Research and Analysis of URLLC Technology Based on Artificial Intelligence

Zhengyu Zhu, Gengwang Hou, Zheng Chu, Xingwang Li, Gangcan Sun, Wanming Hao, and Paramjit S. Sehdev

Abstract

Ultra-reliable low-latency communications (URLLC), as one of the three application scenarios of the fifth generation (5G) mobile networks, has attracted extensive attention in the industry. URLLC can play an important role in many scenarios such as traffic safety, remote surgery, and unmanned driving. However, the existing technology is not enough to fully meet its business requirements. Artificial intelligence (AI) is promising to solve the technical problems in the URLLC communication scenario. As a branch of machine learning, deep learning has made a lot of achievements in academia and industry in recent years. It has become one of the landmark technologies of AI. Deep learning can optimize the system end to end, effectively process massive data, and cope with complex channel changes. It is considered as one of the practical tools to deal with physical layer communication. In this article, we first introduce the performance indicators and critical technologies of URLLC in the physical layer. Then we expound on the advantages of deep learning in solving technical problems in the physical layer. Finally, the challenge and opportunity of URLLC based on AI in the sixth-generation (6G) mobile networks are presented.

Introduction

The fifth generation (5G) mobile network presents the vision of "information is at one's heart, and everything is at one's fingertips." As a new generation of mobile communication technology, 5G has defined three application scenarios: enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable low-latency communications (URLLC) [1]. It also defines the various dimensional requirements of critical technical indicators, including peak rate, spectrum efficiency, time delay, network reliability, connection density, and user experience rate. Large-scale antenna arrays, ultra-dense networks, new waveform multiplexing, channel compilation codes, and millimeter-wave access will be the core technologies of 5G wireless networks. At present, eMBB is mature and can be deployed and applied, while mMTC and URLLC still have a lot of technical difficulties.

With the development of the Industrial Internet of Things (IIoT) and the proposal of Industry 4.0, the application of URLLC has gained more and more attention in the industrial field [2]. The use cases of URLLC include industrial automation, the Internet of Vehicles, smart grids, and augmented reality (AR)/virtual reality (VR), which have high requirements for delay and reliability. Table 1 shows the requirements of latency and reliability for some scenarios in the IIoT field. Specifically, the requirement for remote driving is to achieve the reliability requirement of 10^{-5} with 3 ms delay. The power distribution system requires reliability of 10^{-6} with 2 ms delay. Factory automation requires reliability of 10^{-6} with 1 ms delay.

At present, many countries have participated in research on sixth generation (6G) mobile communication. Compared to 5G, the challenges of 6G include massive hyperlinks, extensive communication, large-scale data, more intelligent learning so on. The critical theories of 6G are space information theory, compressed sensing theory, and artificial intelligence (AI) theory. The leading communication technologies applied to 6G include visible light communication, massive multiple-input multiple-output (MIMO), new battery, and simultaneous wireless information and power transfer (SWIPT) technology [3].

With the development of 5G, the Internet of Things (IoT) is becoming increasingly important because it can provide faster data transmission rate for more types of devices. At the same time, it can meet the productivity increase of industry. Compared to 5G, the definition of 6G cannot only consider its commercial value. More importantly, 6G needs a comprehensive definition to meet the requirements of society for future communication, including determining the trends, demands, and challenges faced by the society in the future. In the 5G era, mobile network operators will remain the dominant players in network deployment. In contrast, in the 6G era, ultra-efficient short-distance connectivity solutions driven by more market participants may create new ecosystems outside the traditional mobile network operation, which will also make the 6G network more inclusive.

As one of the essential revolutionary technologies, AI will play a significant role in various fields. The appearance of AI makes the industrial field change into intelligent production mode. 6G can be combined with AI technology in all

Zhengyu Zhu, Gengwang Hou, Gangcan Sun, and Wanming Hao are with Zhengzhou University; Zheng Chu is with the University of Surrey; Xingwang Li is with Henan Polytechnic University; Paramjit S. Sehdev is with Coppin State University

Digital Object Identifier: 10.1109/MCOMSTD.001.2000037

User scene	Reliability	Empty delay	Size of the packet
Rel-15: AR/VR	99.999%	1 ms	32 B and 200 B FTP Model3
Remote driving	99.999%	3 ms	1 Mb/s: packet size 5220 B
Distribution of electricity	99.9999%	2–3 ms	100 B FTP model3
Industrial automation	99.9999%	1 ms	32 B periodic and deterministic service

TABLE 1. Some URLLC user scenario requirements.

