Capacity Enhancement for Irregular Reconfigurable Intelligent Surface-Aided Wireless Communications


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Reconfigurable intelligent surface (RIS)

- A two-dimensional electromagnetic metasurface
- Control the propagation of electromagnetic waves
- Manipulate the wireless environment to improve the quality of the signal

Traditional wireless communications: Heavily rely on the environment

RIS-aided wireless communications: Intelligently control the environment

Background

- RIS-aided wireless communications
  - Overcome the **blockage**
  - Enhance the **signal quality**
  - Save the **power consumption**

Background

- **Beamforming design**
  - Base station (BS) + RIS + user ends (UE)
  - Line-of-sight path (BS-UE) + reflection path (BS-RIS-UE)
  - Precoding (BS) + reflection coefficients (RIS)

- **Optimization objective**
  - Sum-rate
  - Energy efficiency
  - Transmit power

Challenge

- Prior works have only considered the regular RIS structure
- **Regular RIS**: High capacity requires a large number of RIS elements
- Unbearable system complexity and signal processing overhead

How to improve the **capacity** with a **limited** number of RIS elements?

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Capacity Enhancement by Irregular RIS

**Challenge**
- Regular array: Elements are regularly arranged with constant interelement spacing
- High capacity requires a large number of RIS elements

**Proposal**
- Irregular array: Elements are irregularly arranged on an enlarged surface
- Additional degrees of freedom and spatial diversity for more capacity

More space leads to more system capacity
System Model

- Irregular RIS-aided communications
  - $K$ single-antenna users, BS with $M$ antennas
  - Irregular RIS comprising $N$ elements distributed over $N_s$ grid points

$$y = \left( H_r^H Z \Theta G + H_d^H \right) x + n,$$
$$x = \sum_{k=1}^{K} w_k s_k$$

RIS topology

$$Z = \text{diag}(z), \quad z = [z_1, z_2, \cdots, z_{N_s}]^T, \quad z_i \in \{1, 0\}$$

$$\Theta = \text{diag}([\beta_1 e^{i\theta_1}, \beta_2 e^{i\theta_2}, \cdots, \beta_{N_s} e^{i\theta_{N_s}}]), \quad \beta_n = 1, \quad \theta_n \in F = \{0, \pi\}$$

- The signal-to-interference-plus-noise ratio (SINR) of user $k$

$$\gamma_k = \frac{\left| \left( H_r^H Z \Theta G + H_d^H \right) w_k \right|^2}{\sum_{i \neq k} \left| \left( H_r^H Z \Theta G + H_d^H \right) w_i \right|^2 + \sigma^2}$$
System Model

- **Channel model**

\[ y = \left( H_r^H Z \Theta G + H_d^H \right) x + n, \quad H_d^H = \left[ h_{d,1}, h_{d,2}, \cdots, h_{d,K} \right]^H \in \mathbb{C}^{K \times M}, \quad H_r^H = \left[ h_{r,1}, h_{r,2}, \cdots, h_{r,K} \right]^H \in \mathbb{C}^{K \times N}, \]

- **The small-scale fading:** uncorrelated Rayleigh fading channel model
- **The large-scale fading:** distance-dependent path loss
- **Path loss: BS-RIS-UE channel**

\[ f_r(d_{BR}, d_{RU}) = C_r d_{BR}^{-\alpha_{BR}} d_{RU}^{-\alpha_{RU}}, \]

**Distance**  **Channel fading**

- **Path loss: BS-UE channel**

\[ f_d(d_{BU}) = C_d d_{BU}^{-\alpha_{BU}}, \]

**Path loss exponent**

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Problem Formulation

- **Weighted sum-rate (WSR) maximization**
  - **Joint optimization**: RIS topology and beamforming design
  - The topology design lacks methodological guidance

\[
\begin{align*}
\mathcal{P}_1: \max_{\mathbf{z}, \mathbf{w}, \mathbf{\Theta}} & \quad R = \sum_{k=1}^{K} \omega_k \log_2 (1 + \gamma_k) \\
\text{s.t.} & \quad C_1: \sum_{k=1}^{K} \| \mathbf{w}_k \|_2^2 \leq P_T, \\
& \quad C_2: \theta_n \in \mathcal{F}, \forall n = 1, 2, \cdots, N_s, \\
& \quad C_3: z_i(z_i - 1) = 0, \forall i = 1, 2, \cdots, N_s, \\
& \quad C_4: \mathbf{1}^T \mathbf{z} = N.
\end{align*}
\]

