ADVANCED WIRELESS COMMUNICATION SYSTEMS

A COMPREHENSIVE GUIDE

Editors:
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Advanced Wireless Communication Systems: A Comprehensive Guide

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FOREWORD

The rapid evolution of wireless communication has transformed the landscape of technology, creating a world where connectivity is ubiquitous, instantaneous, and essential. From the humble beginnings of radio transmissions to the sophisticated 5G networks and beyond, the field of wireless communication has undergone profound changes, enabling new possibilities and driving innovation across various industries. As we stand on the threshold of the 6G era, the importance of a comprehensive understanding of these technologies cannot be overstated.

This book, Advanced Wireless Communication Systems: A Comprehensive Guide, comes at a pivotal time in the history of wireless communication. It offers a thorough exploration of the key concepts, technologies, and trends that are shaping the future of this dynamic field. The authors have meticulously crafted each chapter to provide readers with both foundational knowledge and advanced insights, making this book an indispensable resource for students, researchers, engineers, and professionals alike.

The content of this book is organized to take readers on a journey through the evolution of wireless communication, starting with an in-depth look at the historical development and the technological milestones that have defined this field. From there, the book delves into the current challenges and trends, offering a nuanced perspective on the complexities of spectrum management, energy efficiency, security, and the integration of emerging technologies.

One of the standout features of this book is its comprehensive coverage of regulations and standards, which are critical for the global harmonization and interoperability of wireless systems. The chapters on channel modeling, and wireless networks provide a solid technical foundation, while the sections on advanced wireless communication systems offer a glimpse into the future of high-speed, low-latency connectivity.

Security and privacy, two of the most pressing concerns in today's wireless networks, are addressed in detail, providing readers with the knowledge to safeguard their systems against evolving threats. The book also explores future trends, including massive MIMO, millimeter-wave communications, and cognitive radio, ensuring that readers are well-prepared for the next wave of innovation.

The inclusion of case studies and practical applications bridges the gap between theory and real-world implementation, demonstrating how these technologies are being applied in smart cities, industrial automation, healthcare, and beyond. The final chapters on machine learning-driven network slicing for 5G and latency optimization for URLLC in 5G NR highlight the cutting-edge research that is driving the next generation of wireless communication.

In an era where wireless communication is central to virtually every aspect of our lives, this book serves as a vital resource for anyone looking to deepen their understanding of this field. I am confident that readers will find this book to be both informative and inspiring as they navigate the challenges and opportunities of advanced wireless communication systems.

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PREFACE

In recent years, the rapid advancement of wireless communication systems has revolutionized the way we connect, communicate, and interact with the world around us. From the early days of radio transmission to the sophisticated and high-speed 5G networks of today, wireless communication has become an indispensable part of modern society. As we stand on the brink of the 6G era and the proliferation of the Internet of Things (IoT), the need for a comprehensive understanding of these technologies has never been more crucial.

This book, Advanced Wireless Communication Systems: A Comprehensive Guide, is designed to serve as a definitive resource for students, researchers, engineers, and professionals working in the field of wireless communication. It covers a wide range of topics, from fundamental concepts to cutting-edge technologies, providing readers with both theoretical knowledge and practical insights.

The book begins with an exploration of the evolution of wireless communication technologies, tracing their development from the early 20th century to the present day. It then delves into the current challenges and trends that shape the future of wireless communication, including spectrum scarcity, energy efficiency, security, and integration with emerging technologies.

As wireless communication is governed by strict regulations and standards, Chapter 2 offers a detailed overview of international and national regulations, along with the various wireless communication standards that have been developed over the years, including GSM, CDMA2000, WCDMA, LTE, and 5G.

The book also provides a thorough examination of the fundamentals of wireless channel modelling and simulation, which are essential for understanding the behaviour of wireless systems in real-world environments. The topics covered include electromagnetic spectrum, RF propagation, antenna theory, and various channel models.

In the subsequent chapters, readers will find in-depth discussions on wireless networks, advanced wireless communication systems, and the critical issue of security and privacy in wireless communication. The book also explores future trends in the field, such as massive MIMO, Millimeter wave communications, cognitive radio, and the potential of 6G and beyond.

To bridge the gap between theory and practice, the book concludes with case studies and practical applications, illustrating how wireless communication technologies are being applied in smart cities, industrial automation, healthcare, satellite communication, and more.

I hope this book will serve as a valuable guide for those seeking to deepen their understanding of wireless communication systems and contribute to the ongoing evolution of this dynamic field.

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CHAPTER 1

Introduction to Advanced Wireless Communication Systems

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Abstract: This chapter provides a comprehensive overview of the evolution of wireless communication technologies, tracing their development from early radio transmissions to the advanced 5G networks of today. The chapter begins by highlighting the pioneering work of Marconi and Tesla, whose early experiments laid the groundwork for modern wireless communication. It then delves into the advent of cellular networks, starting with the analog First-Generation (1G) systems and progressing to the digital Second-Generation (2G) networks, which introduced enhanced security and mobile data services. The rise of mobile internet with Third-Generation (3G) networks is discussed, emphasizing the role of technologies like UMTS and HSPA in enabling broadband access on mobile devices. The chapter also covers the transformative impact of Fourth-Generation (4G) networks, particularly LTE, which revolutionized mobile data speeds and efficiency, paving the way for widespread use of mobile applications and IoT devices. Finally, the chapter introduces Fifth-Generation (5G) networks, highlighting their potential to deliver ultra-fast data speeds, low latency, and support for emerging technologies like AR, VR, and autonomous systems. The chapter concludes by addressing current challenges in wireless communication, including spectrum scarcity, energy efficiency, security, and the integration of emerging technologies like AI and IoT.

Keywords: 3G/4G evolution, Artificial Intelligence (AI), Cellular networks, Energy efficiency, Internet of Things (IoT), LTE (Long Term Evolution), Millimeter-wave technology, Spectrum management, Spectrum scarcity, Wireless communication.

INTRODUCTION

Wireless communication has seen a remarkable evolution over the past few decades. From the early days of radio transmission to the sophisticated 5G

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networks of today, the journey has been marked by significant technological advancements and groundbreaking innovations [1, 2].

Early Beginnings

The origins of wireless communication trace back to the late 19th and early 20th centuries, marked by the pioneering efforts of Guglielmo Marconi and Nikola Tesla, who demonstrated the possibility of transmitting signals without wires.

The groundwork for wireless communication theory was laid by James Clerk Maxwell in the 1860s through his formulation of the equations of electromagnetism. Maxwell's equations forecasted the presence of electromagnetic waves capable of traveling through space without requiring a physical medium. In the late 1880s, Heinrich Hertz experimentally validated Maxwell's predictions by creating and detecting electromagnetic waves, which eventually became known as radio waves. Hertz's experiments provided the necessary empirical evidence to substantiate the theoretical basis of wireless communication [1, 3].

Guglielmo Marconi is widely recognized for pioneering practical wireless telegraphy. However, prior to Marconi's achievements, Prof. Jagadish Chandra Bose had already demonstrated the wireless transmission of electromagnetic waves over short distances in the late 19th century, using millimeter waves and innovative semiconductor detectors. In 1895, Marconi successfully transmitted signals across several kilometers using basic radio transmitters and receivers. In 1901, he achieved a significant breakthrough by sending the first transatlantic radio signal from Cornwall, England, to Newfoundland, Canada. Marconi's approach involved a spark-gap transmitter that produced a series of damped waves. The receiver utilized a coherer, a device sensitive to radio waves, to detect these signals. Despite its simplicity, this system demonstrated the feasibility of long-distance wireless communication [3].

Nikola Tesla made substantial contributions to advancing wireless communication. During the 1890s, Tesla conducted experiments centered on high-frequency Alternating Current (AC) and the transmission of electrical energy without the need for physical wires. In 1893, he showcased wireless energy transmission at a public lecture in St. Louis, Missouri, employing his Tesla coil—a high-voltage, high-frequency transformer. Tesla envisioned a future where wireless transmission could supply both energy and communication over extensive distances [3].

Early Radio Broadcasting

From the technical development point of view, the 1920s marked the dawn of commercial radio broadcasting. KDKA in Pittsburgh, Pennsylvania, is frequently recognized as the first commercial radio station, beginning regular transmissions in 1920. These pioneering broadcasts featured news, music, and entertainment, captivating a wide audience and showcasing the immense potential of wireless communication as a medium for mass communication [1].

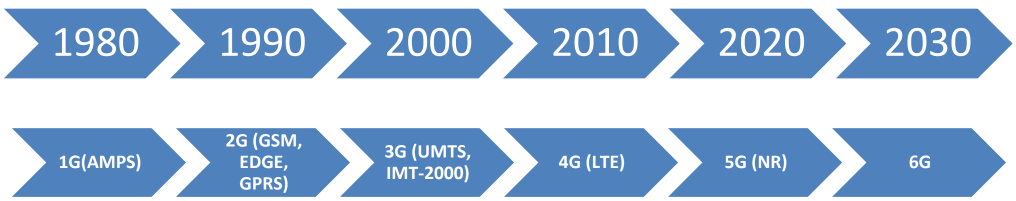

Fig. (1). The evolution of wireless technologies.

Development of Cellular Networks

The development of cellular networks marked a significant turning point in the history of wireless communication. These networks introduced a structured and scalable approach to mobile communication, addressing the limitations of earlier technologies and setting the stage for the mobile revolution. Engineers at Bell Labs introduced the concept of cellular networks in the 1940s. They proposed dividing a geographic area into small cells, each served by a distinct base station. This approach facilitated frequency reuse, allowing multiple users to utilize the same spectrum without causing interference. The cellular network architecture offered a scalable solution to accommodate a growing number of mobile users [1]. Fig. (**1**) shows the timeline that represents the evolution of wireless technology over time.

