo simulations.

Table: Simulation Parameters

Symbol	Value	Explanation
N	$N = N_h \times N_v$	The number of RIS elements
M	8	The number of the BS elements
K	8	The number of ComUTs
L_t	8	The number of radar transmitting antennas
L_r	8	The number of radar receiving antennas
I	1,2,3,4,5	The number of quantization bits
σ_C^2	0dBm	Average noise power to the BS.
σ_R^2	0dBm	Average noise power to the radar transmitter.

Numerical Results

- The effect of the RIS size on the normalized sum-rate performance R.
- The sum-rate increases monotonically as the RIS with more elements due to a higher beamforming gain.
- Improving the interference mitigation capability.
- The quantization level of the RIS phase shifts affects the performance.
- At least 3 bits.

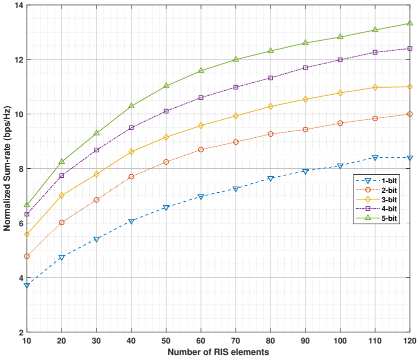


Figure: The achievable sum-rate R vs the number of RIS elements N.

Numerical Results

- Comparison of the achievable sum-rate performance vs. the interference power bounds, i.e., $\hat{p}_0$.
- the performance sum-rate is monotonically increased with the growing interference power from the BS to the radar system.
- Trade-off between the performance of communication and the radar. .

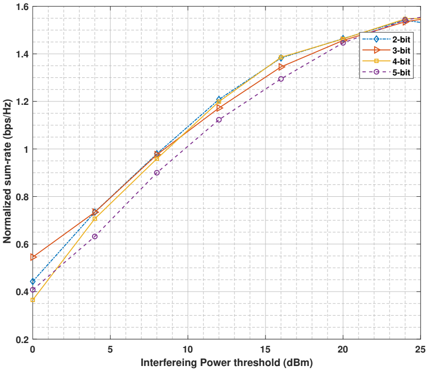


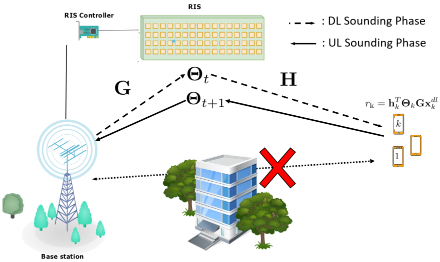
Figure: The achievable sum-rate R vs the radar interfering power threshold.

Summary of the 3rd Work

- A new approach to improve the performance of the MU-MIMO radar and communication coexistence system.
- The sum-rate maximization problem for the communication system UEs.
- Local search algorithm since we adopted a practical scenario of the RIS deployment.

Outline

Channel Estimation For RIS-Assisted MIMO Systems with Hardening Effects



	τ_1	τ_2
k^{th} UT	Receive: $r_k = \mathbf{h}_k^T \boldsymbol{\Theta}_k \mathbf{G} \mathbf{x}_k^{dl} + \mathbf{n}_k^{dl}$	Transmit: r_k^*
The BS	Transmit Orthogonal Pilots: $\mathbf{X}\mathbf{X}^{\mathrm{H}} = \mathbf{I}$	Receive: $\mathbf{G}^T \boldsymbol{\Theta}_t \mathbf{H}\mathbf{H}^H \boldsymbol{\Theta}_{t+1} \mathbf{G}^* \mathbf{X} + \hat{\mathbf{N}}_{t'}$
RIS Configuration	$\boldsymbol{\Theta}_t$	$\boldsymbol{\Theta}_{t+1}$

Figure: System Model for RIS-Assisted MU-MIMO Communication System.

