Spatial Equalization Before Reception: Reconfigurable Intelligent Surfaces for Multi-path Mitigation

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- Problem Formulation
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- Simulation Results
- Conclusion

Introduction

Moving Towards 6G: Ubiquitous Intelligent Network

Higher data rates

Lower power consumption

Larger Coverage

Smarter devices

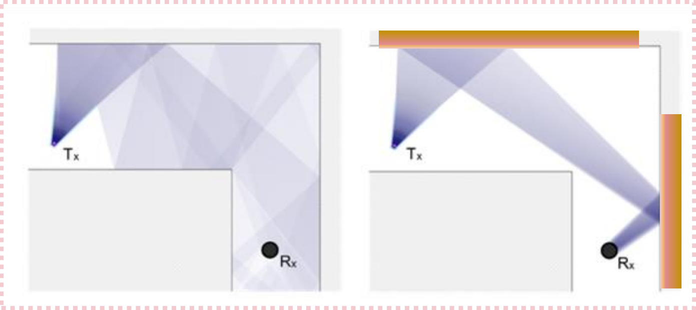
Introduction

Challenges on Existing Technologies

- Existing methods (relays and MIMO systems) cannot provide high quality-of-service (QoS) in presence of harsh propagation environment
- Uncontrollable interactions of transmitted signals with surrounding objects

Solution: Reconfigurable Intelligent Surface (RIS)

- Consist of meta-material inlaid with multiple sub-wavelength scatters
- Cost efficient in manufacture and deployment
- Control and customize favorable radio environments by adjusting its phase shifts



Introduction

Literature Review

- Applications of RIS for beamforming
  - Maximize the data rate by adjusting the phase shifts of the RIS [1]
  - Jointly consider power allocation and phase shift design [2]

RIS as Spatial Equalizer

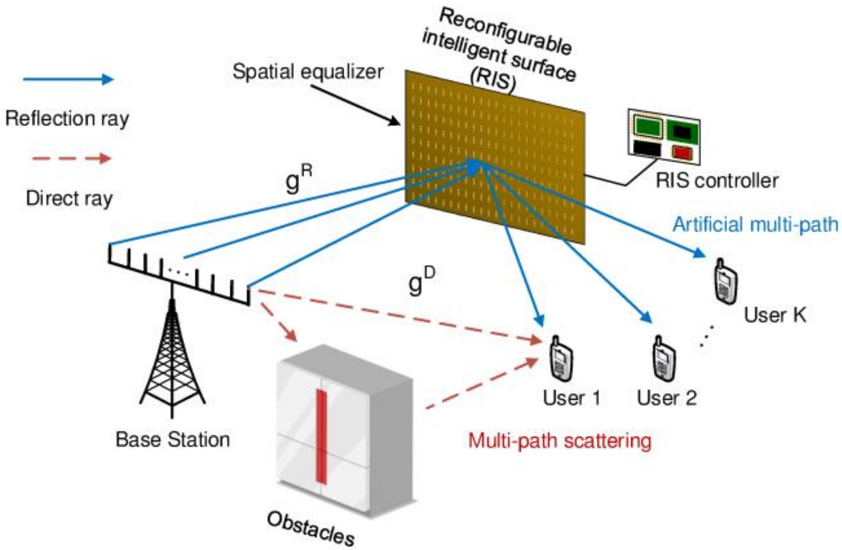
- The phase shift makes the RIS potential to serve as a spatial equalizer
- Different from traditional communication systems, where equalization is done at receivers, the RIS can achieve equalization in the transmission process
- Basic idea:
  - Some controllable paths are introduced against the multi-path fading

[1] X. Yu, D. Xu, and R. Schober, "Miso wireless communication systems via intelligent reflecting surfaces," in Proc. IEEE/CIC ICCC, Changchun, China, Aug. 2019.
[2] Y. Gao, C. Yong, Z. Xiong, D. Niyato, Y. Xiao, and J. Zhao, "Reconfigurable intelligent surface for miso systems with proportional rate constraints," in Proc. IEEE ICC, Dublin, Ireland, Jun. 2020

System Model

Scenario Description:

- Multi-user MISO Communications
- Downlink scenario
- An RIS is deployed as spatial equalizer
- *N* RIS elements
- *K* users
- Within considered period, the phase shift for each element is fixed