Fig. (**2**) shows the basic Cellular Network Structure. In Fig. (**3**), the geographic region is segmented into hexagonal cells, each containing its own base station. These cells are linked to a Mobile Switching Center (MSC), which handles communication between cells and connects to the Public Switched Telephone Network (PSTN).

First-Generation (1G) Systems

The First-Generation (1G) cellular systems, introduced in the 1980s, were analog and primarily focused on voice communication. Key examples of first-generation systems include:

CHAPTER 2

Regulations and Standards in Wireless Communication

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Abstract: This chapter explores the regulatory framework governing wireless communication at both international and national levels, emphasizing key regulations and their real-world impact. It examines the role of the International Telecommunication Union (ITU) and World Radiocommunication Conferences (WRC) in global spectrum management, highlighting policies that influence spectrum allocation and interference mitigation. The chapter also presents case studies demonstrating successful regulatory practices across different countries. At the national level, it analyzes the functions of regulatory authorities, spectrum licensing processes, auction mechanisms, and compliance policies, illustrating their effects on network deployment and market dynamics. Additionally, the chapter discusses the evolution of major wireless communication standards—GSM, CDMA2000, WCDMA, LTE, and 5G—focusing on their regulatory frameworks, technical adoption, and societal impact. The discussion extends to next-generation standards like 6G, addressing regulatory challenges and potential policy adaptations to support future advancements in wireless technology.

Keywords: 5G NR (New Radio), 6G, CDMA2000 (IS-95), GSM, ITU, LTE (Long-Term Evolution), MmWave beamforming, National regulatory authorities, Network slicing, Spectrum allocation, Spectrum auction, Spectrum licensing, WCDMA (UMTS), WRC.

INTRODUCTION

The evolution and global deployment of wireless communication technologies are governed by a comprehensive set of regulations and standards that ensure interoperability, fair usage, and efficient spectrum allocation. These regulation are established by international organizations, such as the International Telecommunication Union (ITU), as well as national regulatory bodies, like the Federal Communications Commission (FCC) in the United States, to harmonize

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the use of radio frequencies and manage spectrum resources effectively. Additionally, simulation and Software-Defined Radio (SDR) techniques have become critical tools for evaluating the performance of these standards [1]. Standards such as GSM, CDMA, LTE, and 5G define the technical specifications for wireless systems, enabling seamless communication across diverse networks and devices. Understanding these regulations and standards is crucial for both researchers and industry professionals as they define the framework within which modern wireless communication systems operate, ensuring robust, secure, and reliable connectivity [2].

In India, the central authority responsible for regulating the telecommunications sector is the Telecom Regulatory Authority of India (TRAI). Established in 1997, TRAI serves as the national regulatory body overseeing various aspects of telecommunications, including spectrum management, licensing, tariff regulation, and ensuring fair competition among service providers. It plays a crucial role in framing and enforcing policies that guide the growth and modernization of the telecom industry. As the digital ecosystem continues to evolve, TRAI has become instrumental in facilitating the adoption of emerging technologies such as 5G, while also focusing on expanding access to communication services in both urban and rural areas.

INTERNATIONAL REGULATIONS

The International Telecommunication Union (ITU) is a specialized agency of the United Nations responsible for all matters related to information and communication technologies. International regulations play a crucial role in the global harmonization of wireless communication systems. These regulations are established by international bodies such as the ITU, which coordinates the global use of the radio-frequency spectrum and satellite orbits to avoid interference between countries' systems and to ensure the efficient and equitable use of the spectrum. The ITU's Radiocommunication Sector (ITU-R) manages the international radio-frequency spectrum and satellite orbit resources [3].

The International Telecommunication Union (ITU) is organized into three distinct sectors, each responsible for different aspects of telecommunications. These sectors were established during the ITU's restructuring at the 1992 Plenipotentiary Conference.

- **The Radiocommunication Sector (ITU-R)**, originally formed in 1927 as the International Radio Consultative Committee (CCIR), oversees the global management of radio-frequency spectrum and satellite orbit resources. This sector became ITU-R in 1992 and is supported by the Radiocommunication Bureau.

- **The Telecommunication Standardization Sector (ITU-T)**, with its roots tracing back to 1956 as the International Telephone and Telegraph Consultative Committee (CCITT), focuses on the standardization of global telecommunications (excluding radio). Renamed ITU-T in 1993, it carries out its work through study groups that address various telecommunication challenges, such as networks, multimedia, and security.
- **The Telecommunication Development Sector (ITU-D)** was established in 1992 to promote equitable, sustainable, and affordable access to Information and Communication Technologies (ICT) worldwide. It also supports initiatives like the Broadband Commission for Sustainable Development.

Role of ITU in Spectrum Management

The ITU-R's primary role is to manage the global radio-frequency spectrum and satellite orbit resources. This management is crucial for ensuring that countries can utilize these resources without causing harmful interference to each other's communication systems.

- **World Radiocommunication Conferences (WRC)**: The ITU organizes WRCs every three to four years to review and revise the Radio Regulations (RR), the international treaty governing the use of the radio-frequency spectrum. These conferences address both the current and future spectrum needs of the global community. For instance, the WRC-19 addressed the allocation of spectrum for 5G services, highlighting the growing demand for high-speed mobile broadband services.
- **ITU-R Recommendations**: The ITU-R develops technical standards known as Recommendations, which provide guidelines and best practices for the use of radio frequencies and satellite orbits. These Recommendations are critical for ensuring the compatibility and interoperability of communication systems globally.
- **Study Groups**: The ITU-R Study Groups are responsible for conducting research and developing the technical bases for WRC decisions and ITU-R Recommendations. These groups bring together experts from around the world to address specific technical issues related to radiocommunication.

Global Spectrum Allocations

The ITU's Radio Regulations (RR) allocate frequency bands to different services on a global basis. This allocation ensures that different types of services, such as mobile, fixed, satellite, and broadcasting, can coexist without causing harmful interference to each other.

CHAPTER 3

Wireless Channel Modeling and Simulation

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Abstract: This chapter provides an in-depth exploration of wireless channel modeling and simulation, essential for the design and optimization of modern communication systems. It begins with path loss and shadowing models, including key models like Free Space Path Loss, Hata, Okumura, and COST231, and discusses their practical applications. The chapter examines the effects of shadowing using the log-normal model and its impact on network performance. Advanced models, such as frequency-dependent and directional path loss models, are introduced, alongside future trends for high-frequency bands and urban environments. Multipath fading, including Rayleigh and Rician models, is analyzed, with simulation techniques and case studies provided. The chapter also covers MIMO technology, focusing on capacity enhancement through beamforming and spatial multiplexing. It concludes with an overview of simulation tools, methodologies, and emerging trends, highlighting the importance of accurate modeling and the challenges in large-scale simulations.

Keywords: Beamforming, Frequency-dependent models, MIMO, Multipath fading, Path loss models, Rayleigh fading, Rician fading, Shadowing effects, Spatial multiplexing, Wireless channel modeling.

INTRODUCTION

The performance and reliability of wireless communication systems are significantly influenced by the characteristics of the wireless channel through which signals propagate. Wireless channel modeling and simulation are fundamental aspects of understanding and predicting the behavior of transmitted signals under various conditions, such as interference, fading, and noise. This chapter delves into the complexities of wireless channels, exploring their nature and impact on communication systems. By comprehensively addressing the modeling and simulation of wireless channels, this chapter lays the groundwork

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for designing, analyzing, and improving modern wireless systems, ensuring efficient and reliable communication across diverse and challenging environments.

Path Loss and Shadowing Models

Path loss is a fundamental concept in wireless communication that describes the reduction in power density of an electromagnetic signal as it travels from the transmitter to the receiver [1, 2]. This attenuation of the signal is caused by various factors, including the distance between the transmitter and receiver, the frequency of the signal, and the characteristics of the propagation environment (*e.g*., obstacles, terrain, and atmospheric conditions).

Path loss is crucial in designing and optimizing wireless communication systems because it directly affects the coverage, capacity, and Quality of Service (QoS). Understanding path loss allows to predict the received signal strength at different distances, which is essential for determining the placement of base stations, setting transmission power levels, and ensuring reliable communication links.

Free Space Path Loss Model

The Free Space Path Loss (FSPL) model is the simplest and most fundamental model used to describe the attenuation of a signal in an ideal environment where there are no obstructions, reflections, or multipath effects. It assumes that the signal propagates in a straight line between the transmitter and receiver, following the inverse square law.

The FSPL can be derived from the basic principles of electromagnetic wave propagation, specifically the inverse square law, which states that the power density of a signal decreases proportionally to the square of the distance from the source. The formula for FSPL in decibels (dB) is given in Eq. (1) by:

$$FSPL(dB) = 20\ \log_{10} d\ + 20\ \log_{10} f - 147.55 \tag{1}$$

where:

- d is the distance between the transmitter and receiver (in meters).
- f is the frequency of the signal (in Hz).
- The constant 147.55 is derived from the speed of light and conversion factors to decibels.

Key Parameters in the FSPL Formula:

- **Distance (*d*):** The distance *d* between the transmitter and receiver plays a crucial role in the FSPL model. As distance increases, the path loss also increases, following the logarithmic relationship. This reflects the physical reality that signal strength diminishes as the distance between the source and destination increases.
- **Frequency (*f*):** The frequency $\boldsymbol{f}$ of the signal also significantly impacts the path loss. Higher frequencies experience greater attenuation compared to lower frequencies over the same distance. This is why higher frequency bands, such as those used in mmWave communication, are more susceptible to path loss and require more careful planning in network deployment.

In practical applications, the FSPL model is used to estimate the minimum path loss in open environments, such as satellite communications, where obstacles are minimal.

Practical Path Loss Models

While the FSPL model provides a baseline, real-world environments often involve complex interactions between the signal and the surrounding environment, leading to deviations from the ideal free space propagation. To address these complexities, several empirical models have been developed to account for factors like terrain, obstacles, and urban density.

