1 Introduction

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Evolving across the previous four generations, wireless cellular technology has transformed the way people communicate and acquire information. This transformation has taken place gradually since the 1990s to the first decade of the twenty-first century, with the first and second generation of cellular systems supporting mobile voice transmission, and the third and fourth generation enabling mobile internet access.

With its fourth generation (4G), wireless cellular technology has arguably completed an arc that was started by the work of Claude Shannon at the Bell Labs in the 1940s. In his seminal 1948 paper, Shannon derived a theoretical upper bound on the amount of information that can be conveyed on a communication link between two endpoints. His achievability proof was famously non-constructive, and hence it left open the problem of engineering efficient systems for the encoding and decoding of information at transmitter and receiver, respectively. The problem was essentially solved by the discovery of turbo and low-density parity check (LDPC) codes and corresponding decoders, all of which are included in the 4G standard.

As suggested by the discussion above, the path followed by the first four generations of cellular technology was one inspired by the goal of reaching the Shannon limit for communication over point-to-point links. In the process, communication engineers strived, and eventually succeeded, to design practical solutions that matched the theoretical results developed by Shannon. In contrast, the next generations of wireless systems, starting with the fifth (5G), face a new design landscape that lacks the strong theoretical guiding principles of Shannon's analysis of point-to-point communications.

In fact, 5G systems aim at providing not only an enhanced version of the 4G broadband communication service, known as enhanced mobile broadband (eMBB), but also new services that operate in the novel regimes of ultra-reliable, low-latency, and massive-access communications. Specifically, the 3rd Generation Partnership Project (3GPP), a collaboration between groups of telecommunications standards associations, has identified, beside eMBB, the services of ultra-reliable low-latency communications (URLLC) and massive machine-type communication (mMTC). The former is meant to support applications that require high reliability and low delays, such as for industrial control tasks or autonomous driving, while the latter enables the connectivity from a massive number of Internet of Things (IoT) devices.

The lack of a strong theoretical framework for the design of wireless systems in the novel regimes calls for a renewed effort by information theorists to extend the scope of Shannon's theory. With the evolution from 4G to 5G, the main design question has in fact shifted from one concerning “how to do” – namely, how to reach the optimal point-to-point performance promised by Shannon – to “what to do,” as effective coding schemes and protocols for the new requirements are unknown. The latter is indeed the central question tackled by information theory through a mathematical lens. Despite its theoretical focus, information theory has proved to be able to offer valuable design insights, even when, as it is often the case in network scenarios, optimal solutions remain elusive the exact information theoretic characterizations, in terms of capacity regions of most relevant network problems for cellular communications, such as the Broadcast, Interference and Relay channels remain unsolved for decades. Yet the theoretical insights on network information theory, gained through the years, carry basic and important practical implications [1].

Broadly speaking, the development of an information theory for 5G requires a shift of focus from point-to-point channels with long transmission blocks to networks of devices with delay and reliability constraints. It is the goal of this book to offer an updated picture of the state of the art on information theoretic results that are relevant for the design of the next generations of wireless systems.

We organize the discussion around three main areas: network architecture, coding and modulation, and protocols. As will be seen in the text, the network architecture of 5G systems and beyond includes new elements that pose novel theoretical challenges, such as device-to-device links; high-speed backhaul links that support a decentralized and heterogeneous infrastructure; caches at the base stations that store popular content; and fronthaul links that allow for the centralization of baseband processing in cloud and fog-based architectures. Furthermore, the design of coding and modulation schemes needs to be revisited in order to account for novel aspects such as massive antenna arrays at the base stations; short-transmission blocks; non-orthogonal and uncoordinated multiple access; and asynchronous transmissions. Finally, communication protocols can benefit from an integration with breakthrough techniques inspired by information theory at the lower layers of the protocol stack, such as interference alignment; cooperative cellular transmission; physical-layer secrecy; and cognitive transmission.

The excitement and importance of 5G developments is attested by the extensive literature on the topic. Several books describe 5G architecture and envisioned use cases, and provide an overview of various techniques that will be deployed in 5G system [2–11]. Described techniques include multiple-access, device-to-device communications, spectrum sharing, mm-wave communications, Massive MIMO (multiple-input, multiple-output), interference management and relaying, among others.

Several books and monographs address 5G-related topics from the information-theoretic view, including Massive MIMO [12], interference alignment [13], security [14], cooperative cellular systems [15], and cloud radio access networks (C-RAN) [16–18]. These books highlight the impact information theory had and is yet to have on 5G and systems that will follow beyond.

Numerous research papers analyze in detail important 5G technologies and approaches, including multiple access [19, 20], modulation and waveforms [21], Massive MIMO [22], mm-wave [23], decentralized processing [24], heterogeneous networks

[25–27], C-RAN [28, 29], cooperation [30], cognitive cooperation [31, 32], polar coding [33], code design for short packets [34], nonorthogonal multiple access (NOMA) [35], caching [36], network coding [37], physical layer security [38], scheduling [39], mMTC [40], and implementation aspects [41]. Many surveys of 5G communications exist [42–60]. Overviews of 5G technologies can be found in the literature [61–67].

