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Reconfigurable Intelligent Surfaces:
Beamforming, Modulation, and Channel Shaping

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This dissertation is submitted for the degree of
Doctor of Philosophy

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
AM	Arithmetic Mean
AmBC	Ambient Backscatter Communication
AO	Alternating Optimization
AP	Access Point
AWGN	Additive White Gaussian Noise
BackCom	Backscatter Communication
BBC	Bistatic BackCom
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 (CSI) 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
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
IoE	Internet of Everything
IoT	Internet of Things
KKT	Karush-Kuhn-Tucker
LoS	Line-of-Sight
M2M	Machine-to-Machine
MAC	Multiple Access Channel
MBC	Monostatic BackCom
MC	Multiplication Coding
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
ML	Maximum-Likelihood
MMSE	Minimum Mean-Square-Error
MRC	Maximal Ratio Combining
MRT	Maximum Ratio Transmission
MSE	Mean-Square Error

NLoS   Non-Line-of-Sight (LoS)
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 (RF) 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
WF	Water-Filling
WIT	Wireless Information Transfer
WPCN	Wireless Powered Communication Network
WPT	Wireless Power Transfer
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 functio $\max(0, \cdot)$
$\lvert \cdot \rvert$	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

$\mathcal{CN}(\mathbf{0}, \Sigma)$ Multivariate Circularly Symmetric Complex Gaussian with covariance Σ

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

Getting started

1.1 Introduction

1.1.1 Simultaneous Wireless Information and Power Transfer

With the great advance in communication performance, a bottleneck of wireless networks has come to energy supply. Simultaneous Wireless Information and Power Transfer (SWIPT) is a promising solution to connect and power mobile devices via RF waves. It provides low power at µW level but broad coverage up to hundreds of meters in a sustainable and controllable manner, bringing more opportunities to the Internet of Things (IoT) and Machine to Machine (M2M) networks. The upsurge in wireless devices, together with the decrease of electronics power consumption, calls for a re-thinking of future wireless networks based on Wireless Power Transfer (WPT) and SWIPT [1].

$$\Theta_g^{(r+1)} = \mathbf{G}_g^{(r)}(\mu^\star). \tag{1.1}$$

1.2 Why do we use loren ipsum?

It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

1.3 Where does it come from?

Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, consectetur, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham

"Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

Section 1.10.32 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo. Nemo enim ipsam voluptatem quia voluptas sit aspernatur aut odit aut fugit, sed quia consequuntur magni dolores eos qui ratione voluptatem sequi nesciunt. Neque porro quisquam est, qui dolorem ipsum quia dolor sit amet, consectetur, adipisci velit, sed quia non numquam eius modi tempora incidunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim ad minima veniam, quis nostrum exercitationem ullam corporis suscipit laboriosam, nisi ut aliquid ex ea commodi consequatur? Quis autem vel eum iure reprehenderit qui in ea voluptate velit esse quam nihil molestiae consequatur, vel illum qui dolorem eum fugiat quo voluptas nulla pariatur?"

1914 translation by H. Rackham: "But I must explain to you how all this mistaken idea of denouncing pleasure and praising pain was born and I will give you a complete account of the system, and expound the actual teachings of the great explorer of the truth, the master-builder of human happiness. No one rejects, dislikes, or avoids pleasure itself, because it is pleasure, but because those who do not know how to pursue pleasure rationally encounter consequences

that are extremely painful. Nor again is there anyone who loves or pursues or desires to obtain pain of itself, because it is pain, but because occasionally circumstances occur in which toil and pain can procure him some great pleasure. To take a trivial example, which of us ever undertakes laborious physical exercise, except to obtain some advantage from it? But who has any right to find fault with a man who chooses to enjoy a pleasure that has no annoying consequences, or one who avoids a pain that produces no resultant pleasure?"

Section 1.10.33 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "At vero eos et accusamus et iusto odio dignissimos ducimus qui blanditiis praesentium voluptatum deleniti atque corrupti quos dolores et quas molestias excepturi sint occaecati cupiditate non provident, similique sunt in culpa qui officia deserunt mollitia animi, id est laborum et dolorum fuga. Et harum quidem rerum facilis est et expedita distinctio. Nam libero tempore, cum soluta nobis est eligendi optio cumque nihil impedit quo minus id quod maxime placeat facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum hic tenetur a sapiente delectus, ut aut reiciendis voluptatibus maiores alias consequatur aut perferendis doloribus asperiores repellat."

1914 translation by H. Rackham: "On the other hand, we denounce with righteous indignation and dislike men who are so beguiled and demoralized by the charms of pleasure of the moment, so blinded by desire, that they cannot foresee the pain and trouble that are bound to ensue; and equal blame belongs to those who fail in their duty through weakness of will, which is the same as saying through shrinking from toil and pain. These cases are perfectly simple and easy to distinguish. In a free hour, when our power of choice is untrammelled and when nothing prevents our being able to do what we like best, every pleasure is to be welcomed and every pain avoided. But in certain circumstances and owing to the claims of duty or the obligations of business it will frequently occur that pleasures have to be repudiated and annoyances accepted. The wise man therefore always holds in these matters to this principle of selection: he rejects pleasures to secure other greater pleasures, or else he endures pains to avoid worse pains."

References

[1] B. Clerckx, R. Zhang, R. Schober, D. W. K. Ng, D. I. Kim, and H. V. Poor, "Fundamentals of wireless information and power transfer: From RF energy harvester models to signal and system designs," *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 1, pp. 4–33, Jan. 2019.