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Introduction

- In the present era, as Internet applications continue to evolve, studies on Internet of Things (IoT) have represented a growing field. This is particularly driven by the advancements in the latest generation of information technology, which leads to various innovative paradigms such as smart agriculture, smart health, and smart logistics. As a result, the concept of intelligent interconnectivity between all objects has become a reality. This has led to a profound transformation in the way people live, work, and travel, ushering in a new era of possibilities.

1.1 IoT in 5G

1.1.1 What Is IoT

IoT refers to the technique of using various devices, such as radio frequency identification (RFID), sensors to collect necessary information of things or progresses, then transmitting the collected data through the network, to achieve the ubiquitous connection between objects and people, objects and objects [1].

The concept of IoT was initially proposed by the Massachusetts Institute of Technology in 1999 [2]. At its early stages, IoT referred to the network created by the RFID technology and equipment. By incorporating the Internet and adhering to agreed-upon communication protocols, this network facilitated intelligent identification and management of product information, enabling seamless interconnectivity [3].

However, with ongoing technological advancements and application development, the scope of IoT has been broadened. In its modern aspect, IoT encompasses the integration of perception, identification, and control of interconnected objects. This integration, combined with networking and intelligent processing capabilities, enables the formation of highly intelligent decision-making systems [4].

IoT Signal Detection, First Edition. Rui Han, Jingjing Wang, Lin Bai, and Jianwei Liu.

As outlined in the White Paper on IoT published by the China Academy of Information and Communications Technology (CAICT) [5], IoT represents an expansive application and network extension of existing communication networks and the Internet. Through the utilization of perceptual technology and intelligent devices, IoT enables the perception and identification of the physical world. By leveraging network transmission and interconnectivity, IoT facilitates computation, processing, and knowledge mining. As a result, it enables seamless interaction and connectivity between individuals and objects, as well as between objects themselves. This, therefore, enables real-time control, precise management, and informed decision-making processes.

Regarding the fifth generation (5G) of wireless technology, advancements of IoT primarily stem from innovations in wireless and network technologies [6]. Within the field of wireless technology, the industry has placed particular emphasis on large-scale antenna arrays, ultra-dense networking, innovative multiple access techniques, and full spectrum access. Network technology has also witnessed significant progress, with the widespread recognition of a new network architecture based on software-defined networking (SDN) and network function virtualization (NFV) [7].

Furthermore, several key technologies have been exploited as important and promising contributors to 5G, including filter-based orthogonal frequency division multiplexing (F-OFDM), filter bank multicarrier (FBMC), full duplex and flexible duplex, multivariate low-density parity check (LDPC) codes, network coding, and polarization codes.

From a network architecture perspective, 5G inherits the overall characteristics of the fourth generation (4G), encompassing access networks, core networks, and upper-layer applications. However, to accommodate the diverse requirements of IoT, 5G has introduced new key technologies in both the core network and access network domains, bringing on technological innovations and network advancements.

1.1.2 Applications of IoT

Currently, there has been a successful combination between 5G communication technology and IoT [8]. This integration has brought on widespread applications in various domains including intelligent manufacturing, wireless healthcare, and smart logistics. The inherent advantages of 5G and IoT, such as enhanced efficiency and reliability, have significantly propelled the improvement of practical applications in these areas. The utilization of 5G-based IoT is expected to incredibly enhance the overall quality of life and transform our work and lifestyle practices fundamentally.

In recent years, the widespread adoption of IoT, particularly in the industrial area, has become increasingly prevalent [9]. A prime example of the combination between 5G communication technology and IoT is the application of wireless healthcare, which has greatly facilitated the life of individuals. The integration of IoT technology into medical devices has brought on an escalating demand for superior communication quality in remote control scenarios [10].

During the era of 4G communications, exposure to issues of signal quality has been shown to be related to adverse effects on the continuity and safety of the entire diagnostic and treatment process. Thankfully, the advent of 5G networks has significantly improved signal quality, offering low-latency and reliable connections. This enhancement enables medical professionals to accurately and promptly assess patients' conditions in remote diagnosis, thanks to high-resolution images and videos, and provide precise feedback in wireless healthcare. Besides, the utilization of remote medical devices in scientific surgical procedures ensures a high-quality service for patients.

Moreover, 5G communications have emerged as powerful platforms for autonomous driving systems. With the benefits of 5G, autonomous vehicles can strengthen their perception, decision-making, and control functions to the edge cloud. This architecture allows the processing and dissemination of data to be carried out utilizing the computational capabilities of the edge cloud, thus reducing the reliance on vehicle sensors [11].