While several topics covered in this book appear also in many other references and books (e.g., [3, 4, 12]), the focus of this book is on the information theoretic framework and theoretical foundations that will make 5G and future wireless systems possible. The approach taken in this book is grounded in the discussed premise that information theory has played, and will play, a central role in developing wireless systems. The book starts with a detailed introductory chapter on network information theory that provides the background and the foundation for later chapters. The chapter covers first the point-to-point communications channel and its capacity. It then presents the main building blocks of communication networks, namely multiple access, broadcast, interference and relay channels, as well as coding schemes developed for each of these channels. Following the discussion above, the rest of the book is divided into three parts. The first part focuses on network architecture, and covers topics of device-to-device communications, caching, backhaul and fronthaul design, and energy harvesting. The second part covers coding and modulations schemes, including polar coding, Massive MIMO, short-packet transmission, NOMA, compute-forward strategies and waveform design. Finally, the third part presents protocols, and it encompasses chapters on 5G protocols, interference management, content delivery, and cooperative, cognitive, and confidential communications.

The first chapter in Part I covers device-to-device communications (D2D) that allow users in close proximity to establish direct communication with each other. In order to understand the fundamental limits of D2D critical for developing practical D2D strategies, this chapter analyzes the spectral efficiency of D2D communication, while relying on a novel modeling approach for the interference.

Chapter 4 describes backhaul architectures for small cells, in which backhaul is the main bottleneck. The chapter presents approaches in which access nodes not only deliver service to end-users but also act as relays carrying traffic to/from other access nodes, thereby establishing a multihop wireless connection for backhaul traffic.

Chapter 5 presents content caching, a promising direction to substantially improve the capacity of wireless networks by exploiting memories across the network.

Chapter 6 presents an information theoretic analysis of C-RAN, as well as of an extension that includes caches at the edge nodes of the network, also known as Fog-RAN (F-RAN), in the presence of capacity-limited fronthaul links.

The last chapter in the network architecture part of the book is concerned with the design of communication systems that contain wireless devices capable of harvesting energy they need for communication from the natural resources in the environment.

Part II of the book starts with a chapter on polar coding, presenting its general overview, capacity, and practical considerations.

The following chapter presents the most important forms of Massive MIMO and then discusses possible new directions for the physical layer that may go beyond Massive MIMO.

Chapter 10 reviews the most recent advances in finite-blocklength information theory. It provides theoretical principles governing the transmission of short packets, which are expected to be present in large volumes in machine-type communications.

A novel multiple-access technique, NOMA, that uses the power domain for achieving multiple access is presented in Chapter 11 in this part of the book.

Chapter 12 presents a novel way of treating interference in a communications strategy called compute-forward. In compute-forward, instead of treating interference as noise or decoding and canceling it, a receiver decodes a linear combination of simultaneously transmitted codewords, thereby improving the performance.

Chapter 13 provides a review of some of the most compelling waveforms for 5G networks. By employing a general signal-processing framework coupled with an information theoretic approach, the spectral efficiency of different techniques is compared.

Part III of the book starts with a chapter that discusses how to bridge the gap between information theory and protocol design.

Interference is one of the key obstacles in achieving higher spectral efficiency in wireless networks. Chapter 15 describes the most important interference management techniques.

Chapter 16 presents an overview of advanced cooperative communication techniques. and the benefits they attain over standard non-cooperative techniques.

Chapter 17 covers recent advances around the design of algorithms and protocols for the end-to-end optimization of real-time computation services over cloud-integrated 5G networks.

Chapter 18 presents physical layer security and, based on information theoretic ideas, characterizes the ability of the physical channel to achieve secure communication.

Chapter 19 analyzes settings in which transmitting and/or receiving nodes have acquired information about other users and/or interference in the network. As presented in this chapter, such knowledge allows for cooperation and interference mitigation, thereby improving spectral efficiency.

While work on 5G is still ongoing at the time of the writing, researchers have already started to consider technologies that may power the next generation of cellular systems (see, e.g., [75]–[79], [86]). Among the most promising directions for research, we mention here terahertz communication [80], reconfigurable intelligent surfaces [81], super-directive Massive MIMO [82, 83], and the application of artificial intelligence (AI) techniques for network management and operation [84, 85]. Information theory will play an essential role in understanding the fundamental benefits and limitations of all these technologies [87, 88]. Furthermore, as a complement to the analytical approach and fundamental insights obtained by means of information theory, recent activity has advocated the use of data-driven methods in order to overcome modeling or algorithmic deficits of existing solutions. Several important connections between Information Theory and Data Science are explored in detail in [89]. Deep learning is increasingly finding its application in wireless networks, including areas of mobile data analysis, signal processing, network security [67], data analytics in IoT [69], and big data [70]. We refer to [71–74] for further discussion on this expanding line of work.

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