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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 $= \sqrt{-1}$
π	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
$\mathcal{CN}(\mathbf{0}, \mathbf{\Sigma})$	Multivariate Circularly Symmetric Complex Gaussian with covariance $\mathbf{\Sigma}$

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 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 [2]. By 2025, global mobile data traffic is expected to reach 607 exabytes per year [3] while the number of connected devices may exceed 75 billion [4]. At the same time, wireless applications are also evolving in various forms to address world-changing incidents like COVID-19, climate change, geopolitical tensions, 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 [5]. 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 [6–8]:

- *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 over 90% in 6G to reduce carbon footprints.
- *Positioning accuracy:* Thanks to THz base stations, a 3D positioning accuracy of centimeter level may be achieved for indoor and outdoor environments.
- *Coverage:* Poor coverage has been another bottleneck for 5G. A terrestrial-satellite-aerial integrated network would 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.

Beyond the statistical requirements above, the next-generation wireless network is desired to integrate human, machine, environment, and AI seamlessly for a harmonic ecosphere. This paradigm shift from *connectivity* to *intelligence* is fueled by the latest advances in machine learning (theory) and programmable metamaterials (hardware). The former enables the network to understand the environment while the latter evolves the environment from a chaotic medium to a conscious agent that can serve on demand. Together, they form a symbiotic relationship with the potential to revolutionize how the world energize, sense, communicate, and interact.

One promising candidate within this 6G vision is Reconfigurable Intelligent Surface (RIS), a programmable metasurface that recycles and redistributes the electromagnetic waves in the air for improved wireless performance. It could be incorporated into the transmitter and receiver for *beamforming*, employed as a free-rider information source for *modulation*, or simply placed in space as a standalone device for *channel shaping*. These applications have distinctive requirements and trade-offs, but the operation principles are the same and those roles are not mutually exclusive. Imagine a future where everything can be "smartened" by coating with a metamaterial layer and attaching a microcontroller tag. Only a few active radiating sources (like the sun) are needed, while most objects (like the universe) can exploit the surrounding waves to energize themselves, sense the environment, communicate with others, and help those in need when idle. This vision motivates three research questions to be addressed in this thesis:

- *How does RIS impact different wireless applications such as communication and far-field power transfer?*
- *Is it possible to integrate RIS with Backscatter Communication (BackCom) into a versatile tool that blurs the boundary between the network and environment?*
- *What is the ultimate limit of channel reshaping through passive RIS and what are the implications on transceiver designs?*

Before delving into these questions, we first provide a short overview of RIS and introduce some potential applications. A detailed literature review and technical discussion on RIS and other topics will be reserved for Chapter 2.

1.2 Overview on Reconfigurable Intelligent Surface (RIS)

1.2.1 Concept

RIS is commonly known as a planar surface involving numerous wave scattering elements (a.k.a. unit cells, reflective patches), whose amplitude and phase responses can be engineered in real-time to achieve a desired radiation pattern. It behaves like a delicate Radio-Frequency (RF) mirror with adjustable curvature and orientation, which allows the incident signals to be focused and redirected in a particular direction. As shown in Fig. 1.1, its typical architecture consists of three stacked layers and a controller [1]. The top layer is a two-dimensional array of scattering elements printed on a dielectric substrate. The elements directly interact with the impinging waves, which are usually fabricated from metamaterial or patch/dipole antennas with sub-wavelength dimension and spacing. The middle layer is a copper ground plate that provides voltage reference and avoids signal leakage. The bottom later is a circuit board that associate each element with adjustable components, such as varactor and Positive Intrinsic Negative (PIN) diodes [9]. It also hosts a Field-Programmable Gate Array (FPGA) controller that controls the circuit and coordinate with transceivers in the network. By adjusting the scatter response of all elements, the RIS can effectively manipulate the wavefront for a constructive or destructive superposition and thus improve the ambient wireless environment.

1.2.2 Characteristics

The key characteristics of RIS are summarized as follows:

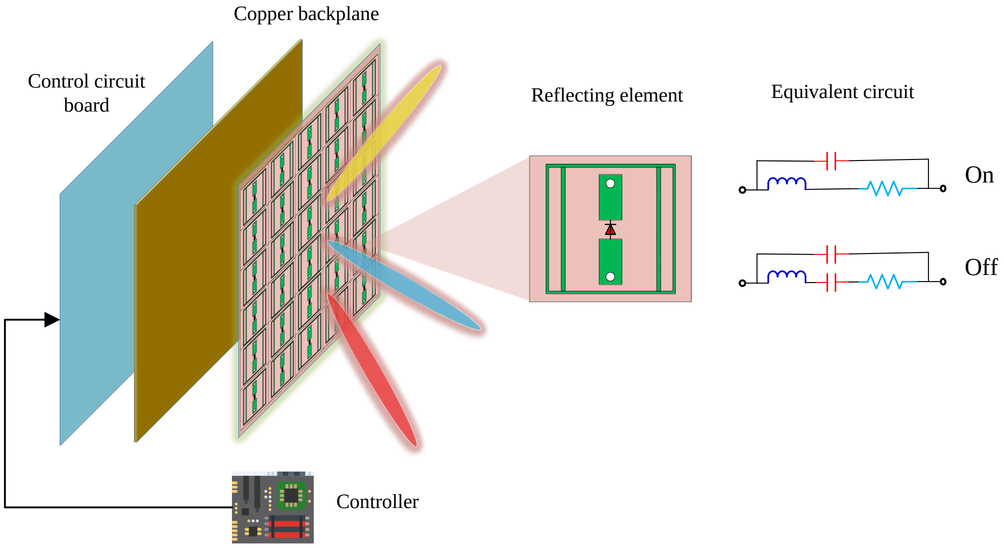


Fig. 1.1 A typical architecture of RIS. Modified from [1].

