IMPERIAL

# Reconfigurable Intelligent Surfaces:
## Beamforming, Modulation, and Channel Shaping


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# Declaration

I hereby declare that the contents presented in this dissertation are original and have been carried out by myself under the guidance of my supervisor Prof. Bruno Clerckx. Any work from other researchers, scholars, or sources have been properly cited and acknowledged. The contents have not been submitted in whole or in part for consideration of any other degree or qualification in any academic institution. I am aware of the ethical standards and academic integrity policies of Imperial College London, and I have adhered to these principles throughout the course of my study. In signing this declaration, I affirm my commitment to academic honesty, intellectual integrity, and the pursuit of knowledge in the service of truth and understanding.



The source code of all simulation results in this dissertation are publicly available at `https://github.com/snowztail/`.

Yang Zhao
March 2024

# Abstract

This is where you write your abstract ...

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# Abbreviations

| | |
|---|---|
| bpcu | bits per channel use |
| bps/Hz | bits per second per Hertz |
| | |
| AF | Amplify-and-Forward |
| AI | Artificial Intelligence |
| AM | Arithmetic Mean |
| AmBC | Ambient Backscatter Communication |
| AO | Alternating Optimization |
| AP | Access Point |
| AWGN | Additive White Gaussian Noise |
| | |
| BackCom | Backscatter Communication |
| BBC | Bistatic Backscatter Communication |
| BCD | Block Coordinate Descent |
| BD | Beyond-Diagonal |
| BER | Bit Error Rate |
| BIBO | Binary-Input Binary-Output |
| BLS | Backtracking Line Search |
| | |
| CLT | Central Limit Theorem |
| CP | Canonical Polyadic |
| CR | Cognitive Radio |
| CSCG | Circularly Symmetric Complex Gaussian |
| CSI | Channel State Information |
| CSIT | Channel State Information at the Transmitter |
| CW | Continuous Waveform |
| | |
| DC | Direct Current |

| | |
|---|---|
| DCMC | Discrete-input Continuous-output Memoryless Channel |
| DF | Decode-and-Forward |
| DMC | Discrete Memoryless Channel |
| DMMAC | Discrete Memoryless Multiple Access Channel |
| DMTC | Discrete Memoryless Thresholding Channel |
| DoF | Degree of Freedom |
| DP | Dynamic Programming |
| EIRP | Effective Isotropic Radiated Power |
| eMBB | enhanced Mobile Broadband |
| FDMA | Frequency-Division Multiple Access |
| FPGA | Field-Programmable Gate Array |
| GM | Geomtric Mean |
| GP | Geometric Programming |
| i.i.d. | independent and identically distributed |
| IC | Interference Channel |
| IM | Index Modulation |
| IoE | Internet of Everything |
| IoT | Internet of Things |
| KKT | Karush-Kuhn-Tucker |
| LC | Low-Complexity |
| LoS | Line-of-Sight |
| M2M | Machine-to-Machine |
| MAC | Multiple Access Channel |
| MBC | Monostatic Backscatter Communication |
| MC | Multiplication Coding |
| MIMO | Multiple-Input Multiple-Output |
| MISO | Multiple-Input Single-Output |
| ML | Maximum-Likelihood |
| MMSE | Minimum Mean-Square-Error |

| | |
|---|---|
| mMTC | massive Machine-Type Communication |
| MRC | Maximal Ratio Combining |
| MRT | Maximum Ratio Transmission |
| MSE | Mean-Square Error |
| NLoS | Non-Line-of-Sight |
| NOMA | Non-Orthogonal Multiple Access |
| OFDM | Orthogonal Frequency-Division Multiplexing |
| PC | Point-to-point Channel |
| PDF | Probability Density Function |
| PGA | Projected Gradient Ascent |
| PIN | Positive Intrinsic Negative |
| PS | Power Splitting |
| PSK | Phase Shift Keying |
| QAM | Quadrature Amplitude Modulation |
| QoS | Quality of Service |
| R-E | Rate-Energy |
| RCG | Riemannian Conjugate Gradient |
| RF | Radio-Frequency |
| RFID | Radio-Frequency Identification |
| RIS | Reconfigurable Intelligent Surface |
| SC | Superposition Coding |
| SCA | Successive Convex Approximation |
| SDMA | Space-Division Multiple Access |
| SDP | Semi-Definite Programming |
| SDR | Semi-Definite Relaxation |
| SIC | Successive Interference Cancellation |
| SIMO | Single-Input Multiple-Output |
| SINR | Signal-to-Interference-plus-Noise Ratio |
| SISO | Single-Input Single-Output |
| SMAWK | Shor-Moran-Aggarwal-Wilber-Klawe |