Okumura Model: The Okumura model, developed in the 1960s by Yoshihisa Okumura, is one of the earliest and most influential empirical models for predicting path loss in mobile communication systems. Based on extensive measurements taken in and around Tokyo, Japan, the Okumura model provides a comprehensive framework for estimating path loss across a wide range of environments, including urban, suburban, and rural areas, as well as various terrain types. Its empirical nature and accuracy have made it a foundational model in the field of wireless communication.

The path loss in the Okumura model is expressed in Eq. (2) as:

$$\boldsymbol{PL(dB)} = PL_{\text{freespace}} + A_{mu}(f, d) - \boldsymbol{H_t(h_t)} - \boldsymbol{H_r(h_r)} - \boldsymbol{G_{area}} \quad \textbf{(2)}$$

where:

- $PL_{\text{freespace}}$ represents the free space path loss, which can be calculated using the Free Space Path Loss (FSPL) formula
- A_{mu} (f,d) represents the median attenuation relative to free space, a crucial term

CHAPTER 4

Wireless Networks

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Abstract: The wireless network provides flexibility and convenience while meeting the communication needs of non-wired devices. Personal Area Networks (PAN), Local Area Networks (LAN), and Wide Area Networks (WAN) are the three general categories into which these networks fall. Different technologies that are suited to particular applications are used in each category. In order to meet personal communication demands like computer-to-printer or computer-to-speaker connections, PAN networks use technologies like Bluetooth, Zigbee, and Near Field Communication. Wi-Fi technology is mostly used in LANs to connect devices in offices or buildings. With the use of technologies like cellular networks, WAN makes it possible for devices located hundreds of kilometers away to communicate with one another. This chapter provides a complete overview of each of these technologies by thoroughly examining their structures, features, access strategies, and other aspects.

Keywords: Bluetooth, Cellular network, LAN, PAN, WAN, Wi-Fi, Zigbee.

INTRODUCTION

Wireless networks make it possible to connect everything that can be connected. There are various ways to connect and communicate depending on the application scenario. These are the most commonly used wireless networks.

Cellular Networks: A stationary transceiver known as a cell site or base station functions in each of the small geographic areas known as cells that make up a cellular network [1]. Such networks employ frequency reuse, using different frequency sets for neighbouring cells, reducing interference and accommodating more users. They support voice calls, data transmission, and text messaging, extending to advanced services like mobile broadband, mobile TV, and mobile payments. In operation, mobile devices Signal the nearest cell site, which assigns channels and frequencies, facilitating communication. Seamless movement

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between cells involves handoffs, reassigning channels, and frequencies. Advantages: Wide coverage, Mobility, Capacity, and Scalability.

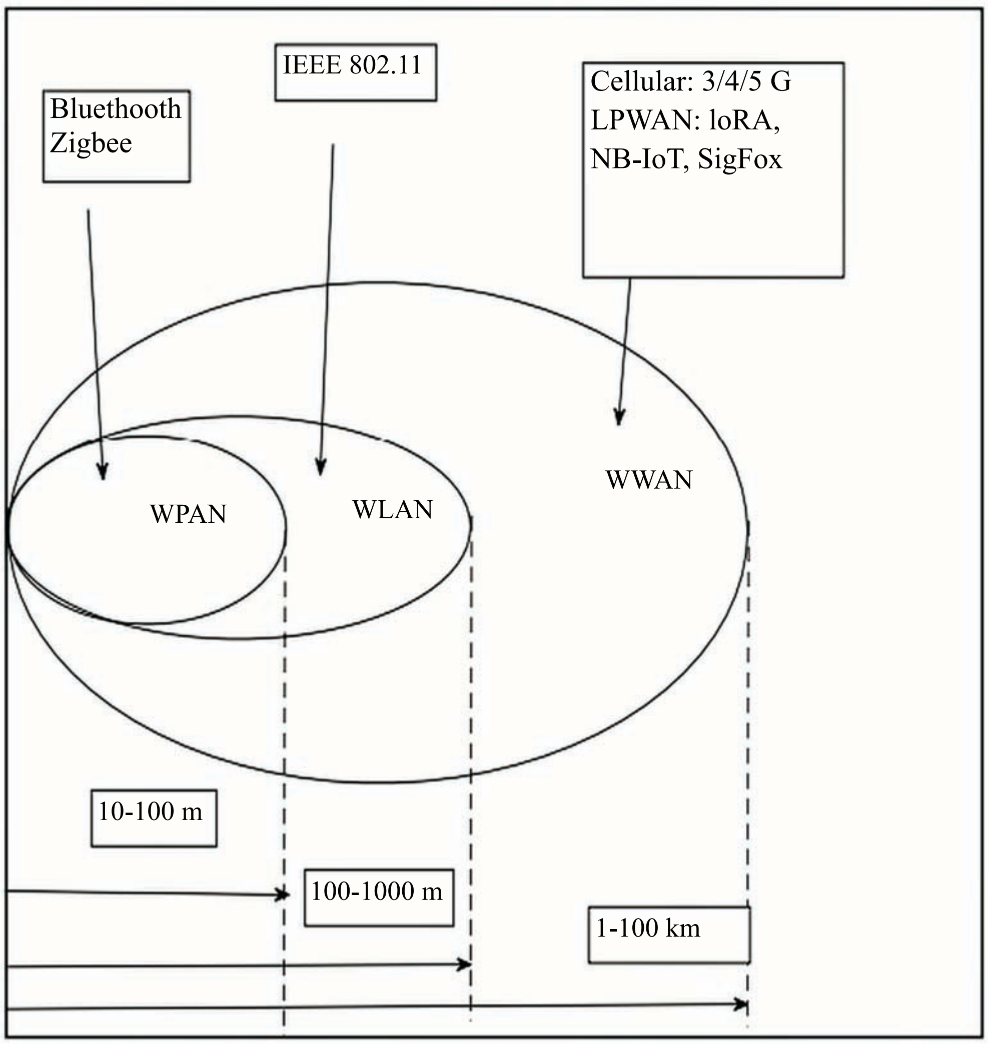

Fig. (1). Types of wireless technologies. WPAN: wireless personal area network, WLAN: wireless local area network, WWAN: wireless wide area network, LPWAN: low power wide area network.

- **Wi-Fi Networks (IEEE 802.11):** Wi-Fi extends Local Area Network (LAN) connectivity wirelessly, facilitating internet and network resource access for devices like smartphones, laptops, and IoT devices. Operating through radio waves at 2.4 GHz and 5 GHz bands, Wi-Fi finds applications in homes, offices, public spaces, and telecommunications [2]. Applications: Home & Business Networks, public Wi-Fi, IoT, educational institutions and telecommunications.

- **Bluetooth Networks (IEEE 802.15):** Bluetooth networks facilitate short-range wireless communication in the unlicensed 2.4 GHz ISM band, connecting devices like headphones, speakers, keyboards, and mice [3]. Applications: Device Connectivity and File Transfer.

IoT encompasses physical objects embedded with sensors, software, and technology, exchanging data over the internet. Wireless connectivity, including cellular networks, Wi-Fi, Bluetooth, Zigbee, and LoRaWAN, enables the IoT applications supported by specific requirements such as range, data throughput, energy usage, as well as, scalability. Examples: Smart Homes, Smart Cities, Industrial Automation, and Agriculture.

Other Wireless Networks Other wireless networks like Infrared (IR), Satellite, and Free Space Optics (FSO) offer unique connectivity options in various applications.

This chapter highlights the functionality, applications, and advantages of diverse wireless network technologies, illustrating their roles in modern connectivity and IoT applications.

- **Zigbee Networks:** Zigbee networks are low-power, wireless mesh networks connecting devices in smart home applications [4]. Operating in the unlicensed 2.4 GHz ISM band, Zigbee networks allow devices to communicate regardless of direct range, ideal for covering extensive areas. Advantages: Low-power consumption, scalability, reliability, and security.
- **LoRaWAN Networks:** LoRaWAN networks, utilizing LoRa radio modulation, connect battery-powered devices over long distances [5]. These networks operate efficiently, facilitating applications in smart cities, agriculture, and industrial automation. Advantages: Long range, low-power consumption, scalability, reliability, and security.

All these communication technologies could be divided into three broad categories depending mainly upon the range of communications, namely a) WPAN: Wireless Personal Area Network, b) WLAN: Wireless Local Area Network, c) WWAN: Wireless Wide Area Network. Fig. (**1**) gives a comparison of various wireless technologies.

CHAPTER 5

Advanced Wireless Communication Systems

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Abstract: The evolving landscape of wireless applications has prompted communication engineers to explore innovative wireless technologies capable of meeting the diverse demands of these applications. Among these advancements, Multiple-Input Multiple-Output (MIMO) systems offer improved spectral efficiency and power efficiency. MIMO leverages multiplexing gain to provide multiple data streams to a single user, and it ensures reliable communication with reduced power consumption through array gain, beamforming gain, and diversity gain. MIMO's ability to serve multiple users simultaneously over the same frequency and time slots using narrow beams is referred to as Space Division Multiple Access (SDMA). Additionally, Orthogonal Frequency Division Multiplexing (OFDM) has gained prominence as a spectral-efficient frequency division multiple access technique, converting frequency-selective channels into flat channels for simplified equalizer design. The combination of OFDM and MIMO is widely adopted in current communication standards like the IEEE 802.11n WLAN standard. Responding to the escalating demand for higher data rates, the inevitability of moving towards higher bandwidth becomes evident. This shift is illustrated by the Shannon-Hartley formula, where, for a power and bandwidth-constrained AWGN channel, Capacity (C) is given by $C = B \log2 (1 + SNR)$ bits/sec. By fixing the SNR at 10 dB and increasing the available bandwidth from 10 MHz to 100 MHz, the capacity grows from 35 Mbps to approximately 350 Mbps. Higher frequency ranges like MMwave and Tera Hz offer higher bandwidth and hence elevated data rates. An additional advantage is their ability to create sharp beam patterns, facilitating improved SDMA and accommodating more users in the same time-frequency slot. However, transitioning to higher frequencies presents hardware challenges, including the need for rapid receiver digital signal processing and smaller antenna sizes due to the reduced wavelength of transmitted signals. Further, researchers propose employing invisible light waves, specifically in Free Space Optical communication (FSO), for areas where RF infrastructure is impractical or heightened security is essential, as in military applications.

