User-Side RIS: Realizing Large-Scale Array at User Side

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Outline

- Introduction
- Concept & Architecture
- System model & Precoding design
- Simulation results
Massive MIMO

- Massive MIMO: Deploying large-scale antenna array at the BS side for low-power communications
- By serving users with precoding and combining operations, orders of magnitude increase in the spectral efficiency can be achieved
Q: Can user employ a large-scale array?

Pros

1. Save the power consumption for users, and prolong the stand-by time.
2. Enhance the wireless coverage, and enable the communications in the basement.

Cons

1. Every antenna has a dedicated high-cost RF chain.
2. Mismatch of the large-scale array and the user in dimensions.

It is almost impossible to employ a large-scale array at the user side.
RIS (Reconfigurable Intelligent Surfaces)

- A large-scale array composed of passive controllable meta-materials
- Cost- and energy-efficient, do not introduce additive noise
- Control the phase of the reflected/penetrated signal, and thus improve the environment of communications


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RIS-aided communications

**Relay-like employment**
Cooperatively serve users with BS

Can we employ RIS at the user side?

A 108-element RIS is 3 times larger than the user side equipment.

CPE (Customer-Premises Equipment)

Still cannot solve the problem of mismatch in dimensions!
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From Base-Station-Side to User-Side

| User-side RIS employs RIS at the user side for the first time |

<table>
<thead>
<tr>
<th>RIS between the BS and the user (Relay-like RIS)</th>
<th>RIS close to the BS</th>
<th>RIS close to the user</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-Station-Side RIS (BSS-RIS)</td>
<td>User-Side RIS (US-RIS)</td>
<td></td>
</tr>
</tbody>
</table>

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User-Side RIS: Architecture

User architecture based on **US-RIS**

**Cons**

1. Every antenna has a dedicated **high-cost RF chain**.
2. Mismatch of the large-scale array and the user in **dimensions**.
## Comparisons

<table>
<thead>
<tr>
<th></th>
<th>BSS-RIS</th>
<th>US-RIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller</td>
<td>one/multi BS(s)</td>
<td>one user</td>
</tr>
<tr>
<td>Beneficiary</td>
<td>one/multi user(s)</td>
<td>one user</td>
</tr>
<tr>
<td>Mode</td>
<td>mainly reflective</td>
<td>transmissive</td>
</tr>
<tr>
<td>Structure</td>
<td>single-layer</td>
<td>single/multi-layer</td>
</tr>
<tr>
<td>Size</td>
<td>very large</td>
<td>small</td>
</tr>
</tbody>
</table>

**US-RIS is essentially different from BSS-RIS**
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**System Model & Problem Formulation**

**Beamforming & RIS Precoding**

\[ n \sim \mathcal{CN}(0, \sigma^2 I) \]

**Combining**

\[ y = g^H (\prod_{l=1}^{L} \kappa \Theta_l f_l) w_s + n \]

\[ z = v^H g^H (\prod_{l=1}^{L} \kappa \Theta_l f_l) w_s + v^H n \]

**SNR Maximization**

\[
\max_{w, \Theta_1, \ldots, \Theta_L, v} \frac{|v^H g^H (\prod_{l=1}^{L} \kappa \Theta_l f_l) w|^2}{\|v^H\|^2 \sigma^2}
\]

**SNR**

\[
\text{SNR} = \frac{|v^H g^H (\prod_{l=1}^{L} \kappa \Theta_l f_l) w|^2}{\|v^H\|^2 \sigma^2}
\]

**Constraints**

\[
\|w\|_2^2 \leq P_{\text{max}}
\]

\[
|\theta_{l,n}| = 1, \forall l, n
\]

\[ \mathbb{E}[s s^H] = 1 \]
Precoding Design

\[
\max_{\mathbf{v}, \Theta_1, \cdots, \Theta_L, \mathbf{w}} \text{SNR} = \frac{\left| \mathbf{v}^H \mathbf{g}^H \left( \prod_{l=1}^{L} \kappa \Theta_l \mathbf{f}_l \right) \mathbf{w} \right|^2}{\left\| \mathbf{v}^H \right\|_2^2 \sigma^2}
\]

\[
\text{s.t.} \quad C_1 : \left\| \mathbf{w} \right\|_2^2 \leq P_{\text{max}}
\]

\[
C_2 : \quad |\Theta_{l,n}| = 1, \ \forall l, n
\]

(9) \[\mathbf{v}^{\text{opt}} = \psi_{\text{max}} \left( \mathbf{g}^H \xi_{(L,1)} \mathbf{w} \mathbf{w}^H \xi_{(L,1)}^H \mathbf{g} \right).\]

(12) \[\Theta_l^{\text{opt}} = \exp \left( \text{arg} \left( \text{diag} \left( \mathbf{f}_l \xi_{(l-1,1)} \mathbf{w} \right)^H \xi_{(L,l+1)}^H g \mathbf{v} \right) \right).\]

(15) \[\mathbf{w}^{\text{opt}} = \sqrt{P_{\text{max}}} \langle \mathbf{w} \rangle^{\text{opt}} = \sqrt{P_{\text{max}}} \left\langle \xi_{(L,1)}^H g \mathbf{v} \right\rangle.\]

**Algorithm 1** Multi-layer Precoding Design for US-RIS-Aided Communications

**Input:** Channel matrices \( \mathbf{f}_1, \cdots, \mathbf{f}_L \), and \( \mathbf{g} \); maximum transmit power \( P_{\text{max}} \); noise power \( \sigma^2 \); loss factor \( \kappa \).

**Output:** Optimized combining vector \( \mathbf{v} \); optimized US-RIS precoding matrix \( \Theta_1, \cdots, \Theta_L \); optimized beamforming vector \( \mathbf{w} \); maximized SNR.

1: Initialize \( \mathbf{v}, \Theta_1, \cdots, \Theta_L, \) and \( \mathbf{w} \);
2: while no convergence of SNR do
3: Update \( \mathbf{v}^{\text{opt}} \) by (9);
4: Update \( \Theta_1^{\text{opt}}, \cdots, \Theta_L^{\text{opt}} \) in term by (12);
5: Update \( \mathbf{w}^{\text{opt}} \) by (15);
6: Update SNR by (5);
7: end while
8: return \( \mathbf{v}, \Theta_1, \cdots, \Theta_L, \mathbf{w} \), and SNR.
Simulation Results

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**Wrap Up**

- **Concept**
  - **BSS-RIS**: Relay-like RIS or RIS employed close to the BS
  - **US-RIS**: A component of the novel user architecture

- **Precoding Design**
  - A user-BS communication with the aid of a **multi-layer** US-RIS
  - **Non-convex** problem with **iterative** optimization

- **Simulation Results**
  - **Higher** decoding SNR by multi-layer RIS
  - **Higher** mainlobe and lower sidelobes by multi-layer RIS
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