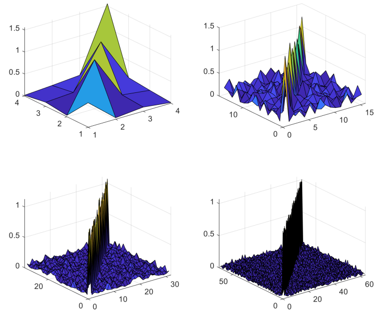


Figure: The magnitudes of $\mathbf{H}^H\mathbf{H}$ for different RIS elements, namely, $N = 4$, $N = 16$, $N = 32$, and $N = 64$.

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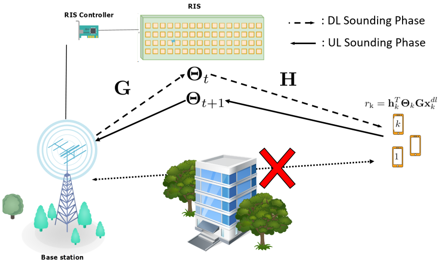
Channel Estimation For RIS-Assisted MIMO Systems with Hardening Effects



	τ_1	τ_2
k^{th} UT	Receive: $r_k = \mathbf{h}_k^T \mathbf{\Theta}_k \mathbf{G} \mathbf{x}_k^{dl} + \mathbf{n}_k^{dl}$	Transmit: r_k^*
The BS	Transmit Orthogonal Pilots: $\mathbf{X}\mathbf{X}^{\mathrm{H}} = \mathbf{I}$	Receive: $\mathbf{G}^{\mathrm{T}} \mathbf{\Theta}_t \mathbf{H} \mathbf{H}^H \mathbf{\Theta}_{t+1} \mathbf{G}^* \mathbf{X} + \hat{\mathbf{N}}_{t'}$
RIS Configuration	$\mathbf{\Theta}_t$	$\mathbf{\Theta}_{t+1}$

Figure: System Model for RIS-Assisted MU-MIMO Communication System.

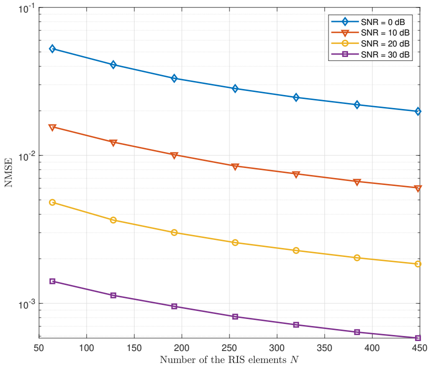


Figure: The NMSE of F vs. number of RIS elements for different SNR values when $M = 32$.

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Outline

Advantages and Limitations of OWC Systems

Advantages

- High data rates
- License-free operation
- Low latency
- Immunity to electromagnetic interference
- High security

Limitations

- Limited range
- Susceptibility to weather conditions
- Alignment requirements
- Sensitivity to obstacles
- Relatively high installation and maintenance costs

Benefits of RIS in OWC Systems

IM/DD OWC Systems

- Enhancing link quality
  - Optimally placing the IRS improves received signal through constructive interference.
  - Compensates for path loss, enhances signal-to-noise ratio (SNR), and improves system performance.
- Coverage extension
  - IRS creates multiple reflection paths, reaching obstructed areas and improving connectivity.
  - Enables coverage of blind spots and enhances system performance in non-line-of-sight (NLOS) conditions.
- Interference mitigation
  - IRS selectively reflects desired signal while attenuating or redirecting interfering signals.
  - Improves signal quality and reduces impact of external interference sources.

Coherent OWC Systems

- Channel equalization
  - IRS compensates for channel impairments (e.g., dispersion, fading, distortion).
  - Intelligently manipulated reflected signals counteract channel effects and improve system performance.
- Beamforming and steering
  - IRS assists in beamforming and beam steering techniques.
  - Adapting reflection phases and angles maximizes received signal power and minimizes interference.
- Increased link budget
  - IRS enhances overall link budget by providing additional power gain.
  - Reflected signals amplify received signal power, extending communication range.