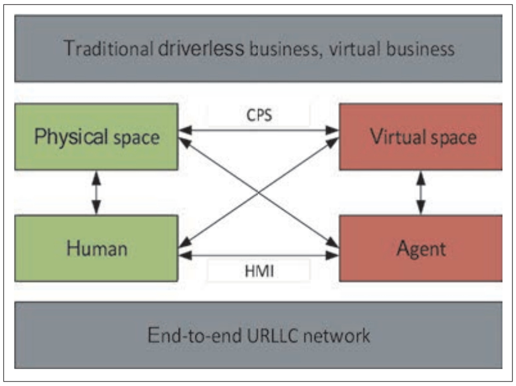

FIGURE 1. URLLC communicates the new scenario.

aspects, which will form a three-dimensional and multi-level interactive network [4]. This technology can make mobile communication service more perfect through the intelligent processing of network operation. Then we can adapt to the current stage of AI development and create an era of IoT. Due to deep learning having achieved fruitful results in theoretical algorithms and practical applications, it has been paid more and more attention from theoretical researchers and major technology companies.

In this context, we comprehensively summarize the research technology and development prospects of URLLC. The vital components and contributions of this article are as follows:
- To provide the basic technical background of URLLC to help researchers understand the concepts, performance indicators, and technical difficulties of URLLC
- To summarize the development status of URLLC and look forward to the prospects and advantages of URLLC+AI

The architecture of this article is as follows. At first, we introduce the development background, key technologies, and performance requirements of URLLC, and analyze the current shortcomings of URLLC. Second, we discuss the physics layer technology based on deep learning in the URLLC scenario. Then we analyze the advantages and prospects of AI+URLLC. Finally, we conclude the whole article.

A Comprehensive Introduction to URLLC

As the three application scenarios of 5G technology, URLLC, eMBB, and mMTC extend person-to-person communication to person-to-material communication and material-to-material communication. With the continuous innovation of information technology, the mobile communication scene will further penetrate virtual space and upgrade from object-object communication to intelligent interaction [5]. As shown in Fig. 1, two application scenarios emerge: the agent interaction and the virtual/real interaction. Virtual and real space interaction relies on perception means and visualization techniques such as cyber-physical systems (CPSs). Both of these scenarios support remote control, which greatly enriches vertical industry applications.

Technologists have applied URLLC services in many industries. One common denominator of these services is the combination of little latency and immense reliability. Reliability is the probability that a packet is not successfully transmitted to the receiver due to error, loss, or late arrival. In other words, reliability ensures that the message is delivered successfully and meets the delay limit. Some examples of URLLC services include smart grid energy distribution automation, factory automation, automated intelligent transportation systems, and remote mechanical regulation. Most URLLC services introduce real-time control applications. In a smart grid, this could be of energy distribution, including fault detection and recovery. In an intelligent transportation system, it can be a real-time maneuvering coordination infrastructure between autonomous vehicles and transport.

The Key Technology of URLLC

Several communication technology improvements have enabled URLLC to perform well in latency and reliability. The key technology to realize delay is introducing smaller units of time resources, such as mini-slots. It enables fast switching of communication links and quick resource scheduling in the time-division duplexing (TDD) mode [6]. The goal of reducing processing time was finally achieved. We also can use a multi-antenna transmission diversity mechanism, MIMO, and other technologies to ensure the reliability of data, low block error rate (BLER), and low signal-to-interference-plus-noise ratio (SINR). These technologies can implement highly reliable transmission.

In 5G, many of the vital technological improvements focus on the physical layer. For URLLC, mini-slot application in the physical layer is also one of the most critical technologies. First, taking the typical ordinary frame structure without mini-slot as an example, the frame structure is 3:1:1 (three downlink slots, one particular slot, and one uplink slot). It means that the upstream and downstream business switching is excessive through individual time slots. A typical unique time slot symbol structure includes several empty time slots, but does not contain uplink service channels. Thus, the user's data can only be transmitted to the next uplink time slot. That is to say, uplink business switching within the same time slot cannot be achieved. The mini-slot technology enables the switching of upstream and downstream business in the same time slot. It can improve user surface response speed.