Keywords: FSO, MIMO, MMwave communication, OFDM, Tera Hz communication.

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INTRODUCTION

The growing demand for emerging wireless application scenarios—such as real-time monitoring, high-end gaming, and remote surgery—has prompted communication engineers to explore advanced wireless communication technologies capable of meeting the stringent requirements of these applications. This has led to the development of systems like MIMO (Multiple-Input Multiple-Output), which offer improved frequency utilization and enhanced power efficiency [1]. MIMO can provide multiple data streams to a single user, a benefit known as multiplexing gain. Additionally, it enables reliable communication at lower power levels through array gain, beamforming gain, or diversity gain. MIMO can also serve multiple users simultaneously over the same frequency and time slots using narrow beams—a technique known as Space Division Multiple Access (SDMA). Similarly, OFDM (Orthogonal Frequency Division Multiplexing) is a spectrally efficient frequency-division multiple access technique that transforms a frequency-selective channel into multiple frequency-flat subchannels. This simplification significantly eases the design of equalizers [2 - 4]. Therefore, the combination of OFDM and MIMO has become highly popular in current communication standards, such as the Wi-Fi standard IEEE 802.11n. As users' demand for higher data rates continues to grow, moving toward wider bandwidths has become inevitable. This trend can be better understood through the Shannon–Hartley theorem, which characterizes the capacity of a power- and bandwidth-constrained AWGN (Additive White Gaussian Noise) channel. The capacity for such a channel is given by C = Blog2(1 +SNR), where SNR is the Signal-to-Noise Power Ratio at the receiver and B is the available bandwidth for communication. Fixing the SNR at 10 dB and increasing the available bandwidth from 10 MHz to 100 MHz, we observe that the capacity increases from 35 Mbps in the earlier setup to approximately 350 Mbps in the later one.

Note that the available bandwidth for the higher frequency range is greater. Specifically,

- In 2G GSM, a bandwidth of 200 KHz was used, with carrier frequencies operating below 2 GHz.
- In 3G, a bandwidth of 5 MHz is utilized, with carrier frequencies reaching up to 2.6 GHz.
- In 4G, the bandwidth is adaptable from 1.4 MHz to 20 MHz, with carrier frequencies below 3.6 GHz.
- In the latest 5G, frequency ranges are adjustable and can extend to several hundred megahertz. The upper limit of the bandwidth is 100 MHzz for under 7 GHz frequencies, while frequencies above 28 GHz allow for bandwidths up to

400 megahertz. The 5G frequency bands span from 7 Gigahertz in the lower range to between 28 GHz and 53 GHz in the higher range.

Thus, the data rates are higher for higher frequency ranges such as MMwave and Tera Hz [5 - 7] (Fig. **1**). One more advantage of using the higher frequency is their sharp beam patterns which allows them to form a very narrow beam and perform better SDMA and therefore accommodate more number of users in the same time frequency slot. However, going towards higher frequency puts a lot of hardware challenges such as fast receiver digital signal processing and very small antenna size due to the small wavelength of the transmitted signals. In what follows, we describe the challenges of using higher frequencies in detail:

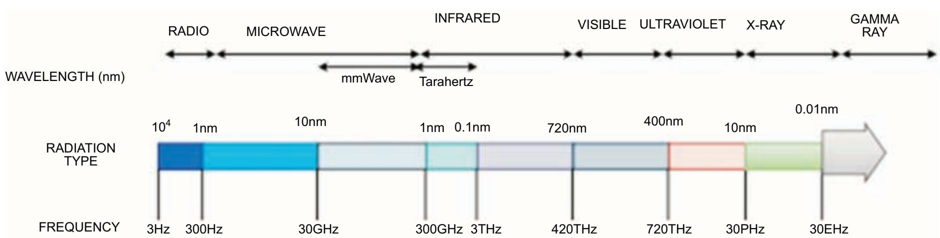

Fig. (1). Various frequency bands in the electromagnetic spectrum.

A significant challenge is the dramatic rise in atmospheric attenuation at greater frequencies. Additionally, path losses due to obstructions increase substantially based on the type of materials. To offset the effects of high path losses, more focused arrays of antennas, which create narrow beams directed towards the desired locations, are utilized. Antenna technology with beam steering capabilities will be crucial in the mmWave regions. Beam steering in the millimeter-wave (mmWave) spectrum is employed in both user equipment and base stations to address the significant path loss challenges. In mmWaves, A single array can contain even hundreds of antenna elements.

- Extremely short wavelengths introduce additional challenges, such as in antenna manufacturing, signal transmission, and electronics. These issues become more pronounced when operating in frequency ranges around 100 GHz.
- Additionally, a critical factor to consider is the Specific Absorption Rate limits (SAR). If high-power density beams, such as those from an antenna close to the body, have the potential to impact tissue, SAR thresholds could be exceeded. Therefore, it is essential to account for this and perform accurate SAR measurements.

Thanks to advancements in antenna and hardware technologies, the use of higher frequencies such as mmWave and THz is now possible. Millimeter waves and

CHAPTER 6

Security and Privacy in Wireless Communication

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Abstract: The advent of 5th generation and beyond wireless communication networks has introduced the challenges of ubiquitous connectivity, including high spectrum efficiency, and low latency. To address these concerns, sophisticated multiple access techniques like Non-Orthogonal Multiple Access (NOMA) have been developed. NOMA has been recognized as a promising solution, providing massive connectivity, high energy efficiency, and better user fairness. However, information in NOMA systems is susceptible to interception by illegitimate destinations because of the broadcast nature of wireless channels. This security issue becomes even worse due to untrusted user scenarios. This chapter investigates the security concerns of cooperative NOMA systems from external and internal eavesdropping and state-of-the-art research using decode-and-forward and amplify-and-forward relaying protocols.

Keywords: Amplify-and-forward relays, Decode-and-forward relays, Imperfect SIC, Non-orthogonal multiple access, Secrecy rate, Untrusted users.

INTRODUCTION

Wireless communication has revolutionized the way we connect and exchange information, enabling seamless communication without the need for physical cables. It encompasses various technologies and protocols that transmit data over radio waves, infrared, or microwave frequencies. From cellular networks to Wi-Fi and satellite communication, wireless technologies have become ubiquitous, powering our smartphones, laptops, and other Internet-of-Things devices. However, the never-ending requirements of exceptionally high data rates and traffic volumes have imposed a heavy burden on the limited radio resources, and this will be further fuelled by the exponentially increasing data traffic in the coming years [1]. As a result, the efficient use of resources has become a significant challenge in the development of next-generation wireless technologies, and this is achieved by non-orthogonal allocation of resources among the devices. The idea of Non-Orthogonal Multiple Access (NOMA), which supports multiple

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devices simultaneously, has been introduced [2]. The key distinguishing characteristic of NOMA is that it exploits a new dimension of the power domain to serve more users through power-domain superposition coding. Furthermore, the cooperative transmission technique has been co-opted with NOMA systems to increase the credibility of users with poor channel conditions without incurring the cost of an extra base station [3].

Since devices share the same resource blocks, the security of information becomes an imminent concern in the evolution of next-generation wireless networks. In this chapter, we begin by discussing the various security issues present in wireless networks. After briefly introducing the security concerns, we present a brief overview of how the physical layer techniques can help in addressing these security concerns. After that, we examine the role of a trusted relay in further enhancing the secrecy and briefly present some novel research directions. Finally, we conclude the chapter with some key takeaways.

SECURITY CONCERNS IN WIRELESS COMMUNICATION

NOMA supports massive access over the limited radio spectrum, an innate requirement for next-generation wireless networks. Additionally, the cooperative NOMA scheme is particularly attractive, incorporating the concept of various relaying protocols, such as Decode-and-Forward (DF), Amplify-and-Forward (AF), and compress-and-forward, to strengthen the system's performance. Moreover, dedicated relays have been deployed in the literature to enhance the performance and communication reliability of wireless systems [4]. At the transmitter side, the source superposes the signals intended for different devices by using a different power level for each signal. Consequently, complicated techniques like multi-user detection (MUD) algorithms are employed at the receiver side to separate these signals and mitigate inter-user interference, increasing the computational complexity.

Given the inherent broadcasting nature of wireless channels and ubiquitous connectivity in modern life, concerns regarding the privacy and security of information-carrying signals have intensified. Therefore, data security is inarguably an imminent concern in the evolution of next-generation wireless networks. These threats can be broadly categorized into external (eavesdropper scenario) and internal (untrusted scenario) threats, as shown in Fig. (**1**), both of which affect the reliability and confidentiality of transmitted data. In this context, Physical Layer Security (PLS) has been used, exploiting the inherent physical characteristics of wireless channels to transmit information securely, unlike the traditional methods based on cryptography.