In an IRS-assisted optical wireless communication (OWC) system, the channel gain between the LS and the PD is denoted as h and can be expressed as:

$$h = h_p h_{\text{irs}} h_a, \tag{23}$$

Here, h_a represents the random atmospheric turbulence component, $h_p = 10^{-\frac{\kappa}{10}(d_i+d_r)}$ is the atmospheric loss dependent on the attenuation factor κ, and h_{irs} represents the geometric loss due to the IRS.

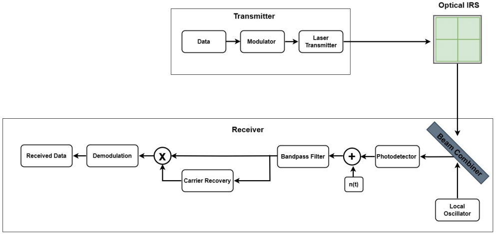

Figure: System model for IRS-assisted Coherent OWC system.

In an IRS-assisted optical wireless communication (OWC) system, the channel gain between the LS and the PD is denoted as h and can be expressed as:

$$h = h_p h_{\text{irs}} h_a, \tag{24}$$

Here, h_a represents the random atmospheric turbulence component, $h_p = 10^{-\frac{\kappa}{10}(d_i + d_r)}$ is the atmospheric loss dependent on the attenuation factor κ, and h_{irs} represents the geometric loss due to the IRS.

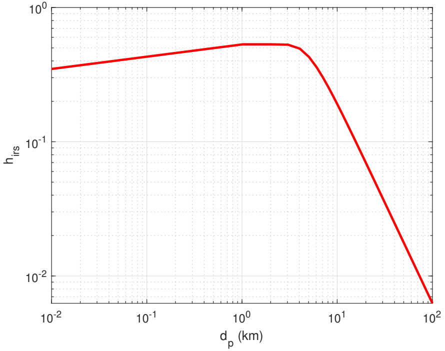

Figure: GML for IRS-based FSO channel between LS and PD versus dp

Conclusions

- We proposed two channel estimation approaches for RIS-aided MIMO communication systems.
  1. In the first scheme, we exploit the semi-definite positiveness of the matrices to estimate the propagation channels.
  2. In the second scheme, we exploit the correlation between the channels for adjacent users to reduce the training overhead.
- We proposed a framework to mitigate the mutual interference in RCC systems by exploiting the passive beamforming of the RIS.
- We will exploit the large number of the RIS elements and the channel hardening phenomenon to improve the CE accuracy in the RIS-assisted MU-MIMO system.

Publications

- **E. Shtaiwi**, H. Zhang, S. Vishwanath, M. Youssef, A. Abdelhadi and Z. Han, "Channel Estimation Approach for RIS Assisted MIMO Systems," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 2, pp. 452-465, June 2021.
- **E. Shtaiwi**, H. Zhang, A. Abdelhadi, A. Lee Swindlehurst, Z. Han, and H. Poor, "Sum-rate Maximization for RIS-assisted Integrated Sensing and Communication Systems with Manifold Optimization", *IEEE Transactions on Communications*.
- **E. Shtaiwi**, A. Hussein, A. Khawar, A. Alkhateeb, A. Abdelhadi and Z. Han, "Implementation of Real-Time Adversarial Attacks on DNN-based Modulation Classifier," *International Conference on Computing, Networking and Communications 2023* (To be published).
- **E. Shtaiwi**, A. E. Ouadrhiri, M. Moradikia, S. Sultana, A. Abdelhadi and Z. Han, "Mixture GAN For Modulation Classification Resiliency Against Adversarial Attacks," *IEEE Global Communications Conference (GLOBECOM)*, Rio de Janeiro, Brazil, Dec. 2022.
- **E. Shtaiwi**, H. Zhang, A. Abdelhadi and Z. Han, "Sum-rate Maximization for RIS-assisted Radar and Communication Coexistence System," *IEEE Global Communications Conference (GLOBECOM)*, Madrid, Spain, Dec. 2021.
- **E. Shtaiwi**, H. Zhang, A. Abdelhadi and Z. Han, "RIS-Assisted mmWave Channel Estimation Using Convolutional Neural Networks," *IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, Nanjing, China, Mar. 2021.

Thank You!

Questions?