| | |
|---|---|
| SMF | Scaled Matched Filter |
| SNR | Signal-to-Noise Ratio |
| SR | Symbiotic Radio |
| SVD | Singular Value Decomposition |
| SWIPT | Simultaneous Wireless Information and Power Transfer |
| | |
| TDMA | Time-Division Multiple Access |
| TS | Time Switching |
| | |
| UE | User Equipment |
| URLLC | Ultra-Reliable Low-Latency Communication |
| | |
| WF | Water-Filling |
| WIT | Wireless Information Transfer |
| WPCN | Wireless Powered Communication Network |
| WPT | Wireless Power Transfer |
| WSR | Weighted Sum-Rate |
| | |
| ZF | Zero-Forcing |

# Notation

### Constants

| | |
|---|---|
| $e$ | Euler's number $\simeq 2.71828\ldots$ |
| $\jmath$ | The imaginary unit $= \sqrt{-1}$ |
| $\pi$ | Archimedes' constant $\simeq 3.14159\ldots$ |

### Objects

| | |
|---|---|
| $a, A$ | Scalar |
| $\mathbf{a}$ | Column vector |
| $\mathbf{A}$ | Matrix |
| $\mathcal{A}$ | Finite set |
| $\mathbf{0}$ | Zero matrix |
| $\mathbf{1}$ | One matrix |
| $\mathbf{I}$ | Identity matrix |

### Sets

| | |
|---|---|
| $\mathbb{R}$ | Real numbers |
| $\mathbb{R}_+$ | Real nonnegative numbers |
| $\mathbb{C}$ | Complex numbers |
| $\mathbb{I}$ | Probability domain $[0, 1]$ |
| $\mathbb{H}_+^{n\times n}$ | Positive semi-definite matrices of dimension $n \times n$ |
| $\mathbb{U}^{n\times n}$ | Unitary matrices of dimension $n \times n$ |

### Operations

| | |
|---|---|
| $(\cdot)^*$ | Complex conjugate |
| $(\cdot)^{\mathsf{T}}$ | Transpose |
| $(\cdot)^{\mathsf{H}}$ | Hermitian (conjugate transpose) |
| $(\cdot)^{\dagger}$ | Moore-Penrose inverse |

| | |
|---|---|
| $(\cdot)^+$ | Ramp function $\max(0, \cdot)$ |
| $\lvert\cdot\rvert$ | Absolute value of a complex number |
| $\lVert\cdot\rVert$ | Euclidean norm of a vector |
| $\lVert\cdot\rVert_{\mathrm{F}}$ | Frobenius norm of a matrix |
| $\arg(\cdot)$ | Argument of a complex number |
| $\mathrm{card}(\cdot)$ | Cardinality of a finite set |
| $\log(\cdot)$ | Natural logarithm of a real number |
| $\exp(\cdot)$ | Exponential of a scalar or square matrix |
| $\mathrm{tr}(\cdot)$ | Trace of a square matrix |
| $\det(\cdot)$ | Determinant of a square matrix |
| $\mathrm{sv}(\cdot)$ | Singular values sorted from largest to smallest |
| $\mathrm{diag}(\cdot)$ | Constructs a square matrix with inputs on the main diagonal |
| $\mathrm{diag}^{-1}(\cdot)$ | Retrieves the main diagonal of a square matrix |
| $\Re(\cdot)$ | Retrieves the real part of a complex number |
| $\Im(\cdot)$ | Retrieves the imaginary part of a complex number |
| $\mathbb{E}(\cdot)$ | Expectation operator |
| $\mathbb{A}(\cdot)$ | Extracts the Direct Current component of a signal |
| $\odot$ | Hadamard product |
| $\otimes$ | Kronecker product |
| $(\cdot)_{[x:y]}$ | Shortcut for $(\cdot)_x, (\cdot)_{x+1}, \ldots, (\cdot)_y$ |