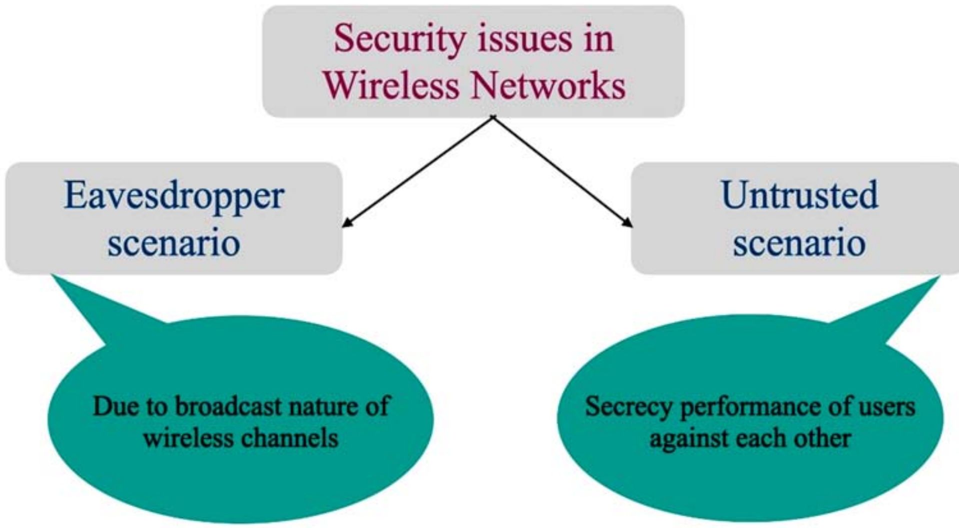

Fig. (1). Security issues in Wireless Networks.

Background

Using PLS as a security measure in NOMA has sparked widespread interest in solving privacy concerns. The concept of PLS was pioneered by Wyner [5], who first demonstrated that a secure exchange of information between the source and destination is possible if the channel conditions at the desired destination are better than those of the illegitimate destination(s). Adopting the information-theoretic point of view of PLS, which utilizes the fading characteristics of wireless channels, one can ensure a secure exchange of information between legitimate nodes in the presence of an eavesdropper(s). This leads us to the definition of secrecy rate, which is defined as the difference between the intended user's rates and the eavesdropper's rates. Mathematically, it is given as:

$$R_s = [R_d - R_e]^+$$

where $x^+ = \max\{0, x\}$, and R_d and R_e are the data rates of the intended user and eavesdropper, respectively.

Security against External Eavesdropping

An external eavesdropper is an unauthorized entity that is not inherent to the trusted wireless network, attempting to intercept, modify or disrupt communication. They are either placed intentionally, or maybe the users of other

CHAPTER 7

Future Trends in Wireless Communication

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Abstract: The chapter explores the emerging technologies set to redefine wireless communication. It covers key innovations like Massive MIMO and Beamforming, focusing on their evolution, technical foundations, and real-world applications. The chapter also delves into the challenges and solutions related to implementing these technologies, such as advanced channel estimation and hybrid beamforming. Further, the chapter examines Millimeter Wave (mmWave) Communications, highlighting their role in achieving higher data rates and addressing propagation challenges through techniques like beamforming. It also discusses Cognitive Radio and Dynamic Spectrum Access (DSA), emphasizing their importance in enhancing spectrum efficiency and managing resources dynamically. Finally, the chapter envisions future trends, including 6G and beyond, exploring the potential applications, technical challenges, and societal impacts of these advancements. The discussion underscores the importance of continuous innovation in shaping the future of wireless communication.

Keywords: 6G networks, Autonomous vehicles, Beamforming, Cognitive radio, Dynamic spectrum access, Massive MIMO, Millimeter wave (mmWave), Spectrum efficiency, Terahertz communication, Vehicular communication (V2X).

INTRODUCTION

Overview of Emerging Trends

Wireless communication systems have witnessed rapid advancements over the past few decades, driven by the increasing demand for higher data rates, improved spectral efficiency, lower latency, and greater reliability [1]. As we look toward the future, several key technologies are emerging that promise to shape the landscape of wireless communication. This section provides an overview of these technologies and the role they will play in the evolution of wireless networks.

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1. **Massive MIMO (Multiple Input Multiple Output):** Massive MIMO is an extension of traditional MIMO technology, where the number of antennas at the base station is significantly increased, often exceeding 64 or more. This technology enables simultaneous transmission to multiple users, improving spectral efficiency and increasing the overall capacity of the network. Massive MIMO is particularly important for 5G and future networks, where high user densities and data demands require efficient utilization of the available spectrum.
2. **Beamforming**: Beamforming is a technique used to direct the transmission or reception of signal beams towards specific users, thereby enhancing signal strength and reducing interference. This is especially relevant in Massive MIMO systems and mmWave communications, where precise beam control is essential for maintaining link quality, particularly in urban environments where signal obstructions are common.
3. **Millimeter-Wave (mmWave) Communications**: The shift to mmWave frequencies (30-300 GHz) is a significant trend in wireless communication, offering large bandwidths that enable extremely high data rates. However, mmWave signals suffer from high path loss and are more susceptible to blockage, making technologies like beamforming and advanced antenna arrays critical for effective deployment. The integration of mmWave in 5G networks is a key step towards achieving the high data rates and low latencies required by modern applications such as Virtual Reality (VR) and Augmented Reality (AR).
4. **Cognitive Radio and Dynamic Spectrum Access**: Cognitive radio technology allows wireless systems to intelligently detect available spectrum and adjust transmission parameters dynamically to avoid interference and optimize spectrum usage. Dynamic Spectrum Access (DSA) further enhances this capability by allowing different users to share spectrum resources efficiently, which is crucial in environments with limited spectral availability. These technologies are pivotal in addressing the spectrum scarcity challenge, enabling more flexible and efficient use of the radio spectrum.
5. **Vehicular Communication Systems (V2X)**: Vehicular communication systems, including Vehicle-to-Everything (V2X) communication, are becoming increasingly important as the automotive industry moves towards autonomous driving. V2X enables vehicles to communicate with each other (V2V), with Infrastructure (V2I), with Pedestrians (V2P), and with the Network (V2N). This communication is essential for enhancing road safety, traffic management, and enabling autonomous vehicles. The integration of V2X in 5G and future networks is expected to support Ultra-Reliable Low-Latency Communication (URLLC), which is critical for real-time applications in automotive contexts.

6. **6G and Beyond**: While 5G is still in its early stages of deployment, research and development efforts are already underway for 6G networks, which are expected to be deployed around 2030. 6G aims to address the limitations of 5G, offering even higher data rates (in the range of terabits per second), lower latency (sub-millisecond), and enhanced reliability. Key technologies for 6G include THz communication, AI-driven network management, and quantum communication. These advancements will enable new applications such as holographic communication, immersive Extended Reality (XR), and pervasive intelligence in smart environments.

Importance of Innovation

Several key factors drive innovation in wireless communication:

1. **Growing Demand for Higher Data Rates:** The proliferation of high-bandwidth applications such as video streaming, online gaming, Virtual Reality (VR), and Augmented Reality (AR) has led to an exponential increase in data traffic. This demand necessitates the development of technologies that can provide higher data rates and greater network capacity. Innovations like Massive MIMO, mmWave, and advanced modulation schemes are crucial for meeting these requirements.
2. **Need for Lower Latency**: Emerging applications, particularly in the realm of autonomous vehicles, industrial automation, and remote surgery, require ultra-low latency communication. These applications rely on near-instantaneous data exchange to function correctly, making latency reduction a critical focus in the development of future wireless networks. Techniques such as edge computing, where data processing is brought closer to the end-user, and URLLC in 5G and 6G networks, are key innovations addressing this need.
3. **Spectrum Efficiency**: The radio spectrum is a finite resource, and as more devices connect to wireless networks, efficient spectrum usage becomes increasingly important. Cognitive radio and Dynamic Spectrum Access (DSA) technologies are at the forefront of this effort, enabling more flexible and efficient use of the spectrum by allowing dynamic sharing and reallocation of frequency bands based on real-time conditions.
4. **Increased Connectivity and Device Density**: The Internet of Things (IoT) and Machine-to-Machine (M2M) communications are rapidly expanding, leading to a massive increase in the number of connected devices. This growth requires networks that can support a high density of devices without compromising performance. Massive MIMO, combined with network slicing and advanced resource management techniques, is critical for accommodating this surge in connectivity.

CHAPTER 8

Case Studies and Practical Applications of Wireless Communication

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Abstract: This chapter delves into the practical applications and case studies of wireless communication across various domains, emphasizing its transformative impact on smart cities, industrial automation, and healthcare systems. The chapter begins by exploring the critical role of wireless technologies, such as IoT, 5G, and LPWAN, in developing smart city infrastructure, with case studies from cities like Singapore, Barcelona, and Dubai. It then discusses industrial automation, highlighting how wireless networks enable smart factories, predictive maintenance, and supply chain management, supported by examples from Siemens, General Electric, and Bosch. The chapter also examines the integration of wireless communication in healthcare, focusing on remote patient monitoring, telemedicine, and emergency response systems, with insights from the Mayo Clinic, NHS, and Apollo Hospitals. Finally, it addresses the security and privacy challenges in wireless networks, proposing solutions, such as encryption protocols, intrusion detection systems, and the potential of emerging technologies, like blockchain and AI.

Keywords: Blockchain, Data privacy, Encryption protocols, Global connectivity, Healthcare systems, Industrial automation, Remote patient monitoring, Smart cities, Smart factories, Telemedicine, Wireless security.

WIRELESS COMMUNICATION IN SMART CITIES INTRODUCTION

Smart cities are urban areas that leverage advanced technologies, including wireless communication, to enhance the quality of life for their inhabitants. The integration of Information and Communication Technologies (ICT) into the infrastructure of cities helps improve efficiency, sustainability, and safety [1].

Wireless communication is the backbone of these systems, enabling real-time data exchange across various devices and platforms.

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Smart cities utilize wireless networks for various applications, such as traffic management, energy distribution, environmental monitoring, and public safety. The convergence of wireless communication technologies, including the Internet of Things (IoT), 5G, Low Power Wide Area Networks (LPWAN), and Wi-Fi, facilitates the seamless operation of smart city services [2, 3]. These technologies help connect devices, collect data, and support decision-making processes that optimize urban services. Table **1** summarizes the details of the key technologies used in smart cities.