Furthermore, the remote driving within the field of Internet of Vehicles (IoV) becomes a key instrument in efficient vehicle control and monitoring from production scheduling centers. The incorporation of remote driving not only ensures the driving safety and well-being of individuals but also gives significant advancements within the automotive industry, which promotes convenient transportation for individuals and generates economic benefits for the automotive sector.

1.1.3 Future of IoT

The Narrowband Internet of Things (NB-IoT) technique has been a major contributor in driving the widespread implementation of IoT within various domains, e.g., industrial interconnection, and improving people's quality of life. This advancement has led to the establishment of a innovative industrial ecosystem and substantial commercial expansion [12].

Looking ahead, the future of IoT promises to experience significant transformations in the next two decades due to the continuous development of innovative technologies. One prominent example is the forthcoming realization of large-scale vehicle and utility automation. This progress will encompass various facets, such as smart grids for energy production, efficient waste management systems, and intelligent environmental monitoring, all aimed at reducing greenhouse gas emissions and pollution.

While the utilization of 5G network in IoT offers numerous benefits and shows remarkable potential for future advancements, it is crucial to acknowledge the issues that arise during the practical implementation of a 5G-based IoT architecture. These issues include inadequate communication security, significant investment costs, increasing energy consumption, and limited availability of high-frequency resources, all of which contribute to the complexities associated with deploying IoT networks.

These difficulties primarily stem from the expansion of network infrastructure, effective management of IoT equipment, and efficient processing of the vast amount of data generated by the extensive deployment of mechanical devices within the IoT ecosystem. Furthermore, interoperability and heterogeneity pose additional challenges within the context of IoT. For instance, seamless integration of heterogeneous networks remains a persistent issue, inhibiting effective connectivity among these networks. In particular, the interoperability problem is increasingly recognized as a serious concern in the communication and exchange of information between numerous mechanical devices and intelligent networks, as well as in establishing connections with various applications. The lack of standardized protocols and compatible interfaces hinders smooth interoperability. Moreover, there are potential concerns regarding information security. Ensuring data integrity and confidentiality within the IoT communication system presents a significant challenge, as vulnerability in the network infrastructure and device ecosystem may compromise the security of the transmitted data.

To effectively tackle the challenges arising from the application of IoT technology in the 5G network and ensure the efficient utilization of IoT systems, it is imperative to establish unified standards for wireless communications, data collection, and security management. These standards should satisfy the specific requirements of 5G IoT applications and facilitate the advancement of robust security management and control mechanisms.

Currently, researches on 5G-based IoT networks are in their early stages and lack a mature research framework and content. Given this, it is crucial to dedicate efforts towards exploring and developing practical technologies for 5G-based IoT systems to satisfy the growing demand of IoT communications. Simultaneously, addressing existing challenges requires enhancing the heterogeneity and mobility of 5G network applications to cater to the scale and characteristics of IoT devices. By doing so, we can effectively tackle the existing obstacles.

1.2 IoT Networks

The IoT network architecture consists of the sensor/perception layer, the network layer, the communication layer, the architecture layer, and the application layer, as shown in Fig. 1.1, which are introduced as follows:

- The sensor/perception layer realizes intelligent perception, information collection and processing, automatic control of the physical world, and connects the