- *Passive and environmental-friendly:* RIS reflects the incident waves in a passive manner and does not require dedicated RF chains.[1] This is different from Amplify-and-Forward (AF) relays that require power-hungry oscillators and introduces additional thermal noise.

- *Flexible:* It provides a software configurable environment that can be adapted for different applications and scenarios. This is different from conventional reflectarray [10] and frequency selective surfaces [11] with predefined radiation patterns and frequency response.

- *Full-duplex and universal:* This physical-layer solution can simultaneously support communication, sensing, and power transfer without self-interference. Thanks to channel reciprocity, the optimal configuration for downlink and uplink coincide with each other [12]. This is different from Decode-and-Forward (DF) relays that are designed for a specific communication link and suffers from packet delays.

- *Low-cost and conformal:* It can be manufactured from low-cost materials and deployed in various forms (e.g., walls, windows, ceilings, tables) to provide seamless coverage and powerful customization for indoor and outdoor environments. This is different from conventional multi-antenna systems that features complex hardware and bulky structures.

[1]The controller may be implemented with low-power components and powered by ambient energy.

1.2.3 Applications

The channel manipulation capability of RIS unlocks a wide range of unprecedented applications, such as signal enhancement [13], interference suppression [14], blockage bypassing [15], coverage extension [16], and security control [17]. It also has the potential to convey additional information [18], compensate for the Doppler effect [19], transform frequency-selective channels into frequency-flat [20], improve the spatial diversity for multi-antenna systems [21], and create artificial time diversity for multi-user orthogonal [22] and non-orthogonal [23] multiple accesses.

Those fancy characteristics and applications of RIS have also attracted significant attention from the industry. The first public testing attempt was made in 2018 by NTT Docomo and Metawave, which demonstrated a metasurface reflectarray in the FR2 band of 5G can boost a downlink data rate from $60\,\mathrm{Mbps}$ to $560\,\mathrm{Mbps}$ [24]. Later in 2020, NTT Docomo developed a transparent dynamic RIS that can allows 28GHz signals to reflect or pass through with negligible power loss. A regional "RIS alliance" was formed in 2021 by Chinese companies and institutes including ZTE, China Mobile, and CAICT, which soon released a white paper [25] to promote the technology and standardization. In December 2022, ITU-R drafted a recommendation report for IMT-2030 (6G) [26] that marks RIS as a key technology to enhance the radio interface for multiple physical dimension transmission. These developments showcase the rapid progress of RIS from theoretical concept to practical implementation, paving the way for its integration into the next-generation network.

1.3 Outline and Contributions

The thesis is outlined as follows:

- Chapter 1 provides an overview of the thesis. It introduces the motivation and objectives, discusses the characteristics and applications of RIS, and summarizes the topics 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 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), 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)

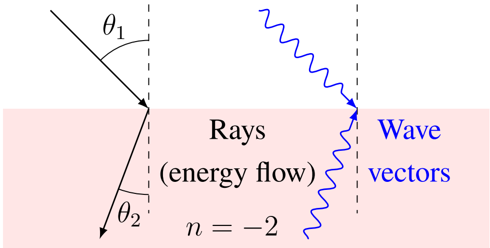
2.1.1 Programmable Metamaterials

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 $\mu < 0$ [31]. 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 [32]. Since then, metamaterials have attracted significant interests due to their counterintuitive properties, to name a few:

- *Negative refraction:* As shown in Fig. 2.1a, the incident and refracted rays stay at the same side of the normal axis [31]. This phenomenon is in contrast to the usual refraction but can still be predicted from Snell's law

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

  It is worth mentioning that a generalized law of refraction and refraction has been proposed in [33], which has become a standard reference for the design and analysis of metamaterials.



(a) Negative-Index Material

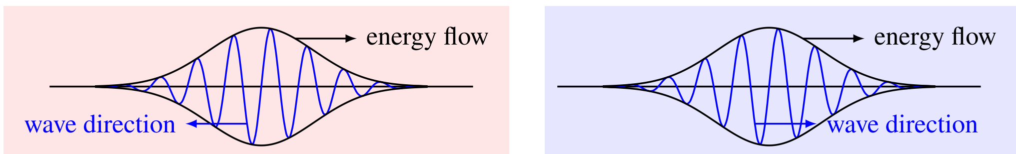
(b) Positive-Index Material

Fig. 2.1 Refraction in negative and positive-index materials. Incident and refracted rays stay at the same side of the normal axis in a negative-index material.