Table 1. Key technologies in smart cities.

Technology	Description
Internet of Things (IoT)	A network of interconnected devices that communicate and exchange data. Used in smart cities for services like waste management, water distribution, and transportation. IoT devices often rely on LPWAN or Wi-Fi for connectivity.
5G	The fifth-generation wireless network offers high-speed data transmission, low latency, and massive connectivity. Enables real-time monitoring and control of smart city services.
LPWAN (Low Power Wide Area Networks)	Technologies like LoRa, Sigfox, and NB-IoT provide long-range communication with low power consumption. Ideal for battery-operated IoT devices in smart cities, such as environmental sensors and utility meters.
Wi-Fi	Commonly used for public internet access and connecting IoT devices in high-density urban areas. Wi-Fi 6 offers improved speed, capacity, and energy efficiency.
Emerging Technologies	Edge computing, blockchain, and AI are integrated into smart city systems for enhanced security, data processing, and automation. AI optimizes traffic flow, while blockchain ensures secure data transactions.

Key Technologies: IoT, 5G, LPWAN, Wi-Fi, and Emerging Technologies

- **Internet of Things (IoT)**: IoT is a network of interconnected devices that communicate and exchange data. In smart cities, IoT devices monitor and manage various services, including waste management, water distribution, and transportation [2]. IoT devices are often connected through wireless networks like LPWAN or Wi-Fi.
- **5G**: The fifth-generation wireless network (5G) significantly enhances the performance of smart city applications. It offers high-speed data transmission, low latency, and massive connectivity, enabling real-time monitoring and control of critical city services.
- **LPWAN (Low Power Wide Area Networks)**: LPWAN technologies, such as LoRa, Sigfox, and NB-IoT, provide long-range communication with low power consumption. These networks are ideal for connecting battery-operated IoT

devices in smart cities, such as sensors for environmental monitoring and utility meters.
- **Wi-Fi**: Wi-Fi networks are widely used in smart cities for public internet access and connecting IoT devices in densely populated areas. Wi-Fi 6, the latest generation, offers improved speed, capacity, and energy efficiency, making it suitable for high-density urban environments.
- **Emerging Technologies**: Technologies, like edge computing, blockchain, and Artificial Intelligence (AI), are increasingly integrated into smart city systems to enhance security, data processing, and automation. For example, AI algorithms analyze data from IoT devices to optimize traffic flow, while blockchain ensures secure data transactions.

Wireless networks are crucial for the operation of smart cities, as they enable real-time communication between devices, sensors, and central management systems. The scalability and flexibility of wireless networks allow for the integration of a wide range of applications, from transportation systems to public safety initiatives. Furthermore, wireless communication reduces the need for extensive physical infrastructure, such as cabling, making it easier to deploy and maintain smart city solutions.

Smart City Architecture and Wireless Infrastructure

Smart City Layers: Sensing Layer, Network Layer, Application Layer

- **Sensing Layer**: The sensing layer consists of IoT devices, sensors, and actuators that collect data from the urban environment. These devices monitor parameters, such as air quality, temperature, traffic flow, and energy usage. The data collected at this layer is transmitted to the network layer for further processing.
- **Network Layer**: The network layer is responsible for transmitting data from the sensing layer to the application layer. This layer includes various wireless communication technologies, such as 5G, LPWAN, and Wi-Fi, which provide connectivity across the smart city infrastructure. The network layer also manages data routing, transmission protocols, and communication standards.
- **Application Layer**: The application layer consists of software and platforms that analyze and manage the data collected by the sensing layer. This layer supports various smart city applications, including traffic management, public safety, and energy optimization. The application layer also provides interfaces for city administrators and citizens to interact with smart city services.

Wireless Infrastructure: Integration of 5G, IoT, and LPWAN

The integration of 5G, IoT, and LPWAN in smart city infrastructure allows for comprehensive and efficient data collection, processing, and distribution. These

CHAPTER 9

Machine Learning-Driven Network Slicing for 5G: Enhancing QoS Management through Predictive Modeling

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Abstract: This chapter investigates the pivotal role of Network Slicing (NS) in optimizing the performance of Fifth-Generation (5G) mobile networks, which offer unprecedented connectivity through vast bandwidth, ultra-low latency, and scalability to support diverse Quality of Service (QoS) requirements. NS allows the segmentation of a physical network into multiple logical networks, each tailored to specific application needs, from mission-critical industrial automation to high-bandwidth video streaming. To classify user requests into the most appropriate Network Slices (NSs), the study applies Machine Learning (ML) models trained on an extensive 5G traffic dataset. Utilizing classical ML methods and advanced ensemble techniques, such as Support Vector Classifier (SVC), K-Nearest Neighbors (KNN), XGBoost, and Random Forest, the models achieve an impressive accuracy of 98.51%, outperforming previous benchmarks. The research contributes to the field through meticulous data preprocessing, including feature selection and oversampling to address class imbalance, as well as rigorous feature engineering to enhance model interpretability and efficiency. Cross-validation and hyperparameter optimization further ensure model robustness. The results highlight the critical role of ML-driven predictive modeling in improving NS deployment, resource allocation, and QoS management in 5G networks, thus enabling more efficient service delivery and a superior user experience.

Keywords: 5G networks, Cross-validation, Data preprocessing, Feature selection, Hyperparameter optimization, Machine learning, Model evaluation, Network slicing, Predictive modeling, Quality of Service (QoS).

INTRODUCTION

The emergence of 5G networks marks a watershed moment in telecommunications, promising unparalleled speed, ultra-low latency, and

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massive device connectivity. This technological leap not only transforms how we communicate but also paves the way for revolutionary applications across diverse sectors, from smart cities to industrial automation and beyond. At the heart of this paradigm shift lies the concept of network slicing, a fundamental architecture that enables the creation of virtualized network instances tailored to specific use cases and service requirements. This introductory chapter serves as a gateway into the intricate realms of predictive modeling and intrusion detection within the dynamic landscape of 5G networks. Our journey navigates through the intricate layers of network slice types, predictive analytics, security protocols, and the imperative need for robust intrusion detection mechanisms.

- **Navigating Network Slice Types**

The orchestration of network slices within 5G ecosystems represents a pivotal advancement, offering unprecedented flexibility and customization. Network slices delineate distinct virtual networks, each finely tuned to accommodate diverse applications with varying demands for bandwidth, latency, reliability, and security. Our exploration delves into the taxonomy of network slice types, encompassing verticals such as enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communication (URLLC), and massive Machine Type Communication (mMTC). Through a lens of predictive modeling, we unravel the intricate relationships between use case types, technology frameworks, Quality of Service (QoS) metrics, and temporal dynamics, illuminating pathways for efficient resource allocation and performance optimization.

- **Unraveling Predictive Modeling**

Predictive modeling plays a central role in the effort to decode the underlying structure of network slice classification. Leveraging a repertoire of machine learning algorithms, including Random Forest, XGBoost, K-Nearest Neighbors (KNN), and Histogram-based Gradient Boosting, our endeavor transcends mere prediction; it delves into understanding the underlying patterns, correlations, and nuances that define network slice behaviors. Feature selection techniques such as mutual information and ANOVA F-score act as compasses, guiding us through the labyrinth of data attributes to extract meaningful insights while mitigating noise and redundancy.

- **Sentinels of Security: Intrusion Detection**

Amidst the promise of 5G's transformative capabilities, the specter of cybersecurity looms large. Our narrative extends to the domain of intrusion detection, where vigilance and resilience are paramount. We traverse the landscape of cyber threats, from network intrusions to anomalous user behaviors, leveraging sophisticated data preprocessing methodologies to distill actionable intelligence. The integration of the 5G-NIDD and UNSW-NB 15 datasets serves as our canvas, painting a vivid picture of threat landscapes and detection challenges. Techniques such as SMOTE for class imbalance handling and evaluation metrics spanning accuracy, precision, recall, and F1-score illuminate the efficacy and robustness of our intrusion detection frameworks.

- **Charting a Course Forward**

As we embark on this scholarly odyssey, our compass is set towards not just understanding the intricacies of 5G networks but also shaping their evolution. This chapter encapsulates a tapestry of methodologies, empirical findings, and scholarly discourse, offering a roadmap for researchers, practitioners, and stakeholders navigating the complex terrain of 5G network management, security, and optimization. Through rigorous analyses, empirical validations, and forward-looking insights, we endeavor to contribute meaningfully to the ongoing dialogue on 5G's transformative potential and the imperatives of ensuring its security and reliability in an interconnected world.

METHODOLOGY

A) Understanding Slicing Dataset

- *Description of the Dataset:* The foundation of any predictive modeling endeavor rests on the quality and richness of the dataset. In our exploration of network slice types in 5G networks, we leverage a comprehensive dataset sourced from real-world deployments and simulations. This dataset encapsulates a myriad of attributes ranging from technical specifications to temporal dynamics, enabling a holistic view of network slice behaviors and performance metrics.
- *Data Matrices and Features:* Within this dataset, we encounter a matrix of attributes that encapsulate key dimensions of network slice characterization. These attributes include but are not limited to Use Case Type, LTE/5G UE Category, Technology Supported, Day, Time, Quality of Service (QoS) metrics such as Packet Loss Rate (Reliability) and Packet Delay Budget (Latency), and the ultimate target variable, Slice Type. Each attribute contributes a unique perspective, capturing nuances in service requirements, user behaviors, and network conditions.
- *Exploratory Data Analysis (EDA):* Embarking on an exploratory journey through this dataset unveils a tapestry of insights and patterns. Through descriptive statistics, distribution plots, correlation analyses, and temporal trends, we unravel the intricate interplay between network slice types and their influencing factors. EDA serves as our compass, guiding us through the

CHAPTER 10

Analysis of Latency Optimization for URLLC in 5G NR

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Abstract: The evolution of communication systems has been marked by a continual push towards lower latency and higher reliability. From the early days of analog cellular networks to the sophisticated digital systems of today, each generation of mobile technology has aimed to reduce response times and enhance user experiences. This chapter traces this progression, culminating in the advent of 5G New Radio (NR), which represents a significant milestone in achieving Ultra-Reliable Low Latency Communication (URLLC). We examine the key latency reduction techniques in 5G NR, including numerology adaptation, mini-slot transmission, grant-free access, edge computing, and network slicing. Furthermore, we explore how 5G NR integrates Enhanced Mobile Broadband (eMBB) and Massive Machine Type Communication (mMTC) to provide a flexible and powerful network infrastructure. Through this analysis, we demonstrate the transformative impact of 5G NR on modern communication systems, paving the way for innovations in autonomous driving, remote surgery, industrial automation, and beyond.