Performance Metrics for URLLC

The next generation wireless network has an explicit definition of URLLC, which requires the ability to transmit information with ultra-high reliability and ultra-low delay. This communication reflects a new wireless mode. The guarantee of ultra-high reliability makes people believe that wireless communication can be used in harsh

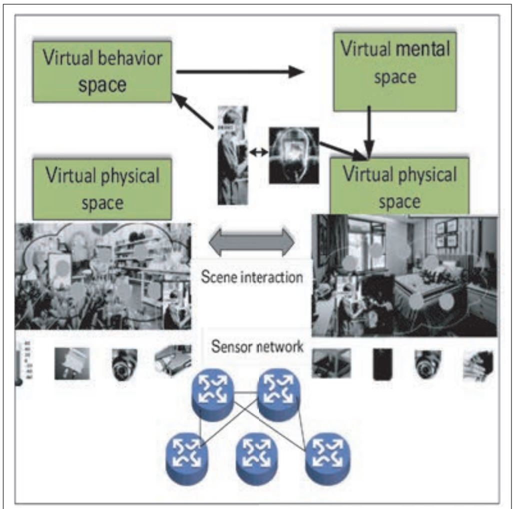

Figure 2. Human–object collaboration business scenario.

environments, while ultra-low delay ensures the real-time function of time-critical interactive communication.

URLLC has strict requirements for latency, reliability, and mobility to ensure that the communication system performs well in harsh scenarios. The delay target is 0.5 ms for downlink and 0.5 ms for uplink. In addition, the delay should be as low as possible to better support the next generation of communication. Reliability refers to the success rate of transmitting information within a given delay. The reliability requirement of URLLC is that the success rate of information transmitted by users can reach 99.999 percent within 1 ms delay. In terms of mobility, it is required to support the normal connection of equipment with a speed of 500 km/h. Although latency and reliability are key technical requirements for URLLC, security is also a critical factor in most URLLC scenarios. For example, leakage of critical and confidential information in URLLC applications would lead to attacks that are hard to defend against.

Shortcomings of URLLC

URLLC is a crucial technology for the application of the 5G industry. However, with the continuous innovation of information technology, a large number of agents and virtual spaces have been generated. Many vertical segmentation scenarios have begun to be upgraded by means of agents and virtual space, including robots, driverless vehicles, virtual reality, and others. These scenarios involve complex perceptual, computing, communication, and control issues. Object perception is characterized by multi-dimensional, multi-temporal, and multi-disciplinary parameters. Object communication presents multi-stream concurrency features of multi-dimensional, heterogeneous, and multiple quality of service (QoS) requirements. Data computing is moving from cloud computing to edge computing to distributed computing and heterogeneous computing. Decisions and controls are characterized by centralized and distributed multilevel architectures [7]. Nevertheless, for these URLLC scenarios, the performance of 5G technology cannot completely fulfill such complex requirements.

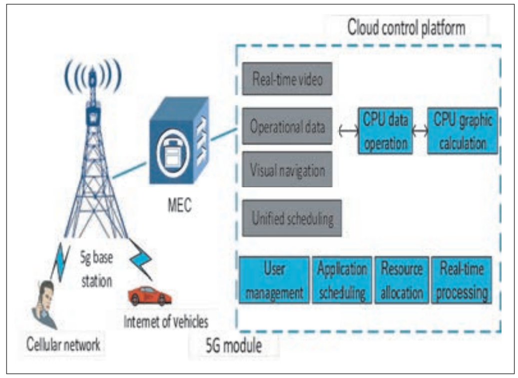

Figure 3. 5G smart factory networking.