**Distributions**

| | |
|---|---|
| $\sim$ | Follows a distribution |
| $\mathcal{CN}(\mathbf{0}, \boldsymbol{\Sigma})$ | Multivariate Circularly Symmetric Complex Gaussian with covariance $\boldsymbol{\Sigma}$ |

**Subscripts**

| | |
|---|---|
| $(\cdot)_{\mathrm{B}}$ | Backward |
| $(\cdot)_{\mathrm{D}}$ | Direct |
| $(\cdot)_{\mathrm{F}}$ | Forward |
| $(\cdot)_{\mathrm{I}}$ | Information |
| $(\cdot)_{\mathrm{P}}$ | Power |

**Superscripts**

| | |
|---|---|
| $(\cdot)^{(r)}$ | $r$-th iterated value |
| $(\cdot)^{\star}$ | Stationary point |

# Chapter 1

# Introduction

## 1.1 Background and Motivation

The quest for better wireless connectivity has been long-standing since Marconi's illuminating radio in 1895. Great successes have been made at the transmitter and receiver sides over the past century, and the communications society is unprecedentedly close to the Shannon limit [1]. By 2025, global mobile data traffic is expected to reach 607 exabytes per year [2] while the number of connected devices may exceed 75 billion [3]. At the same time, wireless applications are also evolving in various forms to address world-changing incidents like COVID-19, climate change, and Artificial Intelligence (AI) revolution. An initial attempt was made in 5G where the network prioritizes among high-throughput, ubiquitous-coverage, high-reliability, low-latency, massive-connectivity, and energy-efficient services [4]. However, the desire of human and machine for better communication shows no signs of slowing down. Emerging applications such as smart cities, autonomous driving, telemedicine, extended reality, federated learning, and generative intelligence are calling for a stronger and smarter wireless infrastructure. It is envisioned that 6G will be designed to meet the following requirements [5–7]:

- *Throughput*: The network would be able to provide a peak data rate of 1 Tbps and an average data rate of 100 Gbps per user.
- *Latency*: Sub-millisecond end-to-end latency would be achieved for low-latency applications like autonomous driving and remote surgery.
- *Reliability*: A success rate of 99.9999% would be guaranteed for ultra-reliable applications like industrial automation and cooperative robotics.

- *Connectivity*: The number of connected devices per kilometer square would be increased to 10 million for supporting Internet of Everything (IoE).
- *Mobility*: Commercial airlines with a maximal velocity of 1000 km/h would be the target application scenario.
- *Energy efficiency*: Power consumption has been a major criticism for 5G. It is expected that energy per bit would be reduced by 90% in 6G to reduce the carbon footprint.
- *Positioning accuracy*: Thanks to THz base stations, a 3D positioning accuracy of centimeter level may be achieved for indoor and outdoor environments.
- *Coverage*: A terrestrial-satellite-aerial integrated network would be able to provide a ubiquitous and uniform coverage for urban, rural, and remote areas.
- *Security and privacy*: Physical-layer security can be improved with narrower beams at higher frequencies and destructive scattering at the environment. Privacy can be enhanced with federated learning and homomorphic encryption.

## 1.2 Overview on Reconfigurable Intelligent Surface (RIS)

### 1.2.1 Background

### 1.2.2 Concept

### 1.2.3 Characteristics

### 1.2.4 Applications

## 1.3 Outline and Contributions

The thesis is outlined as follows:

- Chapter 1 introduces Reconfigurable Intelligent Surface (RIS) as a promising technology for ambient wave redirection and highlights its potential benefits in future wireless networks. It discusses the motivation, objectives, and contributions of each research chapter. A list of publications is also provided.
- Chapter 2 provides the necessary background knowledge for the subsequent chapters, including the fundamental concepts, operating principles, hardware implementation,

signal and system models, performance metrics, and design challenges for RIS, Wireless Power Transfer (WPT), Simultaneous Wireless Information and Power Transfer (SWIPT), Backscatter Communication (BackCom), and Multiple-Input Multiple-Output (MIMO) systems. It also reviews the state-of-the-art research in relevant topics and raise critical questions to be addressed in the following chapters.