Keywords: 5G New Radio (NR), Edge computing, Enhanced Mobile Broadband (eMBB), Grant-free access, Latency reduction, Massive Machine Type Communication (mMTC), Mini-slot transmission, Network slicing, Numerology adaptation, Ultra-Reliable Low Latency Communication (URLLC).

INTRODUCTION

Communication has always been fundamental to human society, evolving from basic verbal exchanges to complex digital networks. The drive for faster, more reliable communication has fueled technological advancements across various generations of mobile networks. Each generation, from the first analog systems (1G) to the latest digital innovations (5G), has sought to overcome the limitations of its predecessor, enhancing speed, capacity, and reliability. Initially, the focus was primarily on voice communication. However, as technology advanced, data

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services became increasingly important. The introduction of 2G brought digital encryption and SMS services, followed by 3G, which enabled mobile internet access and multimedia messaging. The advent of 4G marked a significant leap with high-speed data transfer, enabling streaming services, high-definition video calls, and more [1].

As communication technologies evolved, the importance of latency became increasingly apparent. Latency, the time it takes for data to travel from the sender to the receiver, is crucial for applications requiring real-time interaction. In earlier generations, higher latency was acceptable for services like voice calls and text messages. However, the emergence of applications, such as online gaming, video conferencing, and more critically, autonomous driving and remote surgery, has made ultra-low latency a necessity.

The fifth generation of mobile networks, or 5G, represents a revolutionary step forward in communication technology. Driven by the need for faster speeds, higher capacity, and ultra-low latency, 5G aims to support a wide array of applications that were previously not feasible with older generations [2]. The development of 5G was guided by the 3rd Generation Partnership Project (3GPP), a collaborative effort among seven telecommunications standards development organizations [3]. The 3GPP has been instrumental in defining the specifications and standards for 5G, ensuring interoperability and consistency across the globe.

5G technology is designed to meet several Key Performance Indicators (KPIs), including enhanced Mobile Broadband (eMBB), providing high data rates to support services, such as Virtual Reality (VR) and 4K video streaming; Massive Machine Type Communication (mMTC), enabling connectivity for a large number of IoT devices with low energy consumption and broad coverage; and Ultra-Reliable Low Latency Communication (URLLC), delivering extremely low latency and high reliability for critical applications, such as autonomous vehicles, industrial automation, and remote medical procedures. For autonomous vehicles, latency optimization is crucial to ensure real-time communication between Vehicles (V2V), Infrastructure (V2I), and Pedestrians (V2P). Techniques, such as numerology adaptation and edge computing, enable ultra-fast decision-making, reducing the risk of accidents. For example, a vehicle braking alert needs to be transmitted and received within 1 ms to avoid collisions. The 3GPP specifications for 5G encompass a wide range of technical requirements, including higher frequencies (millimeter waves), massive MIMO (Multiple Input Multiple Output) for improved capacity, and network slicing for creating virtual networks tailored to specific needs. Fig. (**1**) shows the different applications of 5G.

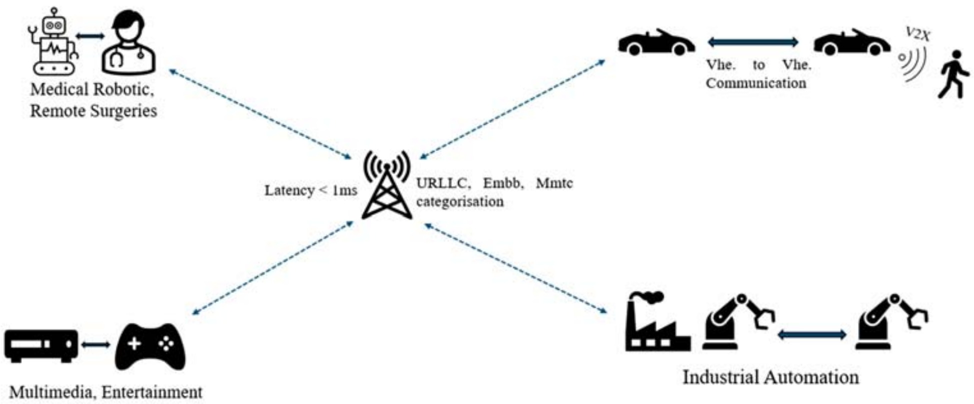

Fig. (1). 5G Applications.

One of the primary objectives of 5G is to significantly reduce latency. In a remote surgery case, a surgeon operating from a distant location requires precise and real-time transmission of surgical instrument movements. The URLLC framework in 5G NR ensures near-instantaneous feedback, making procedures safe and reliable. The combination of mini-slot transmissions, network slicing, and enhanced MIMO significantly reduces end-to-end delay, making telesurgery a practical reality. Several techniques have been developed to achieve this goal. 5G NR uses different subcarrier spacings (numerologies) to optimize transmission for various use cases, helping reduce Transmission Time Intervals (TTIs) and improve responsiveness. Mini-slot transmission allows for the use of mini-slots, which can be scheduled and transmitted in a fraction of the time compared to fixed slot durations, reducing latency. Grant-free access allows devices to transmit data without waiting for a grant, significantly reducing transmission latency. Edge computing processes data closer to the user, reducing the distance it must travel and thereby decreasing latency, with Multi-access Edge Computing (MEC) serving as a key enabler. Network slicing involves creating virtual networks optimized for specific requirements; for instance, a network slice dedicated to URLLC can be finely tuned to ensure minimal latency and high reliability.

The evolution of communication systems has been a journey toward faster, more reliable, and lower-latency networks. 5G New Radio (NR) stands at the forefront of this evolution, offering unprecedented capabilities through advanced techniques and innovations. By understanding and implementing these techniques, 5G aims to meet the growing demands of modern applications, paving the way for a future where ultra-reliable and low-latency communication becomes a standard expectation.

CHAPTER 11

Unlocking the Potential of 5G-Cognitive Radio Network Applications

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Abstract: The fifth generation is the latest cutting-edge technology of next generation wireless mobile communication. The next generation mobile communication ie., 5G, supports technological advancements such as increasing capacity, network coverage, high data rate, better connectivity and low latency compared to 4G networks. Development in recent wireless communications has increased the radio spectrum demand. To meet this demand, the radio spectrum should be utilized effectively. One proposed technique for the future generation of wireless communication that aims to increase spectrum efficiency is CRNs, which stand for dynamic intelligent adaptive networks. Flexible versions of different waveform candidates can obtain the high data rate provided by 5G. This chapter explores how to use the available frequency spectrum for next-generation wireless communication in an interference-free manner. Furthermore, this chapter explores the potential benefits of 5G networks and their applications across various industries including digital agricultural sector, Internet of Things (IoT) and the healthcare sectors.

Keywords: Cognitive radio network, CRN architecture, Cyclo-stationary feature detection, Digital agriculture, Energy detection, Enhanced mobile broad band, Requirements of 5G, Smart health care, Spectrum sensing.

INTRODUCTION

In recent years, wireless mobile communication has experienced exponential growth, fueled by the rising demand for comprehensive end-to-end services. To enhance end-device services, multiple network industries and current studies have

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been continually developing cutting-edge technologies that enable intelligent and dynamic services. The biggest challenge in promoting next-generation wireless communication involves intelligence and adaptability [1]. Software-defined radio networks support this transformation. Furthermore, Cognitive Software-Defined Radios (CSDRs) possess cognitive capabilities that enable them to adapt to changes in the radio environment in real-time, elevating their performance to the next level. To optimise performance and handle varied communication protocols, 5G deployment relies heavily on SDRs and CSDRs [2]. They are useful in many fields, including smart cities, vital infrastructure, and military operations.

The 5G system has been defined by the "Next Generation Mobile Networks (NGMN) Alliance" as an improved system that supports a society that can be completely mobile and fully connected [3]. Both emerging and established use cases are driven by ongoing knowledge dissemination and supported by sustainable frameworks, fostering value creation for clients and stakeholders.

Some important goals of 5G technology, as given in Fig. (**1**), are [4]:

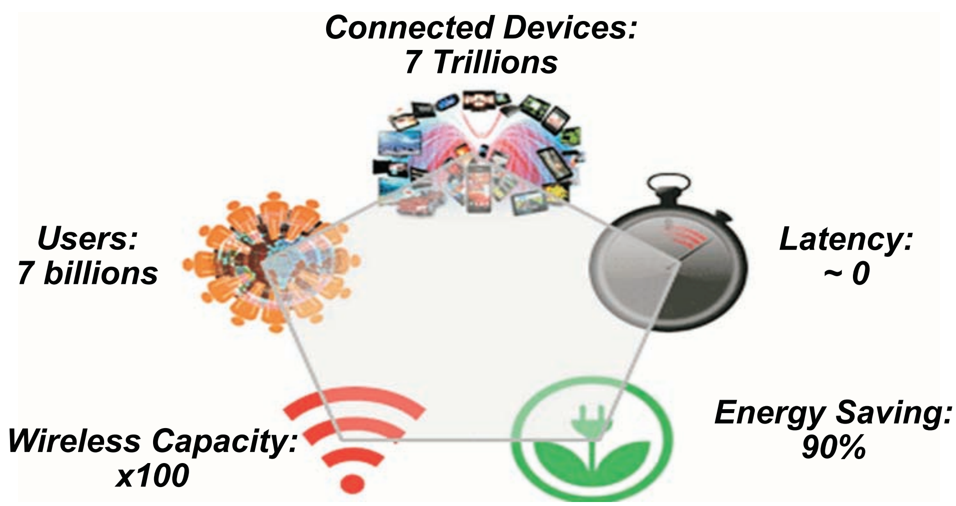

Fig. (1). Goals of 5G [4].