At present, many countries have participated in the investigation of 6G. Compared to 5G, the network latency of 6G can be reduced to the level of microseconds, which means that the traditional mobile communication network will undergo radical changes. The next generation of mobile communication will develop toward higher speed and diversification [8]. With the support of the 6G technology, areas that cannot be covered by traditional base stations, such as mountain villages, lakes, and oceans, can be covered by 6G communication networks. We can implement remote Internet on a large scale. Figure 2 shows the intelligent IoT system, which is a practical human-machine-material-spirit collaboration business scenario. The system can learn a user's preference and make a corresponding decision. Network equipment follow the decision to complete their own work in the system. Based on the construction of this form, unmanned aerial vehicles, airships, and other corresponding communication platforms can carry out synchronous orbit information transmission. In addition, 6G will provide effective high-quality signal transmission in emergency situations and accidents. It would ensure effective information transmission in various complex scenarios, which can satisfy the user's needs as far as possible.

Combination of URLLC and Deep Learning

5G and AI are the most influential technologies in academia and industry. Many scientists have been studying the possibility of combining AI and 5G from various aspects and have achieved many exciting results. For example, a variety of network architecture design schemes for autonomous vehicles have been proposed. 5G has the advantages of fast speed, large bandwidth, high reliability, and low delay. It can achieve a large amount of data transmission, retrieval, and operation in a short period. AI is the use of computer and massive database to realize automatic and intelligent control to simulate the judgment of human minds [9]. 5G can provide a more robust and secure operational basis for AI so that it can be implemented into a broader range of the industrial circle. Figure 3 is a diagram of the smart factory network. In this architecture, the cloud control platform performs the computing task. This will greatly reduce the load on the system and improve resource utili-

In terms of mobility, it is necessary to support the normal connection of equipment with a speed of 500 km/h. Although latency and reliability are key technical requirements for URLLC, security is also a critical factor in most URLLC scenarios. For example, leakage of critical and confidential information in URLLC applications would lead to attacks that are hard to defend against.

Combined with AI technology, CR can perceive the external complex electromagnetic environment and adjust adaptive radio parameters to achieve high-quality communication and maximize spectrum utilization. Actually, CR is a new technology combining intelligent technology and wireless communication technology, making full use of the advantages of 5G and AI technology.

zation. At the same time, AI can accelerate the commercial application of 5G technology.

In order to support the application of URLLC in 5G, non-orthogonal multiple access (NOMA) [10], massive MIMO, millimeter-wave, and other technologies have been developed successively. Although there are many technologies that can improve the performance of 5G systems, the complex spatial structure and complicated NP-hard problem limit their application in industry. As one of the most current research directions of AI, deep learning is extensively used in numerous industries. It has obvious advantages in solving these NP-hard problems. Deep learning has enormous potential in multi-access, channel estimation, performance optimization, and other 5G technologies for the following reasons:

- End-to-end optimization is better than block-based optimization in communication systems, and deep learning is currently one of the best tools to maximize end-to-end performance. The deep neural network (DNN) has the potential to accurately model the communication system.
- In a 5G system, sophisticated and large-scale scenes lead to various communication links and expeditiously changing channel conditions. Thus, accurate acquisition of channel state information (CSI) plays a crucial role in the system. We can apply deep learning techniques to make the communication systems learn unexpected channel models and train them to adapt to new channel situations.
- The emerging 5G system needs fast and effective signal processing algorithms it can use to deal with massive data and complex scenes. Therefore, it is necessary for the system to have a rigorously robust processing method with high computational complexity. Fortunately, deep learning can process massive amounts of data and rapidly changing scenarios based on parallel processing architectures.

According to the above considerations, we study the physical layer technologies in wireless communication systems based on deep learning. In general, DNN has become one of the most prevalent generation models. As stated by the prominent prevalent approximation theorem, if we give sufficient samples, DNN can extract crucial elements from the network inputs to achieve end-to-end learning of prediction or regression. For instance, we can train DNN with a large number of images containing cats. Then DNN can capture basic features such as noses and anchor those essential elements to the next layer of the network. After training the network, it can identify the cat if we supply a few images that contain the cat. In recent years, a large amount of research has been conducted on wireless communication based on deep learning, and the high efficiency of deep learning technology has been proved in channel estimation, encoding, decoding, signal classification, and other scenarios.