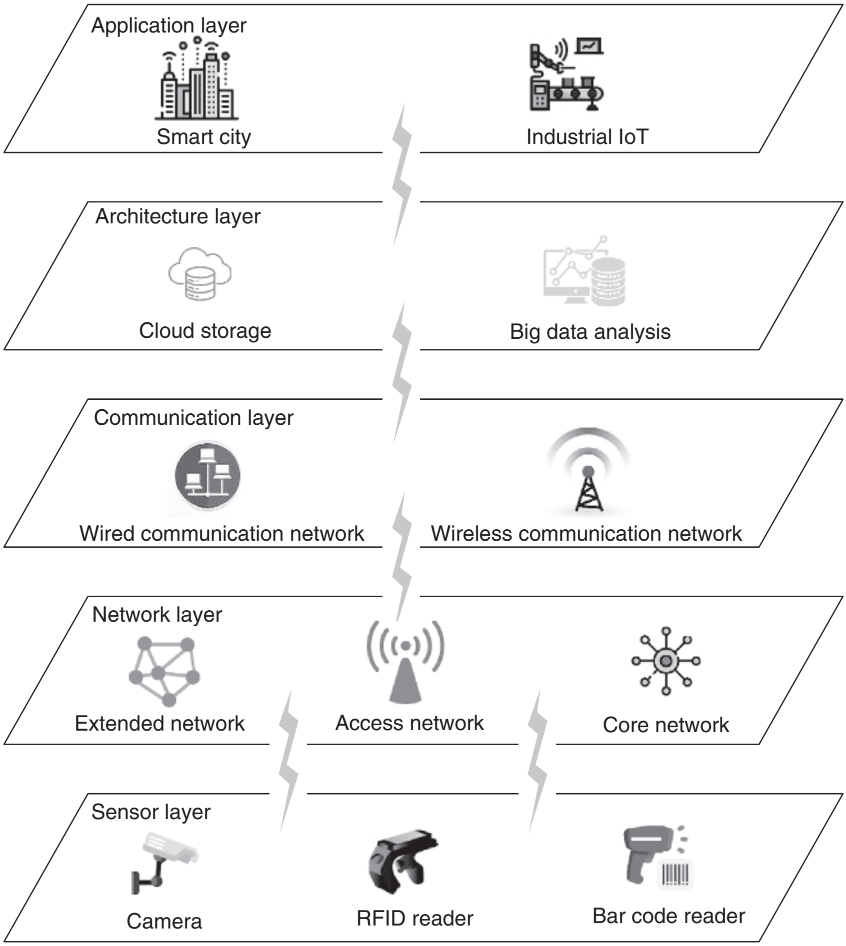

Figure 1.1 Architecture of IoT.

physical entities to the network layer and the application layer through the communication. It includes various IoT terminals composed of IoT chips, modules, sensors, IoT cards, and integrated circuits;

- The network layer mainly has the functions of transmission, routing, and controlling of information, including the extended network, the access network, and the core network. It mainly consists of the Internet, wireless broadband networks, wireless low-speed networks (e.g., ZigBee and Bluetooth), mobile communication networks, and many emerging wireless access techniques such as low power wide area networks (LPWAN) (e.g., long range radio (LoRa) and NB-IoT);

- The communication layer transmits the entire information between layers, which can rely on the Internet and the public telecommunication network, or the industrial private network. It can be considered as the backbone of the IoT architecture;
- The architecture layer, including cloud computing, big data analysis, and other architectures, provides information processing, computing, and other general infrastructure services, capabilities, and resource invocation interfaces for IoT applications. It is the basis for various applications of IoT in various fields;
- The application layer uses the Internet to integrate all devices, sensors, and information through wireless connections, which can realize different IoT applications, such as smart factories, smart homes, smart agriculture, smart transportation, etc [13].

Meanwhile, the IoT network consists of core network, transmission bearer network, and wireless network [14]. The core network needs to support IoT functions and provide IoT service license to meet the writing requirements of users' data. The transmission bearer network uses the existing IP metropolitan area network for data transmission. Among them, the transmission bearing part can be divided into backhaul propagation and fronthaul propagation, where the backhaul propagation refers to the two-layer virtual private network (VPN) docking interaction between the core network and the baseband unit (BBU) through the router, while the forward propagation refers to the direct connection between BBU and radio remote unit (RRU) through optical fiber. The wireless network part is combined with the existing site resources.

Moreover, the network deployment modes can be categorized into independent deployment, protection band deployment, and in-band deployment. The independent deployment mode involves utilizing new bands or unused bands exclusively for deployment purposes. This mode ensures that there is no interference with the existing networks, thereby maintaining optimal network performance. Additionally, the protection band deployment mode primarily utilizes the protection band within the 5G edge spectrum for deployment. By leveraging weak signals, this mode maximizes the utilization of spectrum resources and ensures efficient network operation. Lastly, the in-band deployment mode is predominantly implemented within a specific frequency band of an existing carrier. This mode allows for seamless integration within the carrier's network infrastructure, utilizing the available frequency bands efficiently.

1.3 Characteristics of IoT Signals

In recent years, academia and industry have begun to study the 5G-based IoT. Compared with IoT currently being deployed, 5G-based IoT has more stringent requirements for power consumption, connectivity performance, and coverage. Therefore, it is challenging for traditional technologies to meet these performance requirements. The main challenges are shown as follows:

1) **Signal transmitting with low-time delay:** In order to meet the usage requirements, 5G-based IoT needs to solve the problems of low transmission rate and high delay of 4G networks, which severely limits the applications of IoT and affects the use of various IoT applications. Taking smart home as an example, users need to send information through voice or remote control terminals. After smart home recognizes, receives, and processes the user's information, it will conduct automatic and intelligent operations to achieve the intended purpose of users. All of these processes rely on the high-speed communication network support. Once the network speed is poor or the network time delay is high, the smart home cannot identify, receive, and process the user's information timely, and the entire intelligent operation will have a huge delay, which will seriously affect the actual experience of users. Besides, the automated driving technology, in recent years, also has increasing demands for higher information transmission rate and lower delay of the communication network. If the intelligent vehicle cannot receive terminal instructions or quickly process relevant information of operations due to the low transmission speed, it will cause traffic chaos, and even threaten the life safety of passengers.
2) **Signal detection with low-power users:** IoT continues to evolve from a niche market to a vast network that connects almost every aspect of our lives, thus the power consumption is critical for such a wide range of applications. In the field of IoT, many network devices are sensors, wireless devices, and brakes equipped with data acquisition nodes. In the usual case, these nodes may be power-limited or battery-free devices, which can transmit their data through obtaining and reflecting the energy of the radio frequency (RF) sources. Especially in the industrial installations, these nodes are often placed in areas that are difficult to access or are inaccessible, which means they must operate and transmit data for years on a single button battery.