- Chapter **??** investigate the impact of RIS on wireless information and power transfer. The key contributions include:
  - Introduce RIS to a multi-antenna multi-carrier SWIPT system with different receiver architectures;
  - Consider joint waveform and beamforming design for the proposed system under a practical energy harvester model;
  - Characterize the Rate-Energy (R-E) performance trade-off by maximizing harvested energy subject to different communication rate constraints;
  - Propose local-optimal and low-complexity algorithms and evaluate their narrow and wideband performance through numerical simulations;
  - Discuss the array gain for communication and the scaling order for power transfer in terms of the number of transmit antennas and RIS elements.
- Chapter **??** develops a novel scatter protocol that integrates beamforming and modulation. The key contributions include:
  - Provide an in-depth comparison of RIS with state-of-the-art BackCom technologies and discuss the key properties of active and passive transmissions coexisting systems;
  - Unify RIS and BackCom as one battery-free cognitive radio called RIScatter, where dispersed or co-located scatter nodes ride over an active primary link to modulate their own information and engineering the legacy channel simultaneously;
  - Integrate backscatter modulation and passive beamforming seamlessly into the input distribution design that allows arbitrary trade-off in between;
  - Propose a low-complexity cooperative receiver that sequentially decodes both coexisting links and exploits backscatter detection as part of channel training;
  - Characterize the achievable primary-backscatter rate region over different designs of input distribution at the scatter nodes, active beamforming at the Access Point (AP), and energy detector at the receiver;

  - Discuss the impact of practical factors such as the number of scatter nodes and states, transmit antenna size, backscatter symbol duration, and Signal-to-Noise Ratio (SNR) on the system performance.

- Chapter **??** explores the ultimate channel shaping capabilities of RIS in MIMO systems. The key contributions include:

  - Quantify the capability of a passive RIS to reshape the MIMO Point-to-point Channel (PC) in terms of singular values via analytical bounds and numerical optimization;
  - Focus on a general Beyond-Diagonal (BD)-RIS architecture featuring element-wise connections and demonstrate its superior signal processing performance (subspace alignment and subchannel rearrangement) over the widely-adopted diagonal model;
  - Propose an efficient Riemannian Conjugate Gradient (RCG) algorithm for general BD-RIS optimization and provide low-complexity solutions for quadratic problems;
  - Characterize the Pareto frontiers of channel singular values and obtain power- and rate-optimal BD-RIS configurations in MIMO PC;
  - Investigate the impact of BD-RIS on leakage interference suppression and Weighted Sum-Rate (WSR) maximization in MIMO Interference Channel (IC);
  - Discuss how channel shaping helps to decouple joint RIS-transceiver designs with comparable performance and significantly reduced complexity.

## 1.4 Publications

- Y. Zhao, B. Clerckx, and Z. Feng, "IRS-aided SWIPT: Joint waveform, active and passive beamforming design under nonlinear harvester model," *IEEE Transactions on Communications*, vol. 70, pp. 1345–1359, 2022

- Y. Zhao and B. Clerckx, "Riscatter: Unifying backscatter communication and reconfigurable intelligent surface," 12 2022

- ——, *RIS in Wireless Information and Power Transfer*. John Wiley & Sons, Ltd, 2023, pp. 271–295

- Y. Zhao, H. Li, M. Franceschetti, and B. Clerckx, “Channel shaping using reconfigurable intelligent surfaces: From diagonal to beyond,” *To be submitted to IEEE Transactions on Wireless Communications*