We consider a typical NOMA system, as shown in Fig. 4. Instead of a conventional block-based model, we treat the entire NOMA system as a black box. The entire system can be approximated as a DNN model. It consists of the base station, wireless channels, and all users. The inputs of DNN include original transmission signal and channel vector. The function of the hidden layer is training and recognition. There are 128 neurons in the input layer. The rectified linear unit (ReLU) function adds to each layer as the activation function, which can touch off nonlinear changes. The ReLU function is actually a piecewise linear function, which changes all negative values to 0 while the positive values remain unchanged. This operation is called unilateral inhibition. Because of this unilateral inhibition, the neurons in DNN also have sparse activation. Moreover, because the ReLU function has no saturation region, there is no problem with gradient disappearance. We can send the original transmission signal vector into the input layer and use the linear function in the output layer to obtain the output signal in the NOMA system. Finally, according to the results of data detection and analysis, we believe that integrating deep learning into NOMA is an effective and reliable strategy.

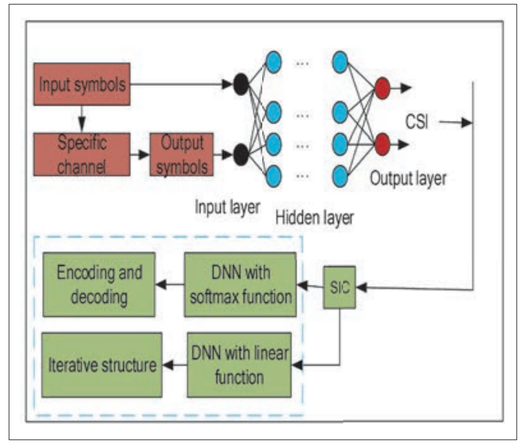

FIGURE 4. Deep-learning-based NOMA system for data detection, encoding, and decoding.

In 5G communication systems, resource allocation, and energy management issues must be considered. However, traditional approaches have great limitations in dealing with massive data. Deep reinforcement learning can optimize system performance and is considered an effective alternative for solving resource allocation problems, such as improving system performance by addressing CSI, latency, and bandwidth management [11]. As a new wireless communication technology, cognitive radio (CR) has become an ideal solution to solve the problem of insufficient spectrum utilization. CR is an intelligent wireless communication technology based on software radio. Combined with AI technology, CR can perceive the external complex electromagnetic environment and adjust adaptive radio parameters to achieve high-quality communication and maximize spectrum utilization. Actually, CR is a new technology combining intelligent technology and wireless communication technology, making full use of the advantages of 5G and AI technology.

Because of the characteristics of wireless channels, wireless communication systems are vulnerable to attack, counterfeiting, and eavesdropping. Thus, their physical layer security needs special attention. Furthermore, wireless communication systems are becoming more and more complex. The modules of the system are usually closely related to each other. The traditional security protection mechanism cannot guarantee the security of communication completely. Moreover, they are not suitable for processing massive data in very large-scale networks [12]. Deep learning has significant advantages in dealing with massive data. Deep learning technology is a very effective method to solve security problems in the physical layer, especially abnormal data detection and uncertain CSI. It can greatly improve the detection efficiency and reliability of abnormal data.

The Future of AI+URLLC

Historically, mobile communications have been upgraded about every decade. Through the introduction of emerging technologies, the spectrum efficiency and capacity can be improved, which provides the basis for the cultivation of new services [13]. Compared to 5G, 6G will adopt new technologies and new modes, which can surpass the communication performance of 5G. This will greatly accelerate the digitization of the economy and society. The first 6G Mobile Summit was held in Finland in March 2019. The event presented the 6G vision of "wireless intelligence everywhere."

There is currently no single solution that can satisfy all requirements if we want the system to have URLLC, eMBB, mMTC, and low energy consumption. This means we should coming up with more efficient solutions. The current 5G New Radio network has not been able to meet all the rigorous performance requirements. Applying AI technologies to communication systems would be a direction worth considering [14]. Compared to 5G, the performance of 6G is greatly improved in all aspects. 6G can meet the personalized and diversified demands of future industries. Table 2 shows the comparison of the main performance indicators.

