Reconfigurable Intelligent Surface: Energy Efficiency and Intelligent Configuration in Wireless Communication

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Outline

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   - Background
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2 Recent Research Results
   - Reconfigurable Intelligent Surfaces (RIS) for Energy Efficiency in Wireless Networks (TWC Under third reviewing)
   - Achievable Rate Maximization By Passive Intelligent Mirrors (ICASSP, Apr. 2018, Calgary, Alberta, Canada)
   - Low Resolution Reconfigurable Intelligent Surfaces (Goblecom Dec. 2018, Abu Dhabi, UAE)
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Introduction & Background

5G Use Cases

- **eMBB** (Enhanced Mobile Broadband)
  - People’s Experience driven
  - 10Gbps Peak Rate
  - 100Mbps Anytime Anywhere
  - >3x Spectral Efficiency

- **mMTC** (Massive Machine Type Communications)
  - Vertical’s Digital transformation
  - 10^6 Connections/km²
  - 100x Energy Efficiency

- **uRLLC** (Ultra-reliable and Low-latency Communications)
  - Future IMT
  - Industry automation
  - Mission critical applications
  - Self driving car
  - 1ms Latency
  - 99.999% Reliability
Introduction & Background

A Vision of Beyond 5G Communication


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Introduction & Background

Concerns for Beyond 5G (Post-5G and 6G) Communication

- **Tbps throughput** per connection.
- **Centimeter** level localization.
- **Latency** in the order of nanoseconds.
- Increased **Energy Efficiency** (EE).
- **Intelligent algorithms** in all network layers: learn, predict, and adapt.
What’s Reconfigurable Intelligent Surfaces (RIS)?

- RIS: Man-made surface composed of many small-unit reflectors equipped with simple low-cost sensors and a cognitive engine\(^a\) \(^b\).

- Capability of soft controlling each of the units, which can effectively produce more flexible manipulation of impinging electromagnetic field, such as polarization, scattering, focusing reflection control, absorbing, etc \(^c\).


Figure: The programming and control of impinging electromagnetic field, such as polarization, scattering control, focusing reflection control.

Currently, Most implementation by 2D materials (Meta-surface)

Example: 0.4m² and 1.5mm thickness surface consisting of 102 controllable cells and operating at 2.47GHz.

Each unit cell is a rectangular patch sitting on a ground plane and offering binary phase modulation.

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Key RIS Features

1. **Passive** (nearly): No need any dedicated energy source

2. Can be **contiguous surface**: Ideally, each point can reflect

3. **No receiver noise**: due to no ADCs/DACs and Amplifier

4. **Soft programming**: Ideally, each point of surface can be reconfigured

5. **Full-band response** (Ideally): due to the reconfigurable; can work at any operating frequency wave

6. **Easily deployment**: buildings facades, factory ceilings, human clothing, etc.
**Application Scenarios-Outdoor**

**Figure:** Outdoor wireless network operation (a) Current network (b) Smart network (O1, O2 and O3 coated with RIS).

**Notes:** The objects O1, O2, O3 are now coated with reconfigurable meta-surfaces that modify the radio waves according to the generalized laws of reflection and refraction.
Application Scenarios-Indoor

Notes: (a) the signal experiences path loss and multi-path fading and hardly reaches the target user. Whereas in (b), the signal propagation can be reconfigured by RIS coated in the surfaces so that the signal is directed towards the target user.

Figure: (a) Without RIS Wall, (b) With RIS Wall
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Chongwen Huang, Alessio Zappone, George C. Alexandropoulos, Mérav Debbah and Chau Yuen, “Reconfigurable Intelligent Surfaces for Energy Efficiency in Wireless Networks” Submitted to the IEEE Transactions on Wireless Communications
System Model

The received signal at the $k$-th mobile user

$$y_k = h_{2,k} \Phi H_1 x + n_k,$$

where:

- $h_{2,k} \in \mathbb{C}^{1 \times N}$ represents the channel between RIS and the $k$-th mobile user.
- $H_1 \in \mathbb{C}^{N \times M}$ for the channel between BS and RIS.
- $\Phi \triangleq \text{diag}[\phi_1, \phi_2, \ldots, \phi_N]$ is a diagonal matrix including the effective phase shifting values $\phi_n \forall n = 1, 2, \ldots, N$ for all RIS elements.

