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Introduction

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The roadmap to beyond the fifth-generation (B5G) wireless networks is envisaged to introduce a new spectrum of fully automated and intelligent data-driven services, such as flying vehicles, haptics, telemedicine, augmented and virtual reality, holographic telepresence, and connected autonomous artificial intelligence (AI) systems [1, 2]. Several unprecedented application environments, including machine-to-people and machine-to-machine communications, are expected to be the driving force of B5G systems. As a result, the number of connected Internet-of-Everything (IoE) devices (e.g. sensors, wearables, implantables, tablets) is anticipated to witness a phenomenal growth in the next few years, reaching up to tens of billions [3]. This poses a fundamental challenge on provisioning a ubiquitous seamless connectivity, while concurrently prolonging the lifetime of a massive number of energy-constrained low-power, low-cost devices.

The unprecedented increase of connected devices resulting from the emergence of IoE has created a major challenge for broadband wireless networks, requiring a paradigm shift towards the development of key enabling technologies for the next generation of wireless networks. Fifth-generation (5G) wireless networks have been identified as the backbone of emerging IoE services and prominently support three use cases: enhanced mobile broadband, ultra-reliable and low-latency communications, and massive machine-type communications. These services are rate- and data-oriented, heterogeneous in nature and defined by a diverse set of key

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performance indicators. Therefore, enabling them through a single platform while concurrently meeting their stringent requirements in terms of data rate, reliability, and latency is a challenging task [3].

To address these challenges at the physical layer, 5G wireless systems have leveraged the evolution of cutting-edge technologies, including millimetre wave (mmWave) and terahertz (THz) communications. Although mmWave and THz are highly promising in offering unparalleled data rates and significantly reducing the required device size, their present use is limited due to signal degradation at these extremely high-communication frequency bands. Moreover, wireless links suffer from attenuation incurred by high propagation loss, high penetration loss, multipath fading, molecular absorption, and Doppler shift [4]. With the lack of full control over the propagation and scattering of electromagnetic (EM) waves, the wireless environment remains unaware of the time-variant communication, posing fundamental limitations towards building truly pervasive software-defined wireless networks [5].

Motivated by this, reconfigurable meta-surfaces, also known as Intelligent Reconfigurable Surfaces (IRS), have emerged as a low-complexity and energy-efficient solution that aims at turning the wireless environment into a software-defined entity. Reconfigurable meta-surfaces are envisaged to be indispensable in future sixth-generation (6G) wireless systems due to their potential in realizing massive multiple-input multiple-output (MIMO) gains while attaining a notable reduction in energy consumption. The unique design principle of reconfigurable meta-surfaces lies in realizing artificial structures with massive antenna arrays whose interaction with impinging EM waves can be intentionally controlled through connected passive elements, such as phase shifters, in a way that enhances wireless systems' performance in terms of coverage, rate, and so on, giving rise to the concept of smart radio environments (SREs) [6].

IRS have been deemed as a key contributor in putting down the fundamentals of future 6G networks, and therefore, have attracted a considerable attention from the industrial and academic communities. Therefore, this book will equip the reader with the fundamental knowledge of the operational principles of reconfigurable meta-surfaces, resulting in its potential applications in various intelligent, autonomous future wireless communication technologies. The opportunities opened by IRS have spurred, in a short span of time, research in many areas related to wireless communication systems. This includes multi-user resource allocation, beamforming optimization, design of efficient enabling mechanisms, and performance analysis of IRS-assisted wireless networks.

The aim of this book is to offer the readers the opportunity to explore and comprehend the field of IRS from different angles, including the underlying physics, hardware architecture, operating principles, as well as prototype designs. The book will allow the readers to grasp the knowledge of the interplay of IRS and top-notch technologies, accompanied by the evolution of 6G networks, with comprehensively studying the advantages, key principles, challenges, and potential use-cases.

This book is aimed to be a solid foundation for the theoretical investigation and practical implementation of IRS-enabled wireless networks. The book is envisioned to be a concrete reference for students, researchers, university professors, and industrial people working in the field of intelligent surfaces, in which they can exploit it to identify open research problems, and hence steer their research and industrial activities in those directions. With the diverse aspects studied in our book, we look forward to facilitating a smooth comprehension of the preliminary concepts, as well as providing solid answers to more advanced critical concerns raised in the field of IRS.

Chapter 2 discusses the fundamental principles of IRS-aided communications and provides an analysis on the near-field region, wherein the channel modelling and phase shift design problems differ from those in the far-field. Specifically, the chapter highlights the impact of beamfocusing in manipulating the emitted EM waves to achieve desired signal propagation. This chapter also investigates IRS-aided MIMO communications and the relationship between the number of reflecting elements and the achieved energy efficiency gains.