AI will play a significant part in solving the 6G link layer and physical layer problems. In order to meet all performance requirements, 6G requires an ultra-flexible network with CR [15]. AI can be combined with wireless sensing and positioning to learn the static and dynamic composition of radios. It is used to predict link loss at high frequencies, to actively determine the optimal switching point in dense urban networks, and to determine base stations. It can also determine the best wireless resource allocation for base stations and users, and more. At present, machine learning and AI algorithms can be widely used to improve the performance of the air interface. A semantic recognition scheme is a significant method to solve this problem. Shannon's classical information theory is the cornerstone of all modern communications. However, Shannon's theory does not cover the semantic aspect of information. Now the communication rate has reached the limit predicted by the fragrance theory. The real leap forward comes from combining semantics with communication. Semantic communication can use to make semantic reasoning through sharing knowledge, which can significantly improve communication efficiency.

	Key performance indicators	5G parameter values	6G parameter values	Ability to ascend
1	Maximum transmission rate	20/(DL)/ 10/(UL)	>1Tbit/s	100 times
2	Experience rate	0.1–1	10–100/	100 times
3	Flow density	10 Tb/s/km^2	10^2–10^4 Tb/s/km^2	1000 times
4	Positioning accuracy	1 m (indoor) 10 m (outdoor)	0.1 m (indoor) 1 m (outdoor)	10 times
5	End-to-end delay	1 ms	< 0.1 ms	10 times
6	Error rate	500 km/h	1000 km/h	10,000 times
7	Mobility	450MHz–6GHz(FR1)	95 GHz–3 THz	–
8	Spectrum bandwidth	FR1:100MHz FR2:400MHz	20 GHz	50–100 times
9	Spectrum efficiency	30–100bps/Hz	200–500 b/s/Hz	2–5 times
10	Connection density	10^6 /Km2	10^8/km^2	100 times
11	Network energy consumption	100 bits/J	200 b/J	2 times
12	Base station computing capacity	100-200T ops (operation per second)	1000T ops	5–10 times

Table 2. Performance comparison of 5G and 6G in various aspects.

A pivotal component of the 6G network is that the architecture should be designed to dispose of communication, computing, caching, and control (C4) resources as part of the system. This would enable effective joint optimization of management. In 5G, however, communication and computing resources are handled separately. In contrast, we believe that the limitations of available resources at the edge of the network require us to manage all C4 resources comprehensively. In the new scenario, it is necessary to coordinate the allocation of access points, dynamic caching, and migration of virtual machines to ensure the effective use of end-to-end requirements and assets.

Blockchain is another highly anticipated new technology that stores and shares infrequently changed information in a distributed manner without a hub and keeps a complete record of changes. It could lead to changes in the way data markets are organized and could help operators maintain trust in each other as they set up their network architectures. At present, the application of blockchain is not only in the financial industry, but also in all aspects of our life. In various social industries, such as justice, medical care, and logistics, the application of blockchain technology can realize the information, realize the sharing of information, and solve the problem of trust. It would improve the efficiency of the whole system.

Blockchain technology has five characteristics — decentralization, non-tampering, traceability, anonymity, and transparency — that provide an excellent opportunity to build a secure and credible distributed transaction environment. In order to achieve better performance, blockchain technology can be integrated with 6G networks to build secure and trusted mobile networks and services. 6G will be the terahertz spectrum era. The introduction of blockchain technology into

The decentralized technology of blockchain technology can bring many benefits, but it will also bring more serious harm due to the lack of supervision, which will bring devastating disaster to the communication system. Therefore, if blockchain technology really wants to combine with communication system, it still needs to overcome many difficulties in technology.

spectrum management is expected to enable the design of a more secure and flexible spectrum sharing mechanism. At the same time, it also can improve spectrum utilization and communication security. The distributed collaboration mechanism of blockchain can enhance the robustness between communication service nodes and further promote the coverage, communication, and service of a communication network. Therefore, blockchain technology can be combined with wireless communication technology to become the most promising technology to guarantee 6G network security and privacy.

As a promising technology, blockchain still has a few disadvantages, which may limit its application in communication systems. First, the data confirmation time in blockchain technology is long, which is obviously difficult to accept for a communication network with low delay requirements. Second, blockchain is a high energy consumption system. Its complex calculation will consume a lot of energy, which is inconsistent with the concept of low energy consumption in communication. Finally, the decentralized technology of blockchain technology can bring many benefits, but it will also bring more serious harm due to the lack of supervision, which will bring devastating disaster to the communication system. Therefore, if blockchain technology really wants to combine with communication systems, it still needs to overcome many difficulties in technology.