Reflection Model:

- Reflection factor for element *n*

$$\Gamma_n = \Gamma e^{-j\theta_n}$$

Reflection amplitude Phase shift

System Model

Channel Model:

- **Direct Channel**
  - Channel impulse response of the direct link to user *k*

$$g_k^D(t) = \underbrace{(\beta_k^D)}_{\text{Path loss}}{}^{1/2}\underbrace{h_k^D(t)}_{\text{Fast fading caused by multi-path effect}},$$

- **Reflection Channel**
  - Channel impulse response of the reflection link through RIS element *n* to user *k*

$$g_{n,k}^D(t) = \underbrace{(\beta_{n,k}^R)}_{\text{Path loss}}{}^{1/2}\Gamma_n \underbrace{h_{n,k}^R(t)}_{\text{Fast fading}}$$

- **Received Signals**

$$y_k(t) = \left(g_k^D(t) + \sum_{n\in\mathcal{N}} g_{n,k}^D(t)\right) \underbrace{*}_{\text{Convolution operator}} \underbrace{s_k(t)}_{\text{One-bit signals}}$$

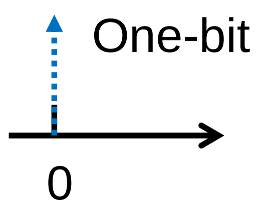
Problem Formulation

Inter-symbol Interference (ISI)

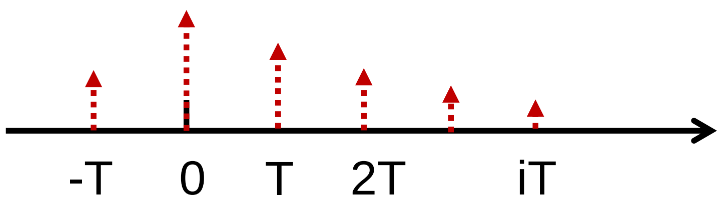
- ISI occurs when a pulse spreads out that it interferes with adjacent at the sample instant
- Assuming that the received signals achieve the maximum at time t = 0, the ISI can be expressed as

$$I_k = \sum_{i=-\infty, i\neq 0}^{\infty} y_k(t - iT)|_{t=0}$$

Transmitted



Received



Problem Formulation

Objective

- Reduce the energy of remaining ISI after equalization
- In consideration of the fairness, we will minimize the maximum power of ISI among these users by adjusting phase shifts at the RIS

Problem Statement

$$(P1): \quad \min_{\{\theta_n\},\eta} \quad \eta, \tag{4a}$$

$$s.t. \quad I_k I_k^* \leq \eta, \forall k \in \mathcal{K}, \tag{4b}$$

$$\eta \geq 0, \tag{4c}$$

Maximum power of ISI among these users

Algorithm Design

Fourier Transformation:

- The ISI is hard to tackle from the time domain: frequency domain
- Fourier Transformation:

$$Y_k(\omega) = \int_{-\infty}^{\infty} y_k(t) e^{-j\omega} dt.$$

- The ISI in the frequency domain

$$Y_k(0) = \int_{-\infty}^{\infty} y_k(t) dt \approx (y_k(0) + I_k)T.$$

$$Y_k(\omega) = \left(H_k^D(\omega) + \sum_{n \in \mathcal{N}} H_{n,k}^R(\omega) \right) S_k(\omega).$$

Will not be influenced by the phase shifts

Phase shifts are included

Algorithm Design

Phase Shift Optimization Algorithm

- Given $y_k(0)$, the optimization problem can be solved by the Lagrange-dual technique
- The Lagrangian can be written as