- To increase the mobile users to more than 7 billion.
- To increase capacity by a hundred times.
- To provide speeds up to 20Gbps.
- To save at least 90% of the energy from the current requirement.
- To show less than 1ms latency.
- To support 100+ trillion connections.

Fig. (**2**) shows some important 5G services.

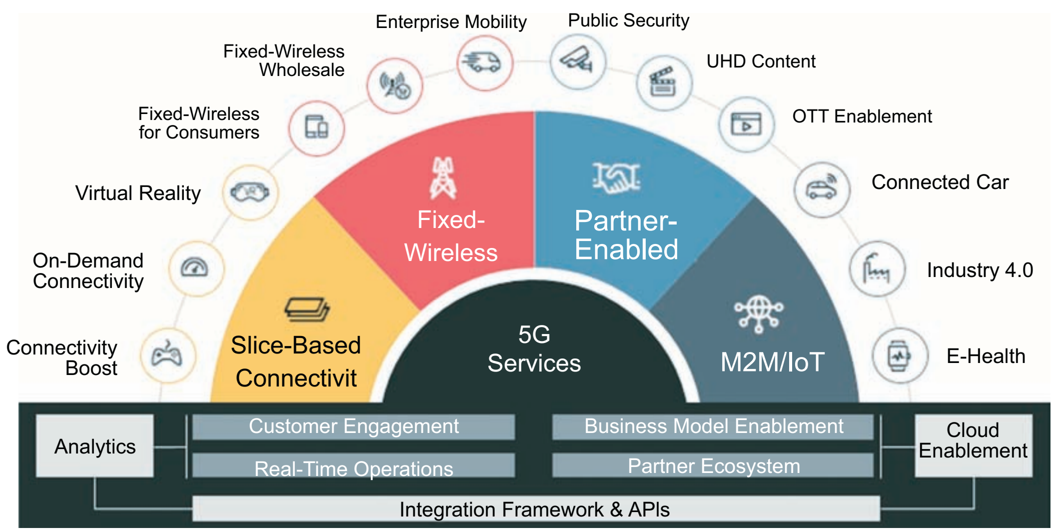

Fig. (2). 5G-Services [Image Credit: Netcracker].

MOTIVATION:

The motivation behind 5G wireless communication is to ensure seamless connectivity—"Every Time, Everywhere, Always Connected." It aims to provide near-instantaneous, high-speed connections with global coverage, all without the need for physical wires. The expectations for 5G were clearly outlined, and its standardization was initiated by the International Telecommunication Union (ITU), with contributions from researchers worldwide in both academia and industry.

5G services from the Enterprise mobility and Industry [5]

i. Fixed-Wireless for consumers and wholesalers
ii. On-demand connectivity
iii. Public Security and E-health
iv. Virtual Reality

As per the ITU recommendations and the depictions in Fig. (**3**) from the source of National Instruments (NI), 5G must support three important services:

CHAPTER 12

Noncoherent Wireless Systems for 5G and Beyond

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Abstract: Advancing into the 5th Generation (5G) and beyond, wireless communications unfolds with three primary use cases, namely, enhanced mobile broadband services, ultrareliable and low-latency communications, and massive machine-type communications. The applications targeting these use cases aim to achieve high peak data rates, ultralow latency, and extensive device connectivity. These attractive features are achieved by the utilization of various technologies, of which noncoherent communications and technologies addressing Line-of-Sight (LoS) communications in an ultra-dense network have piqued interest amongst researchers over recent years. Inspired by the research gaps in these areas, this chapter studies the performance of noncoherent wireless communication systems for 5G applications, considering the presence of a prominent LoS component in the multipath of the fading channel affecting the transmitted signal. This chapter delves into the design of a receive diversity noncoherent wireless communication system, focusing on designing receivers that are both energy-efficient and hardware-efficient. In this system, the transmitter utilizes multi-level one-sided and two-sided Amplitude-Shift Keying (ASK) schemes to transmit data over Rician fading channels. At the receiver end, an optimal noncoherent maximum likelihood detector is employed to efficiently decode the transmitted signals. The performance of the proposed system is evaluated by deriving both series-form and asymptotic closed-form expressions for the union bound on SEPs (Symbol Error Probabilities). These expressions are based on pairwise error probabilities and the proposed detection rule, ensuring accurate system analysis. Moreover, a comprehensive framework is introduced to obtain the optimal multi-level ASK constellations that minimize SEPs while adhering to an average transmit energy constraint. Through numerical analysis, the system's effectiveness is demonstrated, showcasing its improved performance with optimal ASK constellations in comparison to traditional equally-spaced ASK constellations. This highlights the potential of the proposed approach in enhancing the efficiency of noncoherent wireless communication systems.

Keywords: Amplitude shift keying, Noncoherent communication, Optimal constellation, Rician fading, Symbol error probability.

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INTRODUCTION

The 5th-Generation (5G) and beyond wireless communication provides a highly flexible and scalable network technology for connecting everyone, everything, and everywhere. The 5G has three major uses such as enhanced mobile broadband services, Ultrareliable and Low-Latency (URLLC) services, and massive machine-type communications. The applications targeting these use cases are poised to deliver high peak data rates, ultra-low latency, extensive device connectivity, augmented network capacity, heightened availability, and reliability [1]. The applications enable massive connectivity, aiming for a target connection density of one million devices per square kilometer [2], supporting the Internet of Things (IoT)-based services and ensuring seamless access. Further, 5G enables critical applications including autonomous factory manufacturing and remote surgery [3], facilitates real-time services for devices such as autonomous cars, drones, and other smart vehicles [4]. Additionally, these applications are expected to support high mobility communication scenarios of high-speed railways, vehicular ad-hoc networks, and unmanned aerial vehicle communications [5]. Numerous efforts have been made to achieve these attractive features through the utilization of various technologies, of which noncoherent communications and technologies to address Line-of-Sight (LoS) communications in an Ultra-Dense Network (UDN) setup for IoT applications have gained massive interest among the research community.

The critical applications of 5G and beyond also require real-time responsiveness and high reliability [6]. Typical wireless communication systems employ coherent detection, which utilizes training symbols to obtain instantaneous Channel State Information (CSI), ensuring reliable communication. However, such systems compromise the duration of data transmission owing to the additional overhead and delay caused by training symbols. To overcome this aspect, noncoherent receivers are employed in communication systems as they do not rely on the instantaneous CSI to decode the received data. This makes noncoherent communications a promising solution for future wireless communication, targeting to achieve low complexity and low latency.

On another front, the capacity of the 5G and beyond networks is projected to expand by multiple orders of magnitude [7]. Thus, various technologies have been considered to enhance network capacity. Spatial diversity has been used to enhance channel capacity by utilizing numerous antennas at transceivers, greatly outnumbering the users being served [8]. The use of large-scale multiple antennas at the transceivers can exploit beamforming to increase the coverage and capacity of the network. Network densification has also emerged as a potent strategy for meeting the escalating demand for capacity and elevating the overall user experience, particularly in the realm of 5G and beyond communication, where UDN architecture has emerged as a notable solution to address the challenges posed by exceptionally high capacity density requirements [9]. Such networks are generally subjected to fading with a prominent LoS link and mainly find applications in IoT scenarios [10 - 13]. Moreover, as data traffic in networks increases, so does energy consumption, which makes energy efficiency a major concern for such systems. Thus, the design of energy-efficient transceivers for such networks becomes a prime necessity to achieve green communications. Consequently, the optimal design of transceivers employing state-of-the-art noncoherent communications for wireless systems with a prominent LoS channel link is crucial for the design of hardware- and energy-efficient and reliable next-generation wireless communication systems. The following sections provide a more detailed description of each of these aspects.

Noncoherent Communications

Noncoherent communication, unlike its coherent counterpart, operates without necessitating precise CSI at the receiver, relying instead on statistical channel knowledge [14 - 16]. Since the evolution of wireless communication systems, obtaining CSI has consistently been a challenging task. This process typically involves the use of a training sequence, which introduces its own set of difficulties. One of the primary issues is the increased overhead that comes with coherent systems, which subsequently leads to a reduction in spectral efficiency. These challenges become even more pronounced in scenarios involving pilot contamination, where multiple pilot re-transmissions are required to ensure accurate and reliable signal detection in coherent systems [17]. Moreover, the presence of imperfect CSI can further degrade overall system performance, causing additional inefficiencies. In an effort to mitigate these drawbacks, blind signal detection techniques, often referred to as noncoherent detection, have been proposed as a viable solution. Noncoherent detection reduces the need for extensive training sequences, thus lowering overhead and offering a more efficient alternative to traditional coherent methods. This approach has gained attention for its potential to maintain reliable communication while addressing the limitations posed by imperfect CSI and pilot contamination. Although noncoherent communication is more resistant to phase distortions, it usually has lower data rates than coherent communications. In the context of large-scale networks as well, the simultaneous acquisition of CSI from a massive number of antennas or devices, communicating in coordinated or uncoordinated manners, remains a formidable challenge, especially considering high mobility applications like high-speed rails and hyperloop communications. Consequently, there is a compelling need for a paradigm shift towards noncoherent communication,

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