Reconfigurable Intelligent Surface (RIS): Beamforming, Modulation, and Channel Shaping

Viva Presentation

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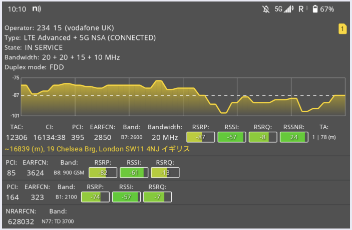
Do we want more waves in the air?

Massive MIMO is here

(a) 8T8R and mMIMO at Imperial



(b) Cellular statistics

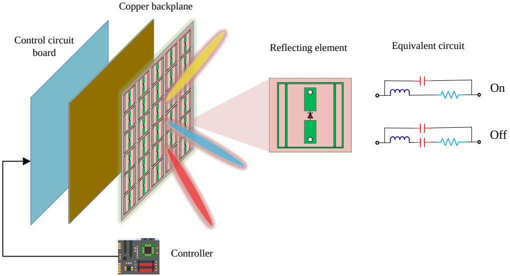
How far are we from the Shannon capacity?

$$C(\mathbf{H}) = \max_{\mathbf{Q}\succeq 0, \mathrm{tr}(\mathbf{Q})\leq P} \log\det\left(\mathbf{I} + \rho\mathbf{H}\mathbf{Q}\mathbf{H}^{\mathsf{H}}\right)$$

- Modulation, coding, and beamforming to adapt to the stochastic channel
- Reconfigurable Intelligent Surface (RIS) can shape and control the channel

What is RIS?

A planar surface of controllable scattering elements for signal amplitude and phase manipulation [1].

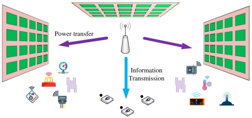


Characteristics

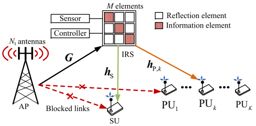
- Low-power and low-cost
- Negligible noise and latency
- Full-duplex without self-interference
- Programmable in real-time

Use cases of RIS

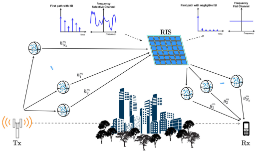
- Beamforming of RIS and transceiver can be jointly designed for a specific performance measure.
- RIS can be used for backscatter modulation by periodically switching the reflection pattern.
- Channel shaping exploits the RIS as a stand-alone device to modify the inherent properties of the propagation environment.



(a) Beamforming [1]



(b) Modulation [2]



(c) Channel shaping [3]

RIS-aided SWIPT: Joint waveform and beamforming design

Overview

- *What does this paper propose?*
  A single-user multi-carrier Simultaneous Wireless Information and Power Transfer (SWIPT) system aided by a passive RIS.
- *How does it differ from previous work?*
  We consider waveform and beamforming design for practical receiver architectures under non-linear harvester and frequency-flat RIS models.
- *What are the benefits?*
  It exploits the spatial-frequency domain and rectifier behavior to enlarge the Rate-Energy (R-E) region, achieving squared asymptotic performance than conventional designs.

From received signal to harvested power

The rectenna efficiency η_3 depends on its input waveform (power and shape).

Rectenna model

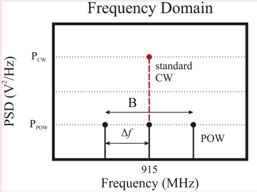
- Linear region (constant η_3): $P_{\text{DC}}^{\text{R}} = \eta_3 P_{\text{RF}}^{\text{R}} = \eta_3 \mathbb{A}\{|y(t)|^2\}$
- Non-linear region: Taylor expansion on diode characteristic equation

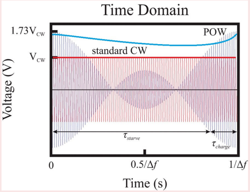
$$\arg_{x(t)} \max P_{\text{DC}}^{\text{R}} = \arg_{x(t)} \max z \triangleq \sum_{i=2,\text{even}}^{n_0} \beta_i \mathbb{A}\{y^i(t)\},$$

where $\beta_i = I_{\text{S}} \frac{R_{\text{A}}^{i/2}}{i!(n v_{\text{T}})^i}$ is a constant and n_0 is the truncation order.