Figure: The considered RIS-based multi-user MISO system comprising of a $M$-antenna base station serving in the downlink $K$ single-antenna users. RIS is assumed to be attached to a surrounding building’s facade.
Problem Formulation

Objective

Jointly optimal design of the RIS phase shifting matrix and the transmit power allocation matrix by maximizing the EE under QoS constraints.

Problem Formulation

\[
\max_{\Phi, P} \frac{\sum_{k=1}^{K} \log_2 (1 + p_k \sigma^{-2})}{\xi \sum_{k=1}^{K} p_k + P_{BS} + K P_{UE} + N P_n(b)} 
\]

s.t. \( \log_2 (1 + p_k \sigma^{-2}) \geq R_{\text{min}, k} \ \forall k = 1, 2, \ldots, K, \)

\( \text{tr}((H_2 \Phi H_1)^H P (H_2 \Phi H_1)^H) \leq P_{\text{max}}, \)

\( |\phi_n| = 1 \ \forall n = 1, 2, \ldots, N, \)

- Problem (4) is non-convex; and
- Optimizing \( \Phi \) is challenging due to the its discrete nature.
Proposed Solution (1/3)

Alternating optimization:

- Optimization with respect to $\Phi$

$$\min_{\Phi} \text{tr}((H_2 \Phi H_1)^+ P (H_2 \Phi H_1)^+ H)$$  \hspace{1cm} (2a)

$$\text{s.t. } |\phi_n| = 1 \forall n = 1, 2, \ldots, N$$  \hspace{1cm} (2b)

- Using **Sequential Fractional Programming**, (4) will becomes

$$\max_y 2\text{Re}(y^H (\lambda_{\text{max}} I_{N^2} - A)y^{(t)})$$  \hspace{1cm} (3a)

$$\text{s.t. } |y_i| = 1 , \forall i = (j - 1)N + j , j = 1, 2, \ldots, N,$$

$$y_i = 0 , \forall i \neq (j - 1)N + j , j = 1, 2, \ldots, N.$$  \hspace{1cm} (3b)

where $y = \text{vec}(\Phi^{-1})$ , $A \triangleq (H_2^+ H \otimes H_1^+) H (H_2^+ H \otimes H_1^+) \in \mathbb{C}^{N^2 \times N^2}$.  

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Communication via Intelligent Surfaces

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Proposed Solution (2/3)

Alternating optimization:

- Optimization with respect to $\Phi$

\[
\min_{\Phi} \text{tr}((H_2 \Phi H_1)^+ P(H_2 \Phi H_1)^+ H)
\]

s.t. $|\phi_n| = 1 \forall n = 1, 2, \ldots, N$

- Using **Gradient Descent Approach**, (4) will becomes

\[
\text{vec}(\Theta)^{(t+1)} = \text{vec}(\Theta)^{(t)} + \mu d^{(t)},
\]

\[
y^{(t+1)} = e^{j\text{vec}(\Theta)^{(t+1)}} \circ \text{vec}(I_N) = y^{(t)} \circ e^{j\mu d^{(t)}},
\]

\[
d^{(t+1)} = -q^{(t+1)} + \frac{(q^{(t+1)} - q^{(t)})^T q^{(t+1)}}{||q^{(t)}||^2} d^{(t)},
\]

\[
q^{(t)} \triangleq \nabla_{\Theta} \left( (y^{(t)})^H A y^{(t)} \right).
\]
Alternating optimization:

- Optimization with respect to \( P \)

\[
\begin{aligned}
\max_P & \quad \frac{\sum_{k=1}^{K} \log_2 (1 + p_k \sigma^{-2})}{\xi \sum_{k=1}^{K} p_k + P_{BS} + KP_{UE} + NP_n(b)} \\
\text{s.t.} & \quad p_k \geq \sigma^2(2^{R_{\min,k}} - 1), \quad \forall k = 1, 2, \ldots, K, \\
& \quad \text{tr}((H_2 \Phi H_1)^+P(H_2 \Phi H_1)^{+H}) \leq P_{\max}.
\end{aligned}
\]

- For fixed \( \Phi \), the numerator of (13a) is concave in \( P \), globally solved with limited complexity using Dinkelbach’s algorithm.
Figure: The simulated RIS-based $K$-user MISO communication scenario comprising of a $M$-antenna base station and a $N$-element intelligent surface.
Particularly, the EE of the RIS-based system is 300% larger than that of the one based on the AF relay.