# Chapter 2

# Background and Literature Review

## 2.1 Reconfigurable Intelligent Surface (RIS)

### 2.1.1 Hardware Implementation

#### 2.1.1.1 Programmable Metamaterials

Metamaterials refer to artificial structures engineered for unusual properties that may not be found in nature. The concept was initially proposed by Victor Veselago in 1967, who conjectured the existence of mediums with negative dielectric constant $\epsilon < 0$ and negative permeability $\mu < 0$ [12]. Such metamaterials are known as "negative-index" because the refraction index is defined as the *negative* square root $n = -\sqrt{\epsilon\mu} < 0$, in order to be consistent with Maxwell's equations. It was not until 1999 that their feasibility was experimentally demonstrated by John Pendry at Imperial College using split-ring resonators [13]. Since then, metamaterials have attracted significant interests due to their counterintuitive properties, to name a few:

- *Negative refraction:* As shown in Fig. 2.1, the incident and refracted rays stay at the same side of the normal axis. This phenomenon is in contrast to the usual refraction but can still be predicted from Snell's law

$$\frac{\sin\theta_1}{\sin\theta_2} = n. \tag{2.1}$$

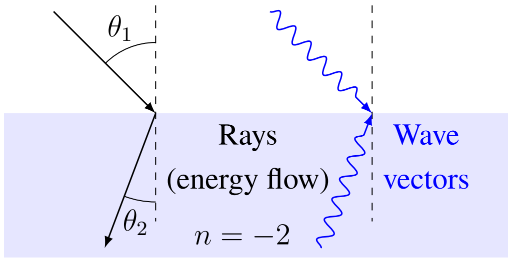


Fig. 2.1 Refraction of electromagnetic waves at the interface between a positive-index and a negative-index material.

- *Opposite wave direction:* As shown in Fig. 2.2, the wave vector and energy flow (indicated by the Poynting vector) are opposite to each other in a negative-index material. This can be inferred from the electric field equation

$$\vec{E} = \vec{E}_0 \exp(\jmath kz - \jmath\omega t) \tag{2.2}$$

where $k = k_0 n < 0$ is the wavenumber, $\vec{E}_0$ and $k_0$ are the free-space reference, $z$ is the propagation distance, $\omega$ is the angular frequency, and $t$ is the time. Negative-index materials are thus also called "left-hand" because the propagation direction of the electric and magnetic fields can be determined by a left-hand rule.

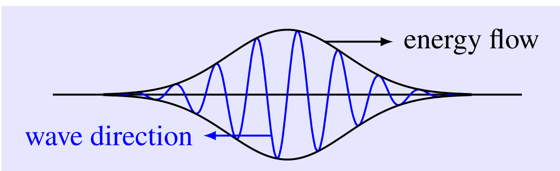


Fig. 2.2 Wave and energy flows in a negative-index material.

#### 2.1.1.2 Physical Architecture

### 2.1.2 Wave Scattering Model

#### 2.1.2.1 Active and Passive Elements

#### 2.1.2.2 Independent Scattering: Diagonal Model

#### 2.1.2.3 Cooperative Scattering: Beyond-Diagonal (BD) Model

#### 2.1.2.4 Impact of Radiation Pattern and Circuit Topology

### 2.1.3 Comparison with Reflectarrays and Relays

#### 2.1.3.1 Functionality

#### 2.1.3.2 Reconfigurability

#### 2.1.3.3 Complexity

#### 2.1.3.4 Power Consumption

#### 2.1.3.5 Dimension and Cost

#### 2.1.3.6 Applications

## 2.2 Wireless Power Transfer (WPT)

### 2.2.1 Near- and Far-Field Techniques

### 2.2.2 Modules and Coupling Effect

#### 2.2.2.1 Block Diagram

#### 2.2.2.2 Blockwise Coupling

### 2.2.3 Non-Linear Harvester Behavior

#### 2.2.3.1 Rectifier Circuits

#### 2.2.3.2 Operation Regions and Signal Models

#### 2.2.3.3 Impact on Waveform Selection

## 2.3 Simultaneous Wireless Information and Power Transfer (SWIPT)

### 2.3.1 Rate-Energy (R-E) Tradeoff

### 2.3.2 Receiver Architectures

## 2.4 Backscatter Communication (BackCom)

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