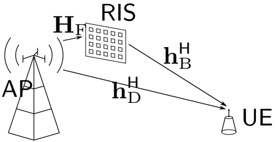
In multi-carrier WPT ...

- $n_0 \geq 4$ allows components to compensate each other for higher DC power
- High Peak-to-Average Power Ratio (PAPR) (e.g., multi-sine) is preferred [4]





From WPT to RIS-aided SWIPT

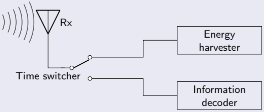


- SWIPT features shared signal, spectrum, and infrastructure
- RIS enhances the RF-to-RF efficiency η_2 which has been a major concern

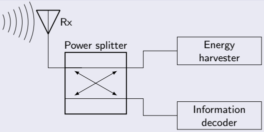
Transmit waveform

$$\mathbf{x}(t) = \Re\left\{\sum_{n=1}^{N}\left(\mathbf{w}_{\mathrm{I},n}\cdot\underbrace{\tilde{x}_{\mathrm{I},n}(t)e^{\jmath 2\pi f_n t}}_{\text{modulated}} + \mathbf{w}_{\mathrm{P},n}\cdot\underbrace{e^{\jmath 2\pi f_n t}}_{\text{multi-sine}}\right)\right\}$$

Receiver architectures



(a) Time Switching (TS) receiver



(b) Power Splitting (PS) receiver

Joint waveform and beamforming design

Problem formulation

$$
\begin{aligned}
\max_{\boldsymbol{\theta},\mathbf{W}_{\mathrm{I}},\mathbf{W}_{\mathrm{P}},\rho} \quad & z(\boldsymbol{\theta},\mathbf{W}_{\mathrm{I}},\mathbf{W}_{\mathrm{P}},\rho) \\
\text{s.t.} \quad & \|\mathbf{W}_{\mathrm{I}}\|_{\mathrm{F}}^2/2 + \|\mathbf{W}_{\mathrm{P}}\|_{\mathrm{F}}^2/2 \leq P, \\
& R(\boldsymbol{\theta},\mathbf{W}_{\mathrm{I}},\rho) \geq \bar{R}, \\
& |\phi_l| = 1, \quad l = 1,\dots,L, \\
& 0 \leq \rho \leq 1,
\end{aligned}
$$

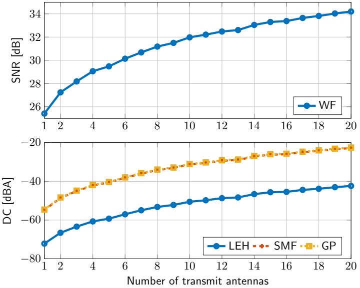
Solution by Block Coordinate Descent (BCD)

- Optimally decouple the spatial and frequency domain design

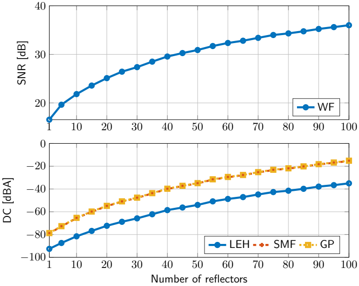
$$
\mathbf{w}_{\mathrm{I/P},n} = \underbrace{s_{\mathrm{I/P},n}}_{\text{frequency}} \underbrace{\mathbf{p}_{\mathrm{I/P},n}}_{\text{spatial}}
$$

- Active beamforming $\mathbf{p}$: Maximum Ratio Transmission (MRT)
- Passive beamforming $\boldsymbol{\theta}$: Successive Convex Approximation (SCA)
- Power allocation s and splitting ratio ρ: Geometric Programming (GP)

Simulation results: Asymptotic behavior



(a) Number of transmit antennas M



(b) Number of RIS elements L

- Active beamforming: array gain M and harvested power order M^2
- Passive beamforming: array gain L^2 and harvested power order L^4
- Superlinear thanks to coherent scattering and rectifier nonlinearity

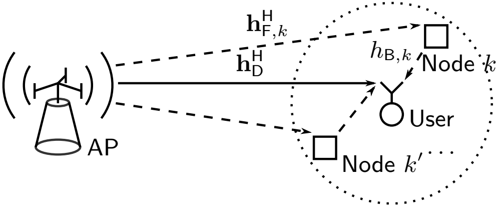
RIScatter: Unifying Backscatter Communication (BackCom) and RIS

Overview

- *What does this paper propose?*
  RIScatter — a batteryless cognitive radio that recycles ambient signal in an adaptive and customizable manner.
- *How does it differ from previous work?*
  Backscatter modulation and passive beamforming are seamlessly integrated from the perspective of probability distribution.
- *What are the benefits?*
  It supports cooperative and distributed deployment, avoids complex architecture and signal processing, and can be built over legacy systems.

Signal model

RIScatter renders the node input distribution as a function of information source, Channel State Information (CSI), and priority of coexisting links.



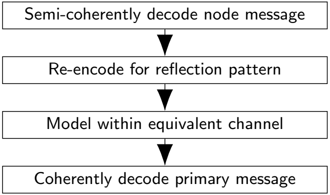
$$y[n] = \underbrace{\left(\mathbf{h}_{\mathsf{D}}^{\mathsf{H}} + \sum_k \alpha_k \mathbf{h}_{\mathsf{C},k}^{\mathsf{H}} x_k\right)}_{\mathbf{h}^{\mathsf{H}}(x_{\mathcal{K}})} \mathbf{w} s[n] + v[n],$$

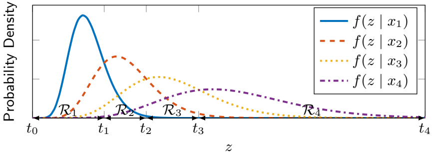
Properties

1. Primary and backscatter symbols are superimposed by double modulation
2. Backscatter signal is much weaker due to double fading
3. The spreading factor (i.e., symbol period ratio N) is usually large
4. Each state is simultaneously part of information and beamforming codeword
5. Reflection pattern over time is guided by input probability distribution

Low-complexity receiver

We propose a low-complexity receiver that exploits the aforementioned properties to avoid Successive Interference Cancellation (SIC).





- Accumulated receive energy $z = \sum_n \left|y[n]\right|^2$ follows Gamma distribution
- Backscatter detection under primary uncertainty is part of channel training
- Requires one energy comparison and re-encoding per backscatter symbol (much simpler than symbiotic radio with N SIC and 1 combining)

Joint beamforming, input distribution, and energy detector design

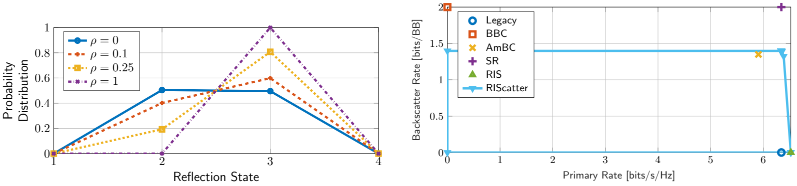
Problem formulation

$$
\begin{aligned}
\max_{\{\mathbf{p}_k\},\mathbf{w},\mathbf{t}} \quad & \rho R_{\mathsf{P}} + (1-\rho)\sum\nolimits_k R_{\mathsf{B},k} \\
\text{s.t.} \quad & \mathbf{1}^{\mathsf{T}}\mathbf{p}_k = 1, \quad \mathbf{p}_k \geq \mathbf{0}, \quad \forall k, \\
& t_{l-1} \leq t_l, \quad t_l \geq 0, \quad \forall l, \\
& \|\mathbf{w}\|^2 \leq P,
\end{aligned}
$$

Solution by Block Coordinate Descent (BCD)

- Input distribution $\{\mathbf{p}_k\}$: Karush-Kuhn-Tucker (KKT)
- Active beamforming $\mathbf{w}$: Projected Gradient Ascent (PGA)
- Energy decision threshold $\mathbf{t}$: Dynamic Programming (DP)

Simulation results: Input distribution and rate region



- Increasing ρ from 0 to 1 evolves from BackCom to RIS
- Backscatter rate is lower than SR (due to energy detection) but higher than AmBC (due to adaptive encoding)
- Active and passive transmission can share resource with mutual benefits

Channel shaping using RIS: From diagonal model to beyond

Overview

- *What does this paper study?*
  To what extent can a passive RIS redistribute the singular values of a Multiple-Input Multiple-Output (MIMO) channel.
- *How does it differ from previous work?*
  We consider a Beyond-Diagonal (BD) architecture, depict the singular value region, derive analytical bounds, and solve the rate maximization problem.
- *What are the benefits?*
  Channel shaping is ubiquitous for communication, sensing, and power transfer, which helps to decouple the RIS-transceiver design. We also propose an efficient and universal BD-RIS design framework.

Wave scattering model

Diagonal RIS

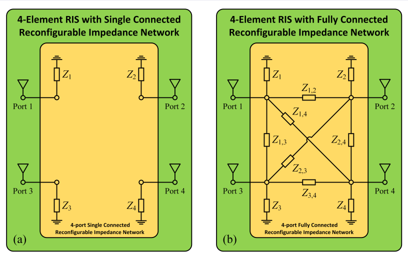
Each element acts as an individual scatterer with phase shift only

$$\boldsymbol{\Theta} = \mathrm{diag}(\theta_1, \ldots, \theta_{N_\mathrm{S}}) = \mathrm{diag}(e^{\jmath\phi_1}, \ldots, e^{\jmath\phi_{N_\mathrm{S}}})$$

BD-RIS

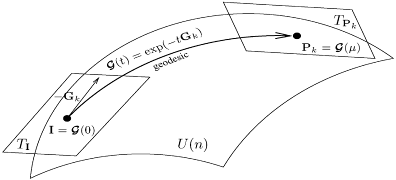
Each group contains L connected elements, allowing amplitude and phase control

$$\boldsymbol{\Theta} = \mathrm{diag}(\boldsymbol{\Theta}_1, \ldots, \boldsymbol{\Theta}_G), \quad \boldsymbol{\Theta}_g^\mathsf{H}\boldsymbol{\Theta}_g = \mathbf{I}_L, \quad \forall g$$



Architecture of diagonal and BD-RIS [5]

Proposed geodesic update via Lie algebra



Non-geodesic vs geodesic Riemannian Conjugate Gradient (RCG)

- Non-geodesic: add then retract

$$\bar{\mathbf{\Theta}}_g^{(r+1)} = \mathbf{\Theta}_g^{(r)} + \mu \mathbf{D}_g^{(r)}, \quad \mathbf{\Theta}_g^{(r+1)} = \bar{\mathbf{\Theta}}_g^{(r+1)} \big(\bar{\mathbf{\Theta}}_g^{(r+1)\mathsf{H}} \bar{\mathbf{\Theta}}_g^{(r+1)}\big)^{-1/2}$$

- Geodesic: multiplicative and rotational update

$$\mathbf{\Theta}_g^{(r+1)} = \mathbf{G}_g^{(r)}(\mu) = \exp(\mu \mathbf{D}_g^{(r)}) \mathbf{\Theta}_g^{(r)}$$

Performance comparison

RCG path	$N_{\mathrm{S}} = 16$			$N_{\mathrm{S}} = 256$		
	Objective	Iterations	Time [s]	Objective	Iterations	Time [s]
Geodesic	4.359×10^{-3}	11.59	1.839×10^{-2}	1.163×10^{-2}	25.58	3.461
Non-geodesic	4.329×10^{-3}	30.92	5.743×10^{-2}	1.116×10^{-2}	61.40	13.50

Problem formulation

Pareto frontier of channel singular values

$$\begin{aligned} \max_{\mathbf{\Theta}} \quad & \sum_n \rho_n \sigma_n(\mathbf{H}) \\ \text{s.t.} \quad & \mathbf{\Theta}_g^{\mathsf{H}} \mathbf{\Theta}_g = \mathbf{I}, \quad \forall g, \end{aligned}$$

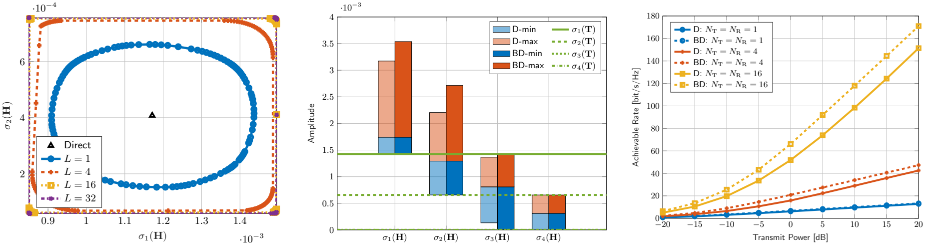
Achievable rate maximization

$$\begin{aligned} \max_{\mathbf{W}, \mathbf{\Theta}} \quad & R = \log\det\left(\mathbf{I} + \frac{\mathbf{W}^{\mathsf{H}}\mathbf{H}^{\mathsf{H}}\mathbf{H}\mathbf{W}}{\eta}\right) \\ \text{s.t.} \quad & \|\mathbf{W}\|_{\mathrm{F}}^2 \leq P, \\ & \mathbf{\Theta}_g^{\mathsf{H}} \mathbf{\Theta}_g = \mathbf{I}, \quad \forall g. \end{aligned}$$

Solution by group-wise geodesic RCG

- Faster convergence thanks to appropriate parameter space
- Optimal and low-complexity solutions

Simulation results: Singular value and achievable rate



(a) $2 \times 32 \times 2$ (b) $4 \times 32 \times 4$ (rank-1) (c) $N_\mathrm{T} \times 128 \times N_\mathrm{R}$

- BD-RIS provides $22\,\%$ and $38\,\%$ dynamic range gain for $\sigma_1(\mathbf{H})$ and $\sigma_2(\mathbf{H})$
- Asymptotic bounds are valid for diagonal and BD-RIS
- Percentage rate gain of BD-RIS scales with MIMO dimension and group size

- Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Communications Magazine*, vol. 58, pp. 106–112, Jan 2020.
- S. Hu, C. Liu, Z. Wei, Y. Cai, D. W. K. Ng, and J. Yuan, "Beamforming design for intelligent reflecting surface-enhanced symbiotic radio systems," in *ICC 2022 - IEEE International Conference on Communications*, May 2022, pp. 2651–2657.
- E. Arslan, I. Yildirim, F. Kilinc, and E. Basar, "Over-the-air equalization with reconfigurable intelligent surfaces," *IET Communications*, vol. 16, pp. 1486–1497, Aug 2022.
- M. Trotter, J. Griffin, and G. Durgin, "Power-optimized waveforms for improving the range and reliability of RFID systems," in *2009 IEEE International Conference on RFID*, Apr 2009, pp. 80–87.
- S. Shen, B. Clerckx, and R. Murch, "Modeling and architecture design of reconfigurable intelligent surfaces using scattering parameter network analysis," *IEEE Transactions on Wireless Communications*, vol. 21, pp. 1229–1243, Feb 2022.