Conclusion

URLLC is one of the three application scenarios of 5G technology. We give a comprehensive overview of URLLC in this article. At present, many industrial scenarios need to meet the requirements of low latency and super reliability, but the existing 5G technology cannot adequately do so in the URLLC scenario. Compared to 5G, 6G has ultrahigh transmission rate, ultra-low delay, and ultrawide coverage. It will integrate communications systems such as terrestrial, marine, and satellite communications. Research on the key requirements of URLLC would help us to better deal with the challenges of mobile communication upgrading. We also discuss the physical layer technology based on deep learning in the URLLC scenario. However, we must admit that many technologies are still in the initial stage of exploration. It is a long-term process to use deep learning to solve the physical layer wireless communication problems, which needs our continuous research.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant 61801434, 61801435, and 61771431, in part by the Project funded by China Postdoctoral Science Foundation under Grant 2020M682345, in part by the Henan Postdoctoral Foundation under Grant 202001015, in part by the Science and Technology Innovation Project of Zhengzhou under Grant 2019CXZX0037, in part by the National Key Research and Development Program of China (2019QY0302, 2019YFB1803200).

References

[1] H. Ji *et al.*, "Ultra-Reliable and Low-Latency Communications in 5G Downlink: Physical Layer Aspects," *IEEE Wireless Commun.*, vol. 25, no. 3, June 2018, pp. 124–30.

[2] J. Sachs *et al.*, "5G Radio Network Design for Ultra-Reliable Low-Latency Communication," *IEEE Network*, vol. 32, no. 2, Mar./Apr. 2018, pp. 24–31.

[3] Z. Zhu *et al.*, "Robust Beamforming Designs in Secure MIMO SWIPT IoT Networks with a Non-Linear Channel Model," *IEEE Internet of Things J.* DOI: 10.1109/JIOT.2020.3014933.

[4] L.Zhang, Y.Liang and D. Niyato, "6G Visions: Mobile Ultra-Broadband, Super Internet-of-Things, and Artificial Intelligence," *China Commun.*, vol. 16,no. 8, 2019, pp. 1–14.

[5] S. Jacob *et al.*, "A Novel Spectrum Sharing Scheme Using Dynamic Long Short-Term Memory with CP-OFDMA in 5G Networks," *IEEE Trans. Cognitive Commun. and Net.* DOI: 10.1109/TCCN.2020.2970697.

[6] R. Li *et al.*, "Intelligent 5G: When Cellular Networks Meet Artificial Intelligence," *IEEE Wireless Commun.*, vol. 24, no. 5, Oct. 2017, pp. 175–83.

[7] E. Calvanese Strinati *et al.*, "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication," *IEEE Vehic. Tech. Mag.*, vol. 14, no. 3, 2019, pp. 42–50.

[8] R. Chen *et al.*, "Physical Layer Security for Ultra-Reliable and Low-Latency Communications," *IEEE Wireless Commun.*, Oct. 2019, vol. 26, no. 5, pp. 6–11.

[9] C. Zhang *et al.*, "Artificial Intelligence for 5G and Beyond 5G: Implementations, Algorithms, and Optimizations," *IEEE J. Emerging and Selected Topics in Circuits and Systems*, vol. 10, no. 2, 2020, pp. 149–63.

[10] X. Li *et al.*, "Residual Transceiver Hardware Impairments on Cooperative NOMA Networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 1, 2020, pp. 680–95.

[11] W. Jiang, S. D. Anton, and H. Dieter Schotten, "Intelligence Slicing: A Unified Framework to Integrate Artificial Intelligence into 5G Networks," *2019 12th IFIP Wireless and Mobile Networking Conf.*, 2019, pp. 227–32.

[12] J. Li and X. Zhang, "Deep Reinforcement Learning Based Joint Scheduling of eMBB and URLLC in 5G Networks," *IEEE Wireless Commun. Letters*, 2020, vol. 9, no. 9, pp. 1543–46.

[13] L. Zhang, Y. Liang, and D. Niyato, "6G Visions: Mobile Ultra-Broadband, Super Internet-of-Things, and Artificial Intelligence," *China Commun.*, vol. 16,no. 8, 2019, pp. 1–14.