   Therefore, 5G-based IoT needs to extend the life of the battery in the device by exploiting low-power technologies. It is also necessary to balance the relationship between transmission power, data processing, data storage, and energy consumption, as well as research low-power signal transmission and processing technologies. In addition, new signal detection technologies are supposed to be explored, so that the receiver can successfully detect and receive the signal of terminals.
3) **Signal collision caused by large number of users:** The traditional random access (RA) scheme faces challenges, e.g., up to ten million idle users,

thousands of simultaneous active users, short packet data transmission, and low energy consumption constraints. In the traditional communication systems, RA is a necessary process to establish a wireless link between the terminal and the network. Only after the RA is completed, the data transmission between the terminal and the network can be carried out normally.

However, when the number of users in a cell increases, the performance of RA begins to degrade significantly. Even if the overload control technologies, such as access class barring (ACB), adaptive ACB (A-ACB), extended access barring (EAB) are adopted, with the continuous increase of the number of supported users in the cell, the access success probability of the whole system will be greatly decreased.

4) **Active user sensing of large-scale burst signals:** In a complex IoT ecosystem, there are various subsystems. For example, different drones can be used to serve thousands of industries, e.g., mining and exploration industries can use them for unmanned inspection, media and entertainment industries can use them for aerial photography. Besides, drones can also act as mobile base stations (BS) to provide high-capacity coverage and high-precision positioning services on demand, and large drones play crucial roles in the logistics industry. The common feature of the above 5G-based IoT scenarios is that a large number of terminals carry scattered services, while the device activation is usually sporadic. In each time slot, only a small number of devices are active and can communicate with the BS. Other devices are temporarily dormant to save energy, and they are only activated when triggered by an external event. Therefore, the fundamental challenge of 5G for IoT is that the BS needs to dynamically identify activated devices and complete data transmission in an efficient and timely manner.

1.4 Outline

The remaining themed chapters of this book are introduced as follows: Chapter 2 considers the background of IoT detection, including RA and some signal detection methods. Among them, RA is divided into two types of introductions, namely grant-based and grant-free, which are distinguished by whether to obtain the reserved channel information. Some traditional signal detection methods, such as maximum likelihood (ML), zero forcing (ZF), etc., are also mentioned. Other signal detection algorithms in use, such as variational inference (VI) detection, Markov Chain Monte Carlo (MCMC) detection, etc., are described in detail.

Chapter 3 is concerned with the sparse signal detection for multiple access, with specific technologies like VI detection and compressive sensing (CS) detection.

In this chapter, the algorithm of VI detection is firstly introduced with corresponding analysis of its performance. Then, the theory of CS detection is discussed, including Bayesian CS algorithm and structured subspace pursuit algorithm with the simulation results of them.

In Chapter 4, collided signal detection for multiple access is introduced. With the displayed system model, we analyze the theory of automatic modulation classification-based detection through the simulation results. Accordingly, the simulation results of collided signal detection for multiple access are offered.

Chapter 5 analyses the round-trip delay estimation for collided signals with ML detection, VI detection, and MCMC detection. Firstly, the system model of the round-trip delay estimation for collided signals is preformed. Then, the ML detection is described and we compare it with the VI detection and MCMC detection. Finally, the simulation results of all these detection algorithms are brought together to show their detection performance.

Chapter 6 presents the signal detection for backscatter signal. After giving the explanation of the system model of backscatter signal, we describe the algorithm of the central limit theorem-based detection and analyze its performance by comparing its simulation results with the ML detection.

Chapter 7 firstly explains the concept of non-orthogonal multiple access (NOMA) and adopts the technique of NOMA in IoT systems. Then, this chapter focuses on throughput and power consumption of NOMA systems. Finally, the puzzle of energy efficiency maximization of a full-duplex cooperative NOMA system is investigated.

The purpose of Chapter 8 is to present the signal design for multi-cluster coordination, including multi-cluster coordination with NOMA, constructive interference-aided multi-cluster coordination, and performance analysis. Then, discussions about successive interference cancellation design, device grouping, and power control to achieve multi-cluster coordination with NOMA are included.

In the end, Chapter 9 gives a brief conclusion for this book.