- Transmit power constraint
- Discrete phase shifts constraint
- Non-convex: hard to solve
- Sparsity constraints
**Problem Formulation**

- **Solution**
  - **Decouple** the RIS topology design and the beamforming optimization
  - For a given topology: Convert the original problem to $P_2$
  - Let $Z_0 = I_N$: Equivalent to regular RIS-aided wireless communications

$P_2 : \max_{W, \Theta} \quad R = \sum_{k=1}^{K} \omega_k \log_2 (1 + \gamma_k)

\text{s.t.} \quad C_1 : \sum_{k=1}^{K} \|w_k\|^2 \leq P_T,

C_2 : \theta_n \in \mathcal{F}, \forall n = 1, 2, \ldots, N_S,

C_3 : Z = Z_0.$

The SINR of user $k$

$$\gamma_k = \frac{\left| h_{r,k}^H Z \Theta G + h_{d,k}^H \right|^2 w_k^2 \left( h_{r,k}^H Z \Theta G + h_{d,k}^H \right)^H w_k}{\sum_{i \neq k} \left| h_{r,k}^H Z \Theta G + h_{d,k}^H \right|^2 w_i^2 + \sigma^2}$$

**Given RIS topology**

**Reflection coefficients (RIS)**

**Precoding (BS)**
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Joint Optimization Framework

- **Overview**
  - **Alternating optimization**: Decouple the decision variables in $P_1$
  - **RIS topology**: Tabu search (TS) method
  - **Beamforming**: Neighbor extraction-based cross-entropy (NCE) method
  - **General solution** to the classical sum-rate optimization problem
Joint Optimization Framework: RIS Topology

- **TS-based sparse deployment of RIS**
  - **Input:** Tabu list, storage size, neighbor distance, neighborhood size, iterations
  - **Output:** Optimal RIS topology $Z$
  - Generate alternative neighbors
  - Select the candidate with the maximum WSR in each iteration

Joint Optimization Framework: Beamforming Scheme

- **NCE-based beamforming optimization**
  - **Input:** RIS topology, iterations, number of candidates/elites, quantized phase shifts set
  - **Output:** Phase shifts matrix $\Theta$, precoding matrix $W$
  - **Generate candidates** based on the probability distribution function
    \[
    \Xi(\Theta; P^{(i)}) = \prod_{n=1}^{N} \left( \prod_{k=1}^{2^b} (P_{n,k}^{(i)})^\delta(\theta_n - F(k)) \right)
    \]
  - **Neighbor extraction:** Change each effective element of the current optimal $\Theta$ in each iteration
  - **Weighted probability transfer criterion**
    \[
    P^{(i+1)} = \arg\max_{P^{(i)}} \frac{1}{C_{\text{elite}}} \sum_{c=1}^{C_{\text{elite}}} \eta_c \ln \Xi(\Theta^{(c)}, P^{(i)}), \quad \eta_c = \frac{R(\Theta^{(c)}) C_{\text{elite}}}{\sum_{c=1}^{C_{\text{elite}}} R(\Theta^{(c)})}
    \]

- **BS: Zero forcing precoding**
  \[
  W = H_{\text{eq}}^H (H_{\text{eq}} H_{\text{eq}}^H)^{-1} P_B^{\frac{1}{2}}
  \]

Simulations

- WSR versus the transmit power
  - Antennas of BS: $M=4$, users: $K=4$
  - RIS elements: $N=32$, grid points: $N_s=64$

The irregular RIS outperforms the regular RIS
Simulations

- WSR versus the size of the irregular RIS
  - Antennas of BS: $M=4$, users: $K=4$
  - RIS elements: $N=32$

The sparse ratio of RIS: tradeoff between the cost and the performance
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Summary

● Challenge
  - **Regular RIS**: High capacity requires a large number of RIS elements
  - **Unbearable** system complexity and signal processing overhead

● Solution
  - **Irregular RIS**: Additional degrees of freedom in space for more capacity
  - Propose a joint optimization framework

● Conclusion
  - The proposed irregular RIS can significantly **improve the system capacity** compared to the traditional regular RIS

● Further works
  - The influence of mutual coupling effect at the RIS
  - Channel estimation for irregular RIS-aided communications
References


References


Thank you

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