Active RISs: Signal Modeling, Asymptotic Analysis, and Beamforming Design

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Outline

- Basics of RIS
- Existing passive RIS
- Proposed active RIS
- Conclusions
What is Reconfigurable Intelligent Surface (RIS)?

- A surface of reconfigurable metamaterials
- Control the propagation of electromagnetic wave
- Manipulate the channel to improve the signal quality

Promising technology for future 6G communications


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Realization of the existing **passive RIS**

- **RIS consisting of a large number of passive elements**
- **Negligible thermal noise, low cost, low power consumption**

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Applications of the existing passive RIS

- An example: passive beamforming for capacity improvement
Fundamental limit: “Multiplicative fading” effect

- The RIS-aided reflection link suffers large-scale fading twice

Signal model: \( y = (h^H + \theta^H \text{diag}(f^H)G)w_s + z \)


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Example

- **System parameters**
  - BS (equipped with 4 antennas, transmit power 10 mW)
  - RIS (equipped with 256 elements)
  - 4 User (equipped with 1 antennas)

![Diagram of a BS, RIS, and users](image-url)
Passive RIS can only achieve negligible capacity gain in typical communication scenarios.

Example

Atypical scenario

Typical scenario

How to overcome the “multiplicative fading” effect

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Concept of **active RIS**

- **Passive RIS**: Reflect signals directionally **without amplification**
- **Active RIS**: Amplify the reflected signals using **power amplifiers**
Realization of active RIS

- Feasible realizations of active reflection-type power amplifier


Signal model of **active RIS**

- Different signal models of **passive RIS** and **active RIS**

\[ y = (h^H + f^H \Theta^H G)w_s + z \]  
**Passive RIS**

\[ y = (h^H + f^H P \Theta^H G)w_s + f^H P n + z \]  
**Active RIS**

- **Phase shift matrix**
- **Amplification matrix**
- **Additional noise introduced by active components**
Capacity maximization of active RIS aided MIMO

- Three variables: BS precoding vector $\mathbf{w}$, phase shift matrix $\mathbf{\Theta}$, and amplification matrix $\mathbf{P}$ of active RIS

Maximize $\mathbf{w}, \mathbf{\Theta}, \mathbf{P}$

$$R_{\text{sum}} = \sum_{k=1}^{K} \log_2(1 + \gamma_k)$$

Subject to

$$\sum_{k=1}^{K} \| \mathbf{w}_k \|^2 \leq P_{\text{BS}}^{\text{max}}$$

$$\sum_{k=1}^{K} \| \mathbf{P} \mathbf{\Theta} \mathbf{G} \mathbf{w}_k \|^2 + \| \mathbf{P} \mathbf{\Theta} \|^2 \sigma_v^2 \leq P_{\text{A}}^{\text{max}}$$

$$\gamma_k = \frac{\left| \left( \mathbf{h}_k^H + \mathbf{f}_k^H \mathbf{P} \mathbf{\Theta}^H \mathbf{G} \right) \mathbf{w}_k \right|^2}{\sum_{j=1, j \neq k}^{K} \left| \left( \mathbf{h}_k^H + \mathbf{f}_k^H \mathbf{P} \mathbf{\Theta}^H \mathbf{G} \right) \mathbf{w}_j \right|^2 + \| \mathbf{f}_k^H \mathbf{P} \mathbf{\Theta} \|^2 \sigma_v^2 + \sigma^2}$$
Proposed joint precoding algorithm

- Optimizing $\mathbf{w}$, $\mathbf{P}$, and $\Theta$ alternatively

Lagrangian dual reformulation

Fractional programming

Derivation

Iteration

Fractional programming

Active RISs: Signal modeling, asymptotic analysis, and beamforming design
Validation of active RIS signal model

- **Experimental measurements** of a fabricated active RIS element

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A fabricated active RIS element

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Device Under Test

- active RIS element
- DC source
- power supply

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DC source

- spectrum analyzer
- vector network analyzer
- vector network analyzer
- LNA
- active RIS element
- pump source
- noise source
- circulator
Validation results

- **Measurement results**

  **25 dB reflection gain**

  ![Reflection gain vs. frequency](image)

  ![Noise power vs. reflection gain](image)

  **(a) Reflection gain vs. frequency**

  **(b) Noise power vs. reflection gain**

  Verify the **correctness** of the proposed **signal model**

Simulation for joint precoding design

- Simulation parameters
  - BS (equipped with 4 antennas, transmit power 10 mW)
  - Active RIS (equipped with 256 elements, reflect power 10 mW)
  - 4 User (equipped with 1 antennas)

![Diagram of the simulation setup](image)

- BS (equipped with 4 antennas, transmit power 10 mW)
- Active RIS (equipped with 256 elements, reflect power 10 mW)
- 4 User (equipped with 1 antennas)
Active RIS can achieve noticeable capacity gain in typical communication scenarios.

(a) Atypical scenario

(b) Typical scenario

Active RIS can overcome the “multiplicative fading” effect.

Experimental measurements of active RIS

- **Experimental measurements** based on an 8×8 active RIS

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<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>3.55 GHz</td>
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<tr>
<td>Bandwidth</td>
<td>40 MHz</td>
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<tr>
<td>Polarization</td>
<td>Vertical (BS)</td>
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<tr>
<td></td>
<td>Horizontal (user)</td>
</tr>
<tr>
<td>BS-RIS distance</td>
<td>2 m</td>
</tr>
<tr>
<td>RIS-user distance</td>
<td>3.5 m</td>
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<tr>
<td>AoA</td>
<td>0°</td>
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</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>Reflection AoD</th>
<th>Received Power</th>
<th>Data Rate</th>
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</thead>
<tbody>
<tr>
<td>Metal plate</td>
<td>15°</td>
<td>-110 dBm</td>
<td>1.2 MHz</td>
</tr>
<tr>
<td>Active RIS</td>
<td>-100 dBm</td>
<td>28.5 MHz</td>
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</tr>
<tr>
<td>Metal plate</td>
<td>45°</td>
<td>-105 dBm</td>
<td>1.5 MHz</td>
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<tr>
<td>Active RIS</td>
<td>-95 dBm</td>
<td>30 MHz</td>
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</table>
Future opportunities of active RIS

- Other **performance metrics** optimization for active RIS
- **Channel estimation** for active RIS aided system
- **Hybrid** passive and active RIS architecture
- Active RIS for other techniques, e.g., security, NOMA, MEC, etc.

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Conclusions

- Basics of RIS
  - Reconfigure the wireless environment

- Existing passive RIS
  - Passively reflect signals \textit{without amplification}
  - Fundamental limit: “multiplicative fading” effect
  - Only achieves negligible capacity gain in typical scenarios

- Proposed active RIS
  - Reflect signals \textit{with amplification} to overcome “multiplicative fading” effect
  - New signal model verified by experimental measurements
  - Achieves noticeable capacity gain in typical scenarios
  - Recent test results based on an 8*8 active RIS
Reproducible Research: http://oa.ee.tsinghua.edu.cn/dailinglong/

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