**Figure**: Average EE using either RIS or AF relay versus $P_{\text{max}}$ for $R_{\text{min}} = 0\text{bps/Hz}$.
Simulation Results

- all designs perform similarly for $P_{\text{max}} \leq 15\text{dBm}$, which indicates that the EE and SE objectives are nearly equivalent for such transmit power levels.
- using full BS transmit power for low $P_{\text{max}}$ is optimal.
- for $P_{\text{max}} > 15\text{dBm}$, the SE maximization design naturally increases the SE, but leads to decreasing EE.
- EE is maximized subject to QoS, the excess transmit power is used in order to fulfill the those constraints, but reduce the EE.

Figure: Average EE using RIS versus $P_{\text{max}}$ for $M = 32$, $K = 16$, and $N = 16$ using: a) EE maximization for $R_{\text{min}} = \{0, 0.2R\}$; b) full power allocation; and c) sum rate maximization.
Simulation Results

- both proposed algorithms yield very similar performance curves that are quite close to the ones obtained from the global optimization.
- larger the $N$ value is, the larger is the achievable SE.

**Figure**: Average sum rate using RIS versus $N$ for $\text{SNR} = 20\text{dB}$, $M = 64$, $K = 64$ and $R_{\text{min}} = 2\text{bps/Hz}$ with both our presented algorithms as well as exhaustive global optimization.
Simulation Results

- When $N$ is quite small, all designs exhibit the same trend.
- Large $N$ to observe EE decreasing, this behavior seems not to happen for $P_n(b) = 0.01\text{dBm}$ due to small $P_n(b)$.
- An optimal trade-off exists between the rate benefit of deploying larger and larger RIS structure and its corresponding energy consumption cost.

**Figure**: Average EE using RIS versus $N$ for SNR $= -10\text{dB}$ and $R_{\text{min}} = 0\text{bps/Hz}$.
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Simulation Results

- The received signal at the $k$-th mobile user

$$y_k = (h_{2,k} \Phi H_1 + h_{1,k}) x + n_k,$$

- where: $h_{1,k} \in \mathbb{C}^{1 \times M}$ the direct channel between BS and the $k$-th mobile user.

- Phase shifting value (finite resolution) for the $n$-th element:

$$\phi_n \in \mathcal{F} \triangleq \left\{ \exp \left( \frac{j2\pi m}{2^b} \right) \right\}_{m=0}^{2^b-1}.$$

Figure: RIS-assisted multi-user MISO communication comprising of a $M$-antenna base station simultaneously serving in the downlink $K$ single-antenna users.
Proposed Joint Design Formulation

- EE maximization problem is given:

\[
\max_{\Phi, P} \frac{\sum_{k=1}^{K} \log_2 \left(1 + \frac{p_k}{\sigma^2}\right)}{\sum_{k=1}^{K} \mu_k p_k + KP_c + NP_n(b)}
\]

\[
\text{s.t. } \log_2 \left(1 + \frac{p_k}{\sigma^2}\right) \geq R_{\min,k} \ \forall k = 1, 2, \ldots, K,
\]

\[
\text{tr}((H_2 \Phi H_1 + H)^+P((H_2 \Phi H_1 + H)^+)^H) \leq P,
\]

\[
\phi_n \in \mathcal{F} = \{1, e^{j2^{1-b} \pi}, \ldots, e^{j2\pi(2^b-1)/2^b}\}, \ b = 1, 2, \ldots
\]

\[
\forall n = 1, 2, \ldots, N.
\]

- Challenges:
  - (10) is non-convex; and
  - Optimizing \(\Phi\) is challenging due to the its discrete nature.
Proposed Joint Design (1/4)

Solution Approach

Employ alternating optimization to separately and iteratively solve for matrices $P$ and $\Phi$.

RIS with 1-bit Phase Resolution

- First, optimization with respect to $\Phi$:

$$
\min_{\Phi} \text{tr}((H_2 \Phi H_1 + H)^{+} P((H_2 \Phi H_1 + H)^{+})^H)
$$

(11a)

s.t. $\theta_n = \{0, \pi\} \ \forall \ n = 1, 2, \ldots, N.$

(11b)

Still non-convex!

- Proposed Solution: Relax the $\theta_n$: constraint as

$$
0 \leq \theta_n \leq 2\pi.
$$
RIS with 1-bit Phase Resolution

- Optimization with respect to $\Phi$:

$$\min_{\Phi} \text{tr}((H_2 \Phi H_1 + H)^+ P((H_2 \Phi H_1 + H)^+)^H)$$  \hspace{1cm} (12a)

$$\text{s.t. } 0 \leq \theta_n \leq 2\pi \ \forall \ n = 1, 2, \ldots, N.$$  \hspace{1cm} (12b)

Convex! Leveraging the function $\text{fmincon}$ in MATLAB

- Approximated solution
  - $\theta_n = 0$: When $\frac{3\pi}{2} \leq \theta_n < 2\pi$ and $0 \leq \theta_n < \frac{\pi}{2}$.
  - $\theta_n = \pi$: When $\frac{\pi}{2} \leq \theta_n < \frac{3\pi}{2}$.

Low Complexity approach!
RIS with 1-bit Phase Resolution

- Optimization with respect to \( P \):

\[
\max_P \frac{\sum_{k=1}^{K} \log_2 \left(1 + \frac{p_k}{\sigma^2}\right)}{\sum_{k=1}^{K} \mu_k p_k + KP_c + NP_n(1)}
\]  
\[
\text{s.t. } p_k \geq \sigma^2 (2^{R_{\min,k}} - 1) \quad \forall k = 1, 2, \ldots, K,
\]
\[
\text{tr}( (H_2 \Phi H_1 + H)^{+} P ( (H_2 \Phi H_1 + H)^{+} )^\dagger ) \leq P.
\]

Convex!

Problem (13) can be globally solved with limited complexity using Dinkelbach’s method\(^a\).

RIS with Finite Phase Resolution Elements

2-bit resolution case:

$$\min_{\Phi} \text{tr}((H_2 \Phi H_1 + H)^+ P((H_2 \Phi H_1 + H)^+)^H)$$  \hspace{1cm} (14a)$$

s.t. \ \theta_n = \{0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}\} \ \forall n = 1, 2, \ldots, N. \hspace{1cm} (14b)$$

Similar with One-bit!

Approximated solution

- $\theta_n = 0$: When $0 \leq \theta_n < \frac{\pi}{4}$ and $\frac{7\pi}{4} \leq \theta_n < 2\pi$.
- $\theta_n = \frac{\pi}{2}$: When $\frac{\pi}{4} \leq \theta_n < \frac{3\pi}{4}$.
- $\theta_n = \pi$: When $\frac{3\pi}{4} \leq \theta_n < \frac{5\pi}{4}$.
- $\theta_n = \frac{3\pi}{2}$: Otherwise.

Similarly, it can be extended to other finite phase resolution.
Figure: The simulated RIS-assisted $K$-user MISO communication scenario comprising of a $M$-antenna base station and a $N$-element intelligent surface.
Simulation Results: Globecom Dec. 2018 (1)

- 2-bit phase resolution performs quite close to the infinite one.

Figure: Achievable sum rate vs the transmit SNR for $K = 16$, $M = 12$, $N = 32$, and $R_{\text{min},k} = \log_2(1 + \frac{\text{SNR}}{2K})$ bps/Hz $\forall k = 1, 2, \ldots, 16$. 
Simulation Results: Globecom Dec. 2018 (2)

- The two low resolution cases result in the highest EE.
- Up to 45% Higher EE than the relay-assisted case.

Figure: Energy efficiency maximization vs the total BS transmit power $P$ for $K = 16$, $M = 12$, $N = 32$, and $R_{\text{min}, k} = 0$ bps/Hz $\forall k = 1, 2, \ldots, 16$. 
The proposed method approaches the optimal.

With RIS, there are huge gain than that of without RIS.

Fig. R2.2. The average SE comparison of the proposed RIS system with no RIS system. a) $M = 32, K = 16$, 