In Chapter 3, the potential of deploying IRSs in merging non-terrestrial networks (NTNs) is explored. This is linked with discussions related to 3GPP standardization guidelines in the context of the various operational aspects, architecture types, and connectivity mechanisms in NTN. Additionally, this chapter highlights how IRSs can be integrated in NTN to enable a typical mobile handset to directly communicate with satellites.

Chapter 4 introduces a new concept called the Internet of MetaMaterial Things (IoMMT), where artificial materials with real-time tunable physical properties can be interconnected to form a network to realize communication through software-controlled EM, acoustic, and mechanical energy waves. After exploring the means for abstracting the complex physics behind these materials, their integration into the IoT world is discussed. The chapter presents two novel software categories for the material things, namely the meta-material Application Programming Interface and Meta-material Middleware, which will be in charge of the application and physical domain.

Chapter 5 overviews the general hardware architecture of IRS that opened a new platform to dynamically manipulate EM waves. This includes describing the design of an IRS structure based on different categorizations. The available IRS modes of operation will be discussed in deployments relevant to wireless communication systems. The chapter also discusses the hardware aspects and features related to the IRS's main operational principles: reconfigurability, interconnection, computing, networking, programmability, and sensing. This chapter reviews the state-of-the-art on advancements in IRS prototype designs for wavefront manipulation and information modulation.

In Chapter 6, the authors discusses practical design considerations for IRS. Specifically, the tunability of the IRS unit-cell elements will be explained. Also, the biasing network of an IRS, which provides a means of control over the individual unit cell reflection characteristics, will be detailed. The chapter will provide a comprehensive treatment on the physical limitations of the IRSs including the trade-off between the bandwidth and phase resolution, the incidence angle response, and the quantization effects.

Chapter 7 explores channel modelling frameworks for facilitating a thorough and accurate evaluation of the system performance of IRS-aided communications operating in the mmWave and sub-6 GHz bands. Specifically, the chapter discusses the channel side limitations of the IRS and sheds light on the important role the channel plays in the IRS implementation. The chapter focuses on discussing small-scale fading and path loss model of IRS-enabled wireless networks, for different scenarios, including far-field and near-field scenarios. Finally, the chapter introduces the open-source, user-friendly, and widely applicable SimRIS Channel Simulator v2.0.

Chapter 8 develops an iterative optimization framework to maximize the data rate of a given user by jointly optimizing the user service mode selection along with phase shifts of the nearest IRS of IRS-assisted users in a large-scale multi-user, multi-base station, multi-IRS network. This chapter presents semi-definite programming (SDP)-based iterative approach for phase optimization, whereas a heuristic approach for mode selection is adopted. In addition, a deep reinforcement learning (DRL) framework is presented with proximal policy optimization (PPO) and double deep policy gradient (DDPG) based solutions to optimize phase shifts.

Chapter 9 investigates the significant role that IRS will play in B5G and 6G wireless networks. Precisely, the chapter discusses the potential of IRS in supporting IRS-assisted multi-user communication, IRS-assisted RF sensing and imaging, IRS-assisted unmanned aerial vehicle (UAV) communication, IRS-assisted wireless power transfer, and IRS-assisted indoor localization. In this context, the authors examine their performance and highlight major performance limiting factors, which open the door for future research directions.

In Chapter 10, the authors study the channel modelling and characterization for multi-IRS-assisted wireless systems. For a distributed multi-IRS (DMI)-assisted system, in which the IRSs have different geometric sizes and are distributively deployed to aid wireless communications, the authors propose a mathematical framework based on the moment-matching method to determine the statistical characterization of the end-to-end (e2e) channel fading of the DMI system. The obtained approximate distributions are employed to derive tight approximate closed-form expressions of the outage probability (OP) and ergodic capacity (EC) of the DMI system.

Chapter 11 presents the fundamental characteristics of the UAVs, major paradigms for integrating the UAVs into the wireless networks, and their possible applications, as well as addressing open problems and challenges in the UAV communications. The chapter sheds light on the possible IRS-assisted UAV systems scenarios. Furthermore, this chapter investigates the performance analysis of the IRS-assisted UAV systems.

Chapter 12 sets the scene for the integration of IRS with optical wireless communication (OWC), as a promising candidate to support blockage-free, and therefore, extended coverage communication. The chapter sheds light on the advantages accomplished by leveraging various RIS functionalities in OWC networks, from a transceiver, as well as propagation environment perspectives. The authors present a case study for an IRS-assisted indoor LiFi system and examine the performance of the considered scenario. The chapter finally highlights some of the challenges and open research directions related to the integration of IRS in OWC.

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