- *Opposite wave direction:* As shown in Fig. 2.2a, the wave vector and energy flow (indicated by the Poynting vector) are opposite to each other in a negative-index material [34]. 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 electric field and wavenumber reference, z is the propagation distance, ω 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.



(a) Negative-Index Material

(b) Positive-Index Material

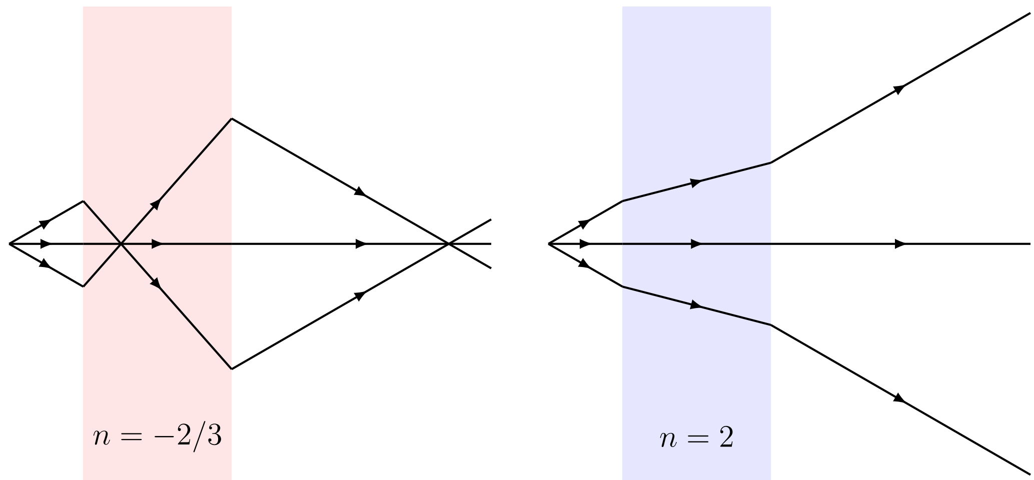
Fig. 2.2 Wave and energy have opposite directions in a negative-index material.

Conventional metamaterials have fixed properties that depend on the geometry and arrangement of their constituent elements. Once fabricated, these properties cannot be easily changed unless the structure is physically altered. This limits their early usage to military and defense, with applications such as invisibility cloaks and optical illusions. In 2014, the concept of "coding" and "programmable" metamaterials was validated by researchers at Southeast University [35], who realized digital control of radar cross-section using biased diodes and FPGA. With a proper model of the target properties and external citation, the metamaterial can be reconfigured in real-time for desired behaviors. For example, a self-adaptive metasurface equipped with motion and light sensors have been developed in [36] for single- and multi-beam steering.

Next, we discuss the principles of electromagnetic wave redirection via refraction and reflection:

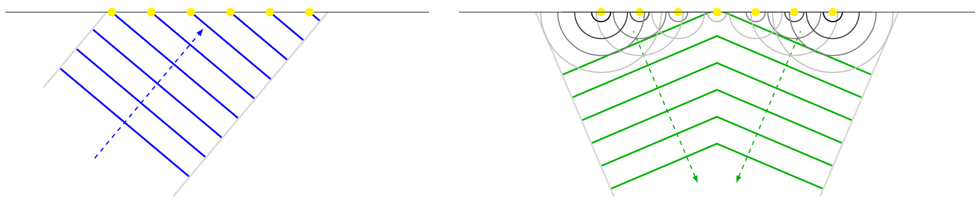
- *Refraction:* As shown in Fig. 2.3a, the negative-index material can re-focus the beams diverging from a point source to another point behind the material [37]. This could be helpful for wireless applications where the transmitter and receiver are at different sides of the material.

- *Reflection:* As shown in Fig. 2.4b, the scattering elements cooperatively alter the phase of the incident wave for a constructive (or destructive) superposition of the reflected waves in the target direction [38]. This could be helpful for wireless applications where the transmitter and receiver are at the same side of the material.



(a) Negative-Index Material (b) Positive-Index Material

Fig. 2.3 Refraction through metamaterials. For negative-index material, beams diverging from a point source is set in reverse and converges back to another point.



(a) Incident Wave (b) Reflected Wave

Fig. 2.4 Reflection through metamaterials. Yellow dots represent scattering elements. Solid and dashed lines denote wavefronts and rays, respectively. The scattering elements work together to manipulate the phases of incident waves, resulting in a focused beam steered in the intended direction.

It is worth noticing that refraction and reflection can be regarded as different forms of *passive beamforming* where the phase and amplitude of the ambient signal are altered by the metamaterial for a desired net effect. In the next subsection, we will some typical RIS scattering models and their assumptions.

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

2.2 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)

2.4.1 Monostatic Backscatter Communication (MBC)

2.4.2 Bistatic Backscatter Communication (BBC)

2.4.3 Ambient Backscatter Communication (AmBC)

2.4.4 Symbiotic Radio (SR)

2.5 Multiple-Input Multiple-Output (MIMO)

2.5.1 Point-to-point Channel (PC): Channel Shaping

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