Lagrangian multiplier

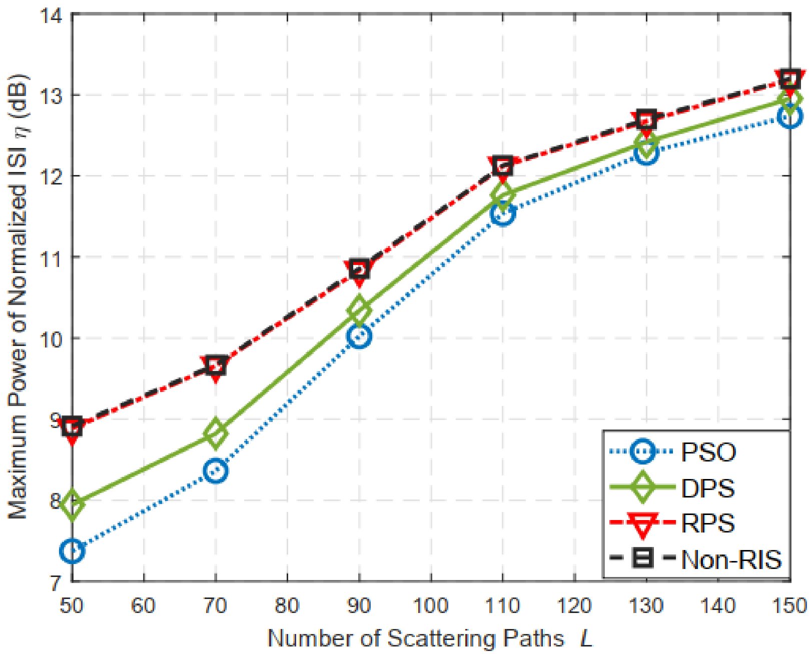
$$L(\theta_n, \eta, \mu_k) = \eta + \sum_{k \in \mathcal{K}} \mu_k \left(\left| \frac{Y_k(0)}{T} - y_k(0) \right|^2 - \eta \right)$$

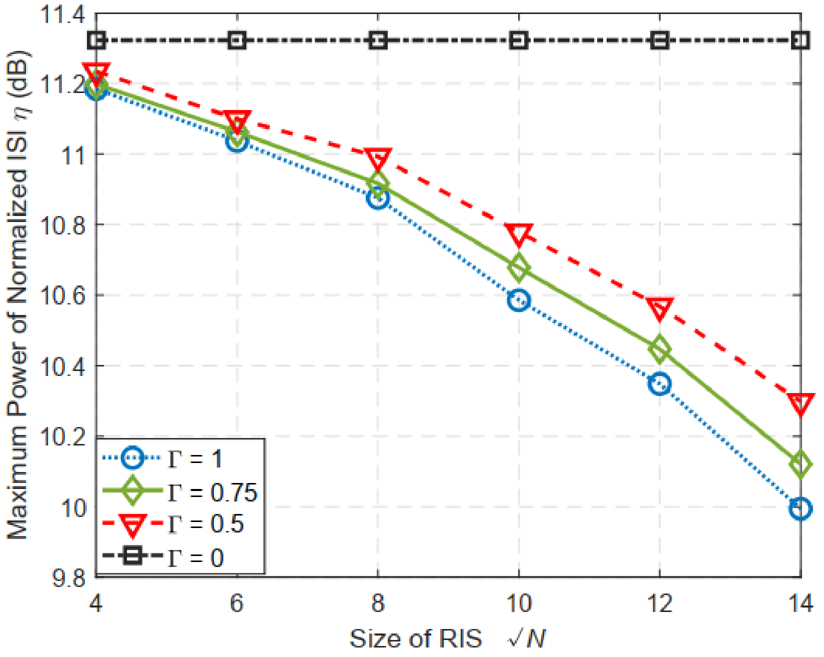
- The problem can be written by

$$\max_{\mu_k \geq 0} \min_{\theta_n, \eta} L(\theta_n, \eta, \mu_k).$$

- **Primal Problem**: fix the dual variable, optimize the phase shifts and minimum ISI energy using gradient descent method
- **Dual Problem**: Update dual variable using the gradient descent method

Simulation Results





- Proposed PSO algorithm can outperform other benchmark algorithms
- Even with 2-bit quantification at the RIS, we can reduce 1 dB compared to that without the RIS filter
- ISI decreases with a larger size of the RIS

Conclusion

- We have proposed the introduction of controllable paths artificially to mitigate multi-path fading through the RIS
- To eliminate ISI for multiple users, we have formulated a phase shift optimization problem and proposed an iterative algorithm to solve it
- From simulation analysis, we can have the following remarks:
  - The proposed RIS-based spatial filter can effectively reduce the ISI even with 2-bit quantification
  - The ISI will be further reduced with a larger RIS

Thank you!