[14] A. Anand, G. D. Veciana, and S. Shakkottai, "Joint Scheduling of URLLC and eMBB Traffic in 5G Wireless Networks," *IEEE INFOCOM 2018*, 2018.

[15] V. Sze *et al.*, "Efficient Processing of Deep Neural Networks: A Tutorial and Survey," *Proc. IEEE*, vol. 105, no.12, 2017, pp. 2295–2329.

Biographies

Zhengyu Zhu received his Ph.D. degree in information engineering from Zhengzhou University, China, in 2017. From October 2013 to October 2015, he visited the Communication and Intelligent System Laboratory, Korea University, Seoul, South Korea, to conduct collaborative research as a visiting student. He is currently a lecturer at Zhengzhou University. His research interests include information theory and signal processing for wireless communications such as B5G/6G, the Internet of Things, machine learning, massive multiple-input multiple-output, millimeter-wave communication, UAV communication, physical layer security, wireless cooperative networks, convex optimization techniques, and energy harvesting communication systems.

Gengwang Hou (hougw@gs.zzu.edu.cn) is a Master's student at Zhengzhou University. His current research interests include deep learning, simultaneous wireless information and power transfer, and physical layer security.

Zheng Chu [M'17] received his Ph.D. degree from Newcastle University, Newcastle upon Tyne, United Kingdom, in 2016. He was with the Faculty of Science and Technology, Middlesex University, London, United Kingdom, from 2016 to 2017. He is currently with the Institute for Communication Systems, University of Surrey, Guildford, United Kingdom. His current research interests include smart radio environments, 5G/6G communication networks, the Internet of Things, wireless security, wireless power transfer, convex optimization, game theory, and machine learning.

Xingwang Li [S'12, M'15, SM'20] received his M. Sc. and Ph.D. degrees from the University of Electronic Science and Technology of China and Beijing University of Posts and Telecommunications in 2010 and 2015. From 2010 to 2012, he worked at Comba Telecom Ltd., Guangzhou China, as an engineer. He spent one year, from 2017 to 2018, as a visiting scholar at Queen's University Belfast, United Kingdom. He is currently an associate professor with the School of Physics and Electronic

Information Engineering, Henan Polytechnic University, Jiaozuo, China. His research interests include non-orthogonal multiple access, physical layer security, unmanned aerial vehicles, MIMO communication, cooperative communication, hardware constrained communication, and the Internet of Things. He has served as a member of many TPCs. He served as the Co-Chair of the IEEE/IET CSNDSP 2020 Green Communications and Networks Track. He also serves as an Editor on the Editorial Board for *IEEE Access*, *Computer Communications*, and *KSII Transactions on Internet and Information Systems*. He is also the Lead Guest Editor for the Special Issue on Recent Advances in Physical Layer Technologies for the 5G-Enabled Internet of Things of *Wireless Communications and Mobile Computing* and the Special Issue on Recent Advances in Multiple Access for 5G-Enabled IoT of *Security and Communication Networks*.

Gangcan Sun received his Ph.D. degree in communication and information systems from Beijing Institute of Technology, China, in 2009. He was promoted to an associate professor in the School of Information Engineering, Zhengzhou University in 2013. His current research interests include communication signal processing, communication modulation recognition, and blind estimation of key parameters of communication signals.

Wanming Hao [M] received his Ph.D. degree from the School of Electrical and Electronic Engineering, Kyushu University, Japan, in 2018. He has worked as a research fellow with the 5G Innovation Center, Institute of Communication Systems, University of Surrey, United Kingdom. He is currently a research fellow with the School of Information Engineering, Zhengzhou University. His research interests include millimeter-wave, edge caching, NOMA, SWIPT, cloud radio access networks, and so on. He served as a 2019 IEEE ICC Technical Program Committee member.

Parajmit S. Sehdev received his Bachelor of Science, Master of Science, and Ph.D. degrees in mathematics from the University of Delhi, New Delhi, India, in 1968, 1970, and 1982, respectively, and a Master of Science degree in computer science from McGill University, Montreal, Quebec, Canada, in 1980. He is currently working as an associate professor with the Department of Mathematics and Computer Science, Coppin State University, Baltimore, Maryland. He has published research papers in the field of complex analysis and computer science. His research interests are in computer graphics, computer vision, image processing, database, and complex analysis.