vivo 6G White Paper

6G Services, Capabilities and Enabling Technologies

vivo Communications Research Institute

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Contents

1 Abstract

In October 2020, vivo Communications Research Institute (vCRI) released two 6G whitepapers [1,2], and proposed a 6G vision for a freely connected physical and digital integrated world. The first whitepaper, "Digital Life 2030+", depicts, through many concrete use cases, a better scenario of digital life for the 6G era in 2030 and beyond. The second whitepaper, "6G Vision, Requirements and Challenges", provides a preliminary analysis of the technical vision, requirements and challenges for 6G system.

In the past two years, the industry is gradually forming a consensus on 6G services and key capability indicators; the research and development of 6G key enabling technologies is progressing. vCRI, together with our partners, has conducted numerous analysis and research of 6G business models, drivers, and application scenarios. vCRI has also been involved in research, evaluation and technical experiments on 6G system architecture and enabling technologies. This white paper presents the latest research findings and preliminary views on 6G services, capabilities, architecture and key technologies. It is expected that this white paper will contribute to the development of 6G technologies.

2 6G services

2.1 From 5G services to 6G services

From 1G to 4G, mobile communication system has evolved around the transmission of information, with the main goal of larger communication capacity, higher data rate and lower latency, a new generation every decade.

5G supports three usage scenarios, i.e., eMBB (Enhanced Mobile Broadband), URLLC (Ultra-Reliable Low-Latency Communications) and mMTC (Massive Machine Type Communication). 5G expands mobile communications from the human-oriented market to the Internet of Things and industrial applications. 5G provides basic telecommunication services such as short message service (SMS), voice over IP multimedia subsystem (VoIMS), with further enhancements to support next generation real time communication (NG-RTC); 5G provides on-demand mobile data connection with different QoS through control plane (CP) and user plane (UP) functions; 5G provides services such as UE positioning and network information to third-party applications by means of NEF (Network Exposure Function) or common API (Application Program Interface) frameworks; and 5G provides edge computing services realized by means of the deployment of multi-access edge computing (MEC). In summary, 5G supports high-performance communication services for individuals and industries, and information services such as UE positioning and network information exposure, and 5G supports computing services through the deployment of MEC.

Towards 2030+, people will pursue a better digital life, the digital upgrade of industry will greatly improve production efficiency, and digital social management will bring us a more harmonious and beautiful social environment. What services will 6G offer?

The technical requirements of the 29 cases of life scenarios described in the whitepaper “Digital Life 2030+” can be summarized in three areas: on-demand connectivity everywhere, ubiquitous and sophisticated digitalization, and pervasive intelligence. The white paper, “6G vision, requirements and challenges”, presented the 6G vision of a "freely connected physical-digital integrated world. Towards 2030 and beyond, 6G will build a ubiquitous digital world, enabling free connection between the physical world and the digital world to realize the tight integration of the two worlds. It will provide rich business applications to make an easy and happy digital life, and promote an efficient and sustainable development of society.

Realizing a freely connected physical-digital integrated world requires ubiquitous sensing and information capturing capabilities to achieve accurate real-time digital acquisition of the physical world, ubiquitous connectivity and converged computing (including computing, storage, and intelligence) capabilities to build a digital world, and strong communication capabilities to achieve free connection between the physical and digital worlds to support digital applications in a wide range of industries. Therefore, communication, information and computing are the three most important fundamental capabilities for building a freely connected physical and digital world. 6G will natively support communication, information and computing services, and will serve as the network information cornerstone to support the efficient and sustainable development of future society.

As shown in Figure 1, super communication, basic information, and converged computing will be the three services offered by 6G system. Systems and technologies of communication, information and computing, together with new materials, new terminals, intelligent human-computer interaction, integrated circuits and other technologies, will build a freely connected physical-digital integrated world which supports digital life, digital governance and digital production in 2030+.

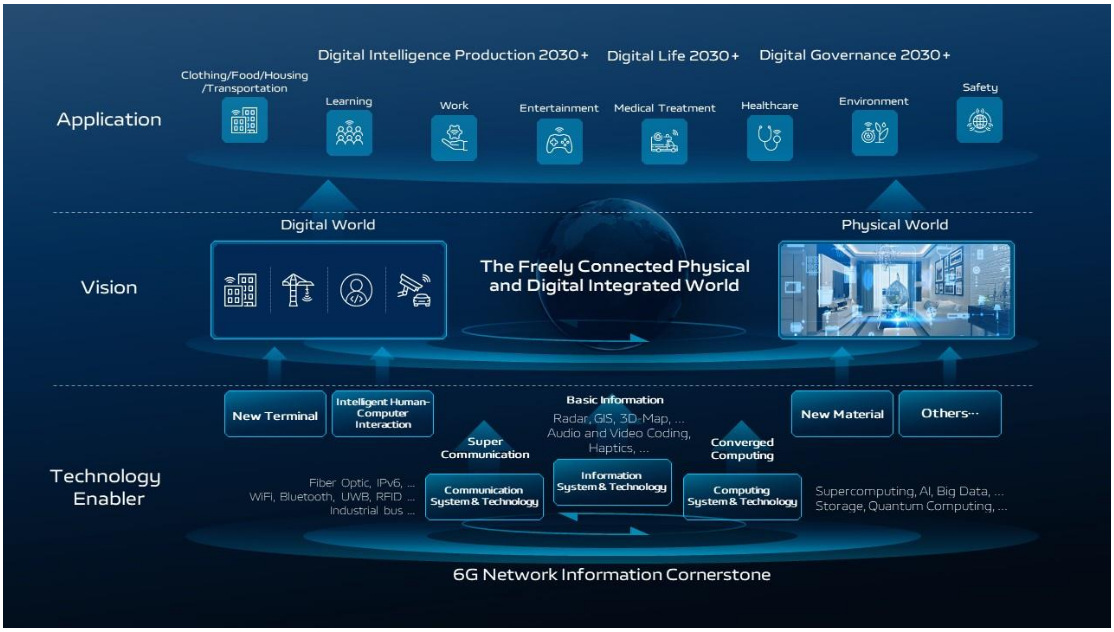

Figure 1. 6G builds a freely connected physical digital integrated world

Super communication service

From its inception, cellular mobile communications were designed to provide seamless communication and connectivity in wireless mobile scenarios. 6G will continue this historic mission and provide super communication service. On the one hand, basic telecommunication services of 6G will support new services such as immersive extended reality (XR), holographic telepresence, and multi-sensory interconnection [3~6], in addition to 5G rich media voice, video, and SMS. On the other hand, 6G mobile data connection services will continue to improve in capacity, data rate, latency, reliability and many other aspects, broadening the range of users and increasing the value of services, with more end-to-end flexibility and adaptability to meet the needs of individuals and industries in more application scenarios. At the same time, 6G will further expand geospatial coverage, lower the access barrier of terminals, improve the accessibility of connections, expand the number of subscribers, and realize the free connection and information transmission between the physical and digital worlds.

Basic information service

6G terminal or base station equipment transmits radio waves for communication, and meanwhile can measure the received signals for wireless sensing. Thus, the information of the radio propagation environment and the target objects can be obtained, such as location, speed, direction, material, or imaging, supporting rich sensing applications and scenarios. In addition, as a ubiquitously connected system, 6G will generate a large amount of valuable basic data information when supporting the connection between the physical and digital worlds. Compared with 5G that provides limited information services on UE positioning and network information provision, 6G is expected to provide comprehensive wireless sensing and positioning services, and further enhance network information provision. In addition, 6G can collect public information of industries such as sensor data and GIS (Geographic Information System) information, to empower all walks of life. This can avoid the duplicated collection of the information by different industry applications. In summary, 6G basic information services include wireless sensing, enhanced network information provision, and public information of industries.

Converged computing service

Computing power is the new productivity in the digital economy. It includes multidimensional resources such as networking, computing and storage. In a digital system based on 5G, the computations required for application services are typically performed at the terminal and in the cloud. 5G system merely provides link between terminals and cloud servers to assist the completion of computing tasks. However, many new use cases such as immersive XR, interactive 3D virtual digital human, collaborative robots, automated driving, and multi-sensory interconnection [3~6] will appear in the 6G era. The computing capabilities, such as computing power, storage, and intelligence, at the terminal is not enough to support these new use cases. The latency at the cloud side cannot meet the demands of the new use cases due to the distance. Although deployment of MEC in 5G networks can meet the needs of some use cases, the convergence of computing and network is not enough. Through the convergence of mobile network and computing, 6G will have natively converged the computing capability [7] and can provide converged the computing services including

AI (Artificial Intelligence), therefore enabling highly integrated physical and digital worlds.

2.2 6G service use cases

As mentioned earlier, 6G will provide three services including super communication, basic information, and converged computing. Based on one or more services, a variety of service use cases will be generated by considering several elements such as service users, service locations, service requirements, etc. For 2030+, more service use cases will involve two or three services, such as communication and information services, communication and computing services, and communication, information and computing services. Automated driving is a complex service use case that simultaneously requires communication, information, and computing services. A diagram of 6G services and service use cases is given in Figure

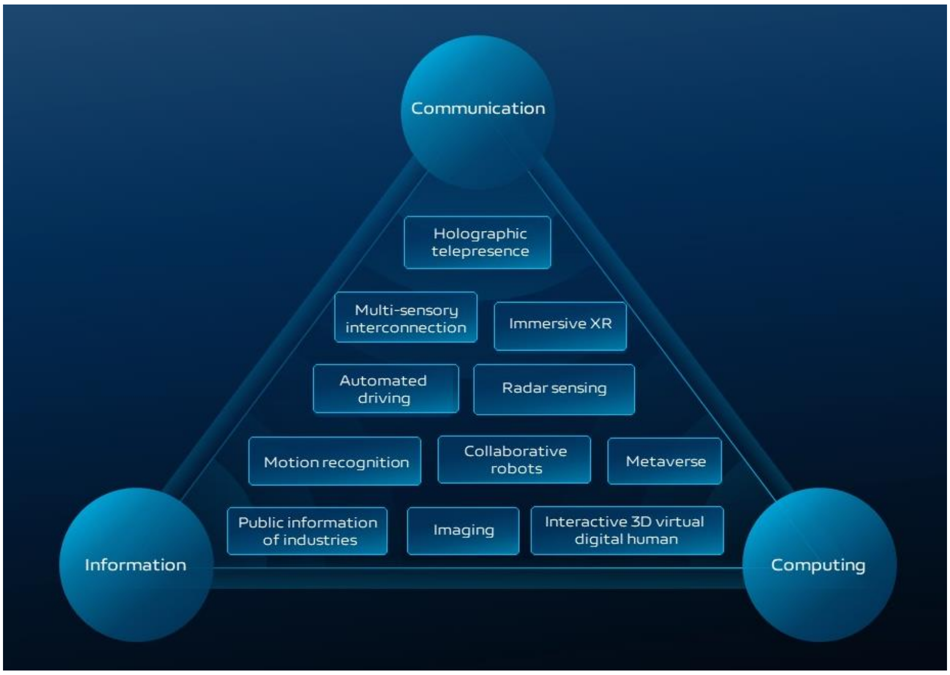

Figure 2. 6G services and service use cases

As the future social network information cornerstone, commercially, the main body of 6G services is 6G operators. The users of 6G services include the connected mobile subscribers and OTT (Over The Top) service providers in thousands of industries. The content of 6G services include three basic services, i.e., super communication, basic information and converged computing, as well as a variety of service use cases derived from the three basic services. Operators provide various services and create value for different customers, through the network infrastructure and terminals in 6G system, constituting the fundamental business logic of 6G service system design.

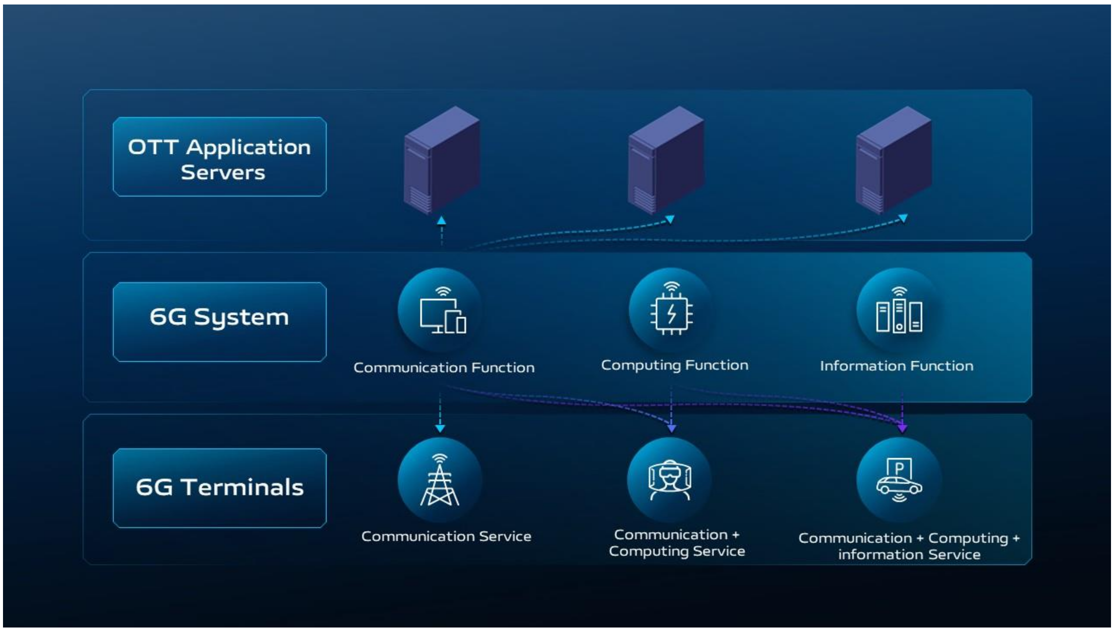

Figure 3. 6G services systems

3 6G capabilities

6G natively supports communications, information, computing, and related integrated services. To support 6G technology selection and system design which enable these services, 6G capabilities need to be defined, which include performance indicators and efficiency indicators. 6G performance indicators refer to the reachable performance of 6G services, which directly affects the service experience of the users. 6G efficiency indicators reflect the cost and efficiency of the provision of 6G services. Defining reasonable 6G efficiency indicators is a prerequisite to ensure sustainable 6G network. As shown in Figure 4, 6G performance indicators include communication performance, information performance and computing performance; 6G efficiency indicators include spectral efficiency, energy efficiency, cost efficiency, etc.

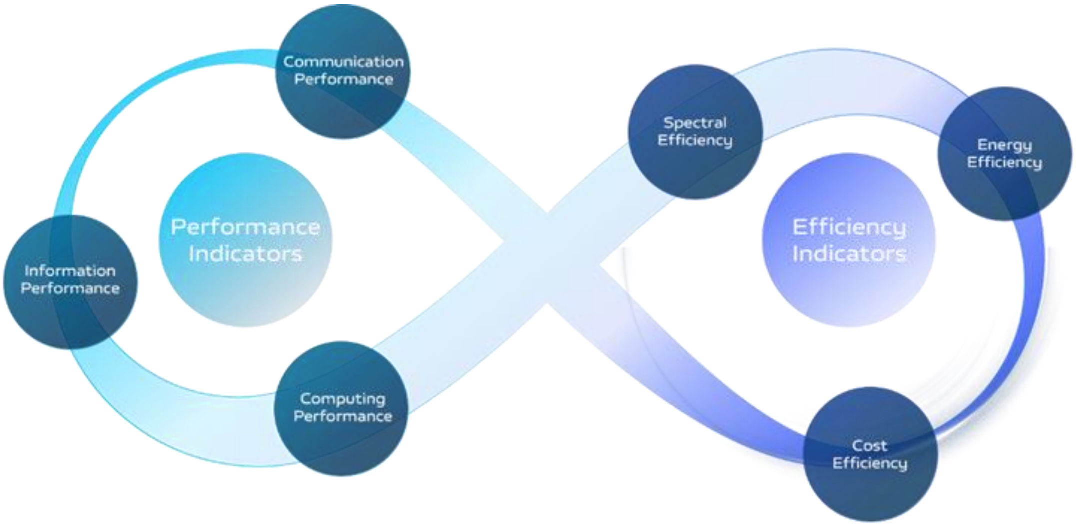

Figure 4. 6G performance indicators and efficiency indicators

3.1 6G performance indicators

3.1.1 Performance indicators of super communication

In order to define 6G communication performance indicators, the similar approach can be followed as in 5G communication performance indicators [8,9], but demanding much higher requirements compared to 5G. To support advanced service use cases such as holographic telepresence, intelligent interaction, immersive XR, real-time remote control, and intelligent connection of all things, 6G data rate (including peak data rate and user experience rate), communication latency and area traffic capacity and other performance indicators are several times or even order of magnitude higher than that in 5G [2,4,10]. The definitions and suggested values for the 6G communication performance indicators are given in Table 1.

Table 1. Comparison of communication performance indicators between 5G and 6G

Communication performance indicators	Definition	5G requirements	6G requirements
Peak data rate	Maximum data rate achievable per user/device under ideal conditions	20 Gbps	>100 Gbps

User experienced data rate	Achievable data rates for mobile users/devices in the target coverage area	0.1-1 Gbps	>1 Gbps
Communication latency	Time span from sending packets at the source to receiving them at the destination	1 ms	0.1 ms
Area traffic capacity	Total traffic throughput provided per unit geographic area	10 Mbit/s/m^2	1Gbit/s/m^2
Connection density	The total number of connected and/or accessible devices per unit area	1/m^2	10-100/m^2
Mobility	The maximum relative speed between the transmitter and receiver when meeting certain QoS	500 km/h	1000 km/h
Reliability	Probability of success in transmitting a fixed size packet within the specified maximum time	0.99999	0.9999999
Timing accuracy	Time synchronization accuracy between devices	Microsecond level	Nanosecond level

In addition to the above quantifiable performance indicators, coverage is also a very important system performance indicator. On the one hand, 6G will support the full coverage of space, air, ground and sea through the technologies of satellite communication and high-altitude platforms. On the other hand, 6G will further extend the terminal access range, integrate technologies such as backscatter communication, support very low power terminal communication, and improve the performance of near-field scenarios such as body area networks.

3.1.2 Performance indicators of basic information

6G basic information services include wireless sensing, enhanced network information provision, and public information of industries, of which the performance indicators are divergent.

Performance indicators of sensing

6G will support object and environment sensing, as well as UE positioning which is also supported by 5G. Without loss of generality, the key performance indicators for 6G sensing services are defined in Table 2, with the reference to the definitions in the field of radar sensing.

Table 2. Sensing performance indicators

Sensing performance indicators	**Definition**
Sensing accuracy	Sensing accuracy refers to the degree of deviation between the true results and the sensing results at a certain confidence level, which can be characterized by the sensing error, e.g., root mean square error. The smaller the sensing error, the higher the sensing accuracy. Sensing accuracy includes distance accuracy, velocity accuracy, angle accuracy, etc.
Sensing resolution	Sensing resolution refers to the ability to distinguish multiple sensing targets in different dimensions, including distance resolution, velocity resolution, angular resolution, etc.
Sensing range	Sensing range refers to the valid range of certain sensing parameters under the premise of satisfying certain sensing indexes, including sensing distance range, sensing speed range, sensing angle range, etc.
Sensing latency	Sensing latency is used to quantitatively describe the real-time requirements of a sensing service, such as the maximum latency from the generation of a sensing service request to the feedback of the sensing result.
Sensing update rate	The sensing update rate is the inverse of the time interval between two adjacent sensing results.

6G sensing performance depends on the frequency band, the system bandwidth, the structures of transmitter and receiver, the number of antennas, and the accuracy of transceiver synchronization of the 6G integrated sensing and communications systems. Table 3 gives the sensing performance indicators for two system configurations. The measurements are based on the radar SNR (Signal-to-Noise Ratio) calculation method and the sensing accuracy calculation method [11].

Table 3. Sense performance indicators for two system configurations

		system configuration 1	**system configuration 2**
System parameters	Central frequency	6 GHz	30 GHz
	Bandwidth	400 MHz	2 GHz
	Number of antenna elements/element gain	256 /8 dBi	512 /8 dBi
	Transmitting power of BS	55 dBm	40 dBm
	Inter-site distance	500 m	200 m
	Reference RCS	0.1 m^2	0.1 m^2
	Target maximum velocity	120 km/h	120 km/h
	Coherent processing interval	5 ms	1 ms
Sensing performance at cell edge	Distance resolution	0.375 m	0.075 m
	Velocity resolution	5 m/s	5 m/s
	Angular resolution (azimuth /zenith)	7.2° /7.2°	3.6° /7.2°
	Distance accuracy	～0.1 m	～0.1 m
	Velocity accuracy	～1 m/s	～7 m/s
	Angular accuracy (azimuth /zenith)	～2° /2°	～5° /10°

Other performance indicators of basic information

In addition to wireless sensing, 6G basic information services include the enhanced network information provision and public information of industries, and their potential performance indicators include availability, responsiveness, etc.

3.1.3 Performance indicators of converged computing

6G will support converged computing services such as computing offloading, in-network computing, AI services, etc. The performance of AI services [12~15] includes achievable performance (e.g., AI performance such as normalized mean square error, cosine similarity, etc., and communication performance such as data rate, coverage, block error rate, etc.), AI model complexity, convergence speed (or training time), generalization capability, data dependency, inference time, computational resource overhead for training, transmission resource overhead for model transfer, and storage overhead. The performance of AI services depends mainly on the development of computing technologies such as AI algorithms and big data technologies in 2030 and beyond.

6G computing performance indicators should be determined by the resources and performance of both computing and communication deployed in 6G system. When we define system-level and user-level performance indicators of 6G computing services, it is necessary to consider the typical service use cases of computing, and the related user density and business model, etc.

Interactive 3D virtual digital humans are expected to be one of the prevalent applications in the 2030+ metaverse era [16]. We assume that the target number of geometries (triangles or faces) of the future high-precision and intelligent interactive virtual digital human is more than 500,000. The preliminary evaluation shows that the computing capacity required by the driving and rendering of the 3D virtual digital human may be no less than 10 Tera FLOPS (floating-point operations per second). Most smartphones cannot meet such a high computing demand. Meanwhile, the real-time interactive experience between the digital human and the real human requires that the total round-trip time delay does not exceed 200 ms. It can be predicted that the computing latency requirement should be between 10 ms to 100 ms, excluding other latency (e.g., transmission latency). The rendering deployed in a centralized cloud can hardly meet the above delay requirement. The low-latency and high-capacity computing services required by the interactive 3D virtual digital human can be provided by 6G system. We assume that the density of active users is one person per 5 m^2; the average time per person per day using the virtual digital human application is 30 minutes; the concentration rate (the ratio of the volume of computing in the busiest hour to the volume of computing throughout the day) is 10%; and the cell coverage area is 10,000 m^2. Taking these assumptions as an example, the performance indicators required by the 3D virtual digital human scenario are shown in Table 4. Due to the diversity of computing use cases, the operator's 6G computing capacity needs to be planned and deployed according to the corresponding requirements.

Table 4. The performance indicators of computing services

Performance indicators of converged computing services		**Definition**	**Requirements based on virtual digital human use cases**
System-level performance indicators	Computing power density	The amount of computing power that can be delivered per coverage unit area of mobile communication network	~100000 Tera FLOPS/km^2
	Connection density for computing	The number of computing service connections that can be provided per coverage unit area of mobile communication network	~10000 / km^2
User-level performance indicators	Peak computing power	The available peak computing power for a single user	~10 Tera FLOPS
	Computing latency	The total latency from the time a user initiates a request for a computing	10 ms – 100 ms

		service to the time a computing response is received	

3.2 6G efficiency indicators

Efficiency indicators of communication services usually include spectral efficiency, energy efficiency and cost efficiency, which can be basically reused to wireless sensing services belonging to information services. The computing services do not involve the use of radio waves, so spectral efficiency is not involved. The definitions and requirements of efficiency indicators for communication, sensing and computing are given in Table 5.

Table 5. 6G efficiency indicators

6G efficiency indicators	**Communication indicators**	**Sensing indicators**	**Computing indicators**
Spectral efficiency	Definition: throughput provided per cell per frequency resource 6G requirements: 2-3 times higher than 5G	The time and frequency resources required to complete one sensing task	N/A
Energy efficiency	Definition: number of bits that can be transmitted per unit of energy, or the amount of energy required to transmit 1 bit 6G requirements: More than 100 times improvement in network energy efficiency	Energy required to complete one sensing task	Number of operations available per unit of energy

	compared to 5G. 10 to 100 times improvement in terminal energy efficiency compared to 5G.		
Cost efficiency	Definition: the number of bits that can be transmitted per unit cost, or the cost required to transmit 1 bit. 6G requirements: more than 100 times improvement compared to 5G	Cost to complete one sensing task	Number of operations available per unit cost

In addition to the above quantitative efficiency indicators, 6G efficiency indicators includes the following aspects.

- Flexibility: 6G system shall be easily deployed and maintained. 6G system shall support adaptation and tailoring of system functions to enable new use cases and new business opportunities, and support smooth evolution from 5G to 6G.
- Intelligence: AI-based network management and O&M, and programmable 6G system which achieves flexible and efficient management of network resources shall be supported.
- Green: In addition to supporting higher energy efficiency indicators compared to 5G, 6G can support the use of renewable energy to ensure the sustainability of the network; 6G will also support extremely low power communication through ambient energy supply and other means, so as to greatly enhance connectivity accessibility and support the Internet of Everything.
- Resilience: 6G system can quickly and autonomously detect and identify network anomalies, equipment failures, operational errors and network attacks,

and then self-recover and self-cure to guarantee the availability and robustness of the network and services.

- Security, privacy and trustworthiness: 6G needs to meet the needs of trustworthiness, security and privacy when providing communication, information and computing services, as well as the related service use cases. For example, basic information services need to observe local laws and regulations, ensure the security of data and information, and protect user privacy. Converged computing needs to consider computing security, storage security, data privacy, algorithm privacy, etc.

3.3 6G usage scenarios

Six communication performance indicators, i.e., data rate, mobility, latency, reliability, area traffic capacity and connection density, and information-based performance indicators and computation-based performance indicators, are considered in Figure 5. The three basic services, i.e., super communication, basic information and converged computing, are associated to the above indicators according to the importance of performance indicators (high, medium or low). Among them, super communication is further divided into three sub-scenarios, i.e., eMBB 2.0, URLLC 2.0 and mMTC 2.0. Given the diversity of 6G service use cases and the scalability of 6G system, in addition to the five usage scenarios mentioned above, 6G will further support more flexible scenarios based on super communications, basic information and converged computing services within the capability boundaries.

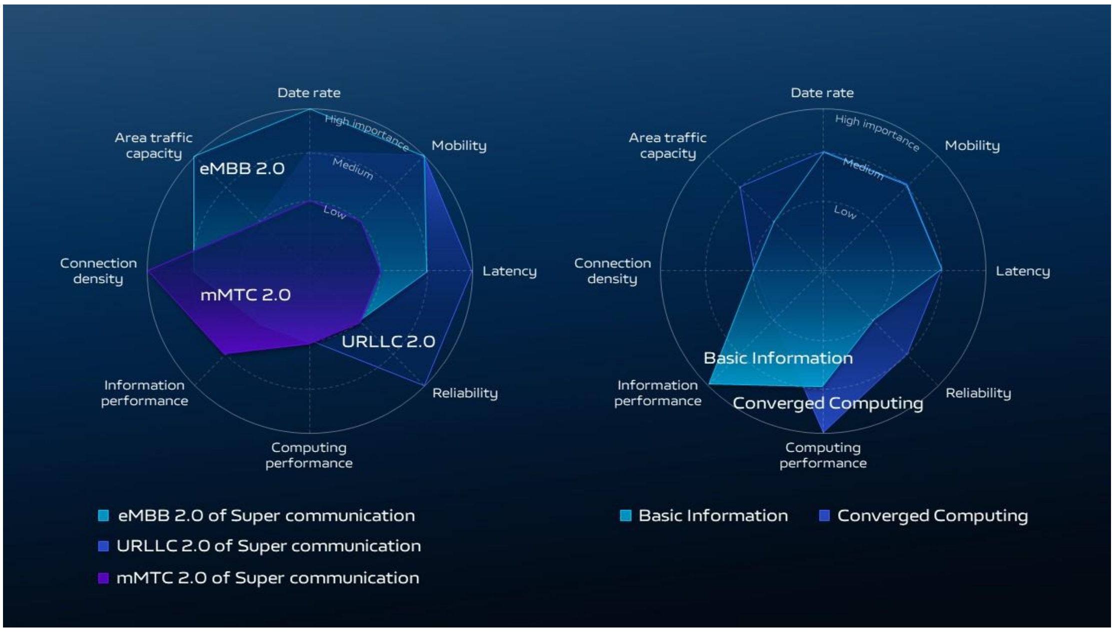

Figure 5. 6G usage scenarios

4 6G enabling technologies

As mentioned earlier, 6G will support higher capabilities and service expansion compared to 5G. Table 6 summarizes the different characteristics of 5G services and 6G services.

Table 6. 5G services and 6G services

Service type		**5G services**	**6G services**
Communication	Basic telecom business	Basic telecom services, VoNR, new voice, 5G messaging, etc.	XR, holographic telepresence, multi-sensory interconnection, etc.
	Data connection	On-demand mobile data connectivity	Higher-performance on-demand mobile data connectivity
Information		UE positioning, some network	Natively support basic information service including

	information	wireless sensing, enhanced network information provision, and public information of industries
Computing	MEC	Natively support converged computing services including computing power, storage, AI, etc.

To support 6G services and capabilities, as shown in Figure 6, on the one hand, the system functional framework for 6G needs to be designed to support a wide variety of 6G service use cases. On the other hand, the key enabling technologies need to be studied to meet the various performance and efficiency indicators of the 6G system.

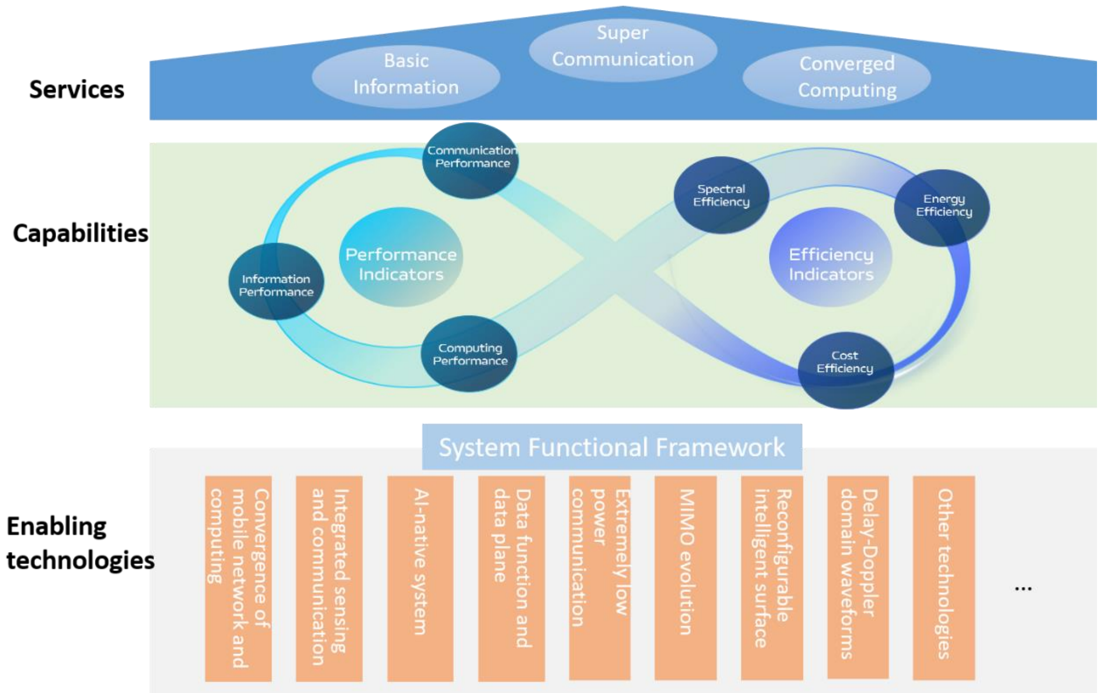

Figure 6. Logic diagram of 6G services, capabilities and enabling technologies

4.1 System functional framework

5G provides main communication services including VoIMS, SMS and NG-RTC, and provides positioning services based on location management function (LMF). The computing services provided by the external central cloud or MEC are related to the application data carried by 5G, which are beyond the scope of 5G system. 6G will enhance the existing communication services and IMS communication services, and further meet the transmission requirements of new use cases such as immersive XR, holographic telepresence, multi-sensory interconnection, etc. Moreover, the services offered by 6G will also be further enriched with the addition of basic information services, converged computing services.

As shown in Figure 7, corresponding to 6G services, the existing communication functions, such as access management, mobility management, session management, policy control, and UP (User Plane) data transmission, need enhancement. Meanwhile, the new network functions, such as sensing function, computing function and data function, need to be introduced to achieve integration of sensing and communication, convergence of mobile network and computing, cross-domain data interaction and AI-native system. From the perspective of resource set, 6G will expand the computing resources and storage resources required for computing services, and further expand spectrum resources and wired network resources for all the three services. 6G will support real-time management and scheduling of all the resources to meet the needs of system flexibility.

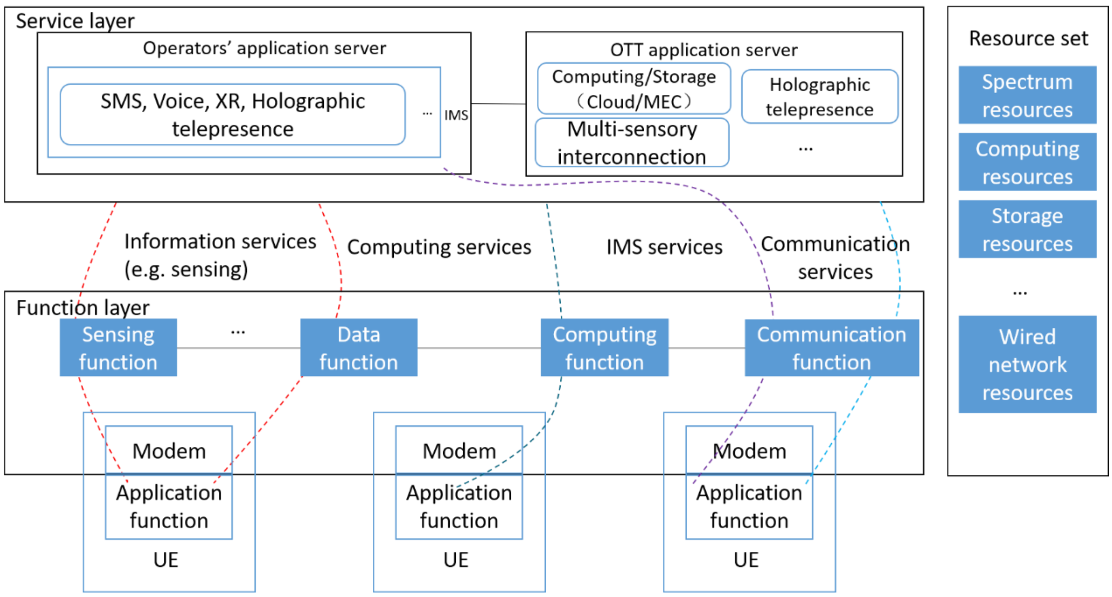

Figure 7. 6G system functional framework

4.2 Convergence of mobile network and computing

The convergence of mobile network and computing focuses on the convergence of communication function and computing function in 6G system to provide computing services for users with computing requirements, where the computing services include both non-AI computing and AI computing. 6G system will better support computing data transmission by coordinating computing latency and transmission latency dynamically. Due to the distributed nature of 6G network function nodes, the widely distributed nodes of integrated communication and computing can shorten the latency of computing data transmission and reduce the load of the backbone network.

For wireless communication networks, the potential protocol impact of 6G computing services may be at IMS service layer, at network function layer of core network, at network function layer of RAN, etc. For wired network, to achieve a better match between computing and wired transport, the transport protocols are enhanced to support the real time interaction of routing information, computing status information and application information. The transport protocols include Internet Engineering Task Force (IETF) Compute First Networking (CFN), Segment Routing over IPv6 (SRv6), Application-aware IPv6 Networking (APN6), etc. Besides, the collaboration between wireless communication networks and wired network to support end-to-end dynamic adaptation between connection and computing is another valuable research direction.

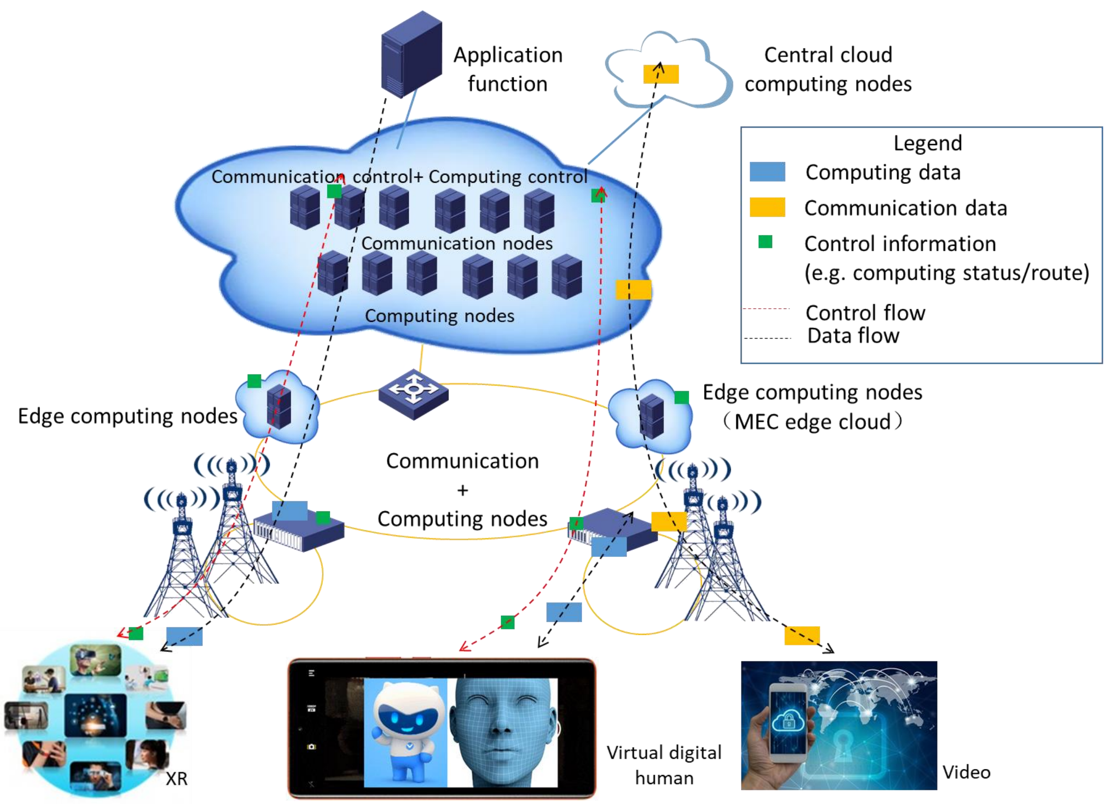

Figure 8. Network architecture diagram on the convergence of mobile network and computing

The computing function in 6G system can provide computing offloading for UE，and also provide in-network computing. In-network computing refers to simultaneous computing services for data during data transmission between application function and UE, as well as between UEs. As shown in Figure 8, UE can select the appropriate computing node and obtain computing services through 6G system. The typical converged computing service flows are described as follows.

- UE requests 6G network computing power from the network computing function, and the network computing function sends the computing results to UE.
- The application function or UE requests 6G network computing power from the network computing function, and the network computing function sends the computing result to UE or application function.
- UE requests external computing power and obtains computing results, where 6G system collaborates with the external cloud function to dynamically adjust the required transmission performance and computing nodes, etc.

Key technologies of convergence of mobile network and computing are described as follows.

- Metrics and awareness of computing service/resources. Metrics of computing service/resources are the fundamental issues. Uniform metrics based on multiple dimensions including computing, storage and networking can provide uniform rules for status sensing, control, management and charging of computing service/resource. Awareness of computing service/resources, i.e., real-time awareness of computing service/resources status of 6G internal or external computing nodes, can support a fast selection of computing node for the computing service and guarantee QoE.
- Control and management of computing services. Based on the computing requirements, 6G system needs to determine whether to divide computational task into sub-tasks, and request and negotiate computing resources for the sub-tasks.
- Control and management of computing bearer. The computing bearer provides the transmission channel for computing data interaction, to meet the demand of both communication QoS and computing QoS. The control and management of computing bearer include the creation, modification, deletion and QoS

management of computing bearer.

4.3 Integrated sensing and communication

Integrated Sensing And Communication (ISAC) is a key 6G enabling technology to provide basic information services. Typical use cases and application scenarios for ISAC are listed in Table 7. It is worth noting that the channel environment related information obtained through sensing can also be used to assist the communication system in channel estimation, beam management, etc., and enhance the performance of the communication system [17].

Table 7. Typical use cases and application scenarios for ISAC

Category of ISAC use cases	Use cases	Application scenarios
Coarse-grained sensing	Weather conditions monitoring, air quality monitoring	Meteorology, agriculture, daily life services
	Flow detection and quantity statistics for traffic and pedestrian, intrusion detection	Intelligent transportation, security monitoring
	Localization, tracking, and range/speed/angle measurement for target object	Application scenarios of radar
	Environment mapping	Smart driving and navigation for car and UAV (Unmanned Aerial Vehicle), smart city
Fine-grained sensing	Motion/pose/face recognition	Intelligent interaction, gaming, smart home

	Vital signs monitoring (Heartbeat respiration, etc.)	Health care, medical care
	Imaging, material detection, composition analysis	Security inspection, industry, biomedicine

To design a unified framework for sensing measurement and report for a variety of sensing scenarios and use cases, three levels of sensing information are defined in Table 8.

Table 8. Three levels of sensing information

Level for sensing information	**Sensing information**	**Content**
1	Received signal or raw channel information	Complex result of received signal or channel response, amplitude/phase, I /Q components and the related arithmetic results
2	Sensing measurements	Delay, Doppler, angle, strength, and their multidimensional combinations
3	Sensing results	Presence or absence of target, distance, velocity, orientation, acceleration, position, trajectory, movement, expression, respiration rate/heart rate, imaging results, weather, air quality, material and composition, etc.

ISAC use cases and application scenarios bring new requirements on the system functional framework design. ISAC system needs to support sensing service request reception, sensing quality of service (QoS) assurance, sensing control and air interface sensing, as well as generating sensing results and sensing service request responses based on the sensing measurements.

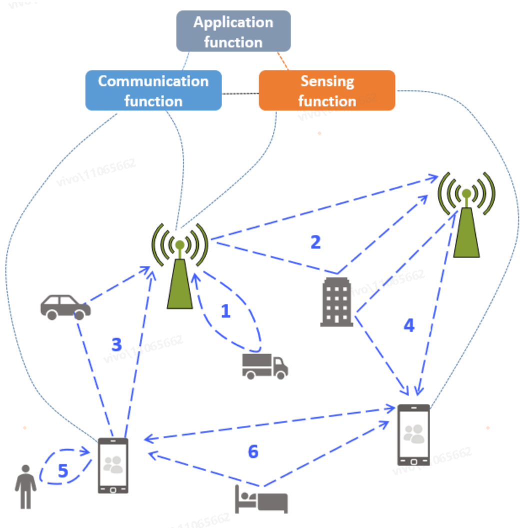

Figure 9. Functional framework of integrated sensing and communication system

The definition of sensing QoS can be referred to the definition of sensing service performance indicators in Chapter 3. The sensing control mainly includes:

1) Configuring sensing signals according to the sensing service request or sensing QoS. Sensing signals could be reference signals, synchronization signals, data signals, etc. The sensing signal configuration includes time, frequency and space resource configuration of the sensing signals, etc.

2) Determining the required sensing measurement quantity and measurement configuration for the sensing service request. The measurement quantity could be layer 1 or layer 2 sensing information shown in Table 8. The measurement configuration includes the indication of the sensing signals to be measured and the transmission format of the sensing measurement quantity, etc.

3) Determining the sensing transmitter(s) and sensing receiver(s), i.e., network equipment (e.g., BS), UE, etc. Different sensing transmitter(s) and sensing receiver(s) constitute different sensing methods, including Uu based sensing (3 and 4 in Figure 9), sidelink based sensing (6 in Figure 9), BS/UE monostatic sensing (1 and 5 in Figure 9), and inter-BS bistatic sensing (2 in Figure 9).

In addition to the above sensing functions, sensing capability registration and interaction, sensing security and privacy, and sensing billing are also important functions for ISAC system.

The key air interface technologies for ISAC system include waveform design, multi-antenna sensing technologies, sensing algorithm design, interference cancellation, etc.

- Waveform design. Waveform design is the key technology of ISAC, which could be communication-waveform-based design, sensing-waveform-based design, and new waveform design. Communication waveforms include OFDM (Orthogonal Frequency Division Multiplexing), SC-FDE (Single Carrier Frequency Domain Equalization), OTFS (Orthogonal Time Frequency Shift), etc. Communication-waveform-based design is to implement sensing functions while ensure the efficiency of communication information transmission. Sensing waveforms include FMCW (Frequency Modulated Continuous Wave), etc. Sensing-waveform-based design is to embed communication information while ensure the performance of sensing parameter estimation. New waveform design, which is still at the early stage of research, requires trade-offs between communication performance and sensing performance. The selection of waveform parameters can be based on the integrated performance metrics of communication and sensing to achieve the optimal overall performance.

- Multi-antenna technologies. ISAC systems need to support multi-antenna technologies in order to improve both communication performance and sensing performance. Take phased-array radar and MIMO radar as examples, the former uses the entire antenna array for beamforming and can form a narrow beam with high gain and high directivity, while the latter uses waveform diversity and virtual array features to obtain higher detection/estimation resolution, higher maximum identifiable target number, and better clutter rejection compared to phased-array radar with the same aperture [18]. The design of massive MIMO hardware architecture and antenna arrays, the design of precoding/beamforming schemes, etc. are important research directions of ISAC.

- Sensing algorithm design. Different from communication systems, sensing systems usually use unmodulated transmit signals and use parameter estimation algorithms e.g. periodogram, MUSIC (Multiple Signal Classification), ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques), and compressed sensing to obtain specific information including amplitude, angle, Doppler, and delay of the channel. The ISAC receiver needs to select the appropriate processing algorithm according to the division of communication and sensing functions and their influence on each other.

- Interference cancellation. Interference in communication systems mainly includes inter-cell interference and intra-cell multi-user interference. The interference in sensing system includes the clutter interference caused by non-sensing targets in addition to the interference in communication system. In particular, for monostatic sensing, there is also self-interference of transceiver, which requires effective isolation between transmitter and receiver, or self-interference cancelation. For ISAC systems, in addition to the above-mentioned interference, potential interference between communication signals and sensing signals also needs to be considered. An advanced interference management and suppression scheme is the key to ensure the performance of ISAC system.

To realize the application of ISAC, in addition to the research needed on the above-mentioned key technologies, there are still the following challenges to be solved:

- Performance balance and joint optimization of communication and sensing. Determining the joint performance metrics of communication and sensing in different scenarios and solving the trade-off between communication data rate and sensing accuracy from the theoretical aspect are of great significance for the design, evaluation and optimization of ISAC.

- Channel measurement and channel modeling for ISAC. Communication channel models cannot be directly used for ISAC scenarios. First, communication channel models cannot distinguish between sensing targets and non-sensing targets, and channel modeling for ISAC scenarios requires at least some level of deterministic modeling of multipath/multipath clusters of the sensing targets and clutter. In addition, the communication channel model does not support self-transmitting and self-receiving. For monostatic sensing, the reflection and scattering characteristics of the sensed target need to be considered in the channel model. The channel experienced by the echo signal has twice the path loss compared to the communication channel, and has additional reflection loss (related to the RCS of the sensed object).

- Impact of non-ideal factors on sensing performance. Extracting accurate CSI (Channel State Information) by detecting the sensing signal is the key to meet the sensing performance, and some non-ideal factors can lead to CSI measurement errors. The hardware non-ideal factors that affect the sensing performance mainly include:

- Uncertainty in power of the received signal. The actual gain adjustment differs from the expected one due to the non-idealities of Low Noise Amplifier (LNA), Programmable Gain Amplifier (PGA), etc. This affects the estimated CSI amplitude [19].
- I/Q imbalance. Due to the limitation of device performance, the phase difference of the I and Q branches of the local oscillator signals cannot be guaranteed to be exactly 90°, the amplitude of the I and Q branches is different, and there is a DC (Direct Current) offset. All the above will affect the orthogonality of the baseband signal.
- Non-ideal clock. Clock deviation at the transmitter and receiver brings Carrier Frequency Offset (CFO), Sampling Frequency Offset (SFO), Symbol Timing Offset (STO), etc. In addition, the noise introduced by the nonlinear oscillator brings random phase noise to the output carrier, and these factors affect the accuracy of parameters estimation such as speed and distance estimation.

4.4 AI-native system

In recent years, AI has achieved great success in several fields such as image recognition and natural language processing in the computer field, and motion control and trajectory planning in the robotics field. If AI is applied to communication systems, it is necessary to combine the requirements of communication systems and the advantages of AI technology to unlock specific use cases. AI can be used to solve the following three types of problems in 6G communication systems:

1) Problems that cannot be accurately modeled. For example, the impact of power amplifiers on the signal, the nonlinear impact of the actual channel and noise (colored and colorless) on the signal. In this aspect, AI can extract the features from a large amount of wireless communication data to complete modeling of complex problems more accurately.

2) Problems in communication systems for which closed-form solutions are difficult to obtain or not available. For example, the problems could be channel variation with time and frequency, UE trajectory prediction, traffic prediction, wireless resource allocation, multi-user pairing, coverage optimization, capacity optimization, and other nonlinear problems and nonconvex problems. In this aspect, AI can summarize the hidden relationship between input and output through a data-driven approach, and directly provide the corresponding solution or approximate solution.

3) Joint optimization problems of multiple functional modules. For example, cross-layer optimization, joint optimization of multiple MIMO-related signal processing modules, joint source and channel coding, joint design of equalization and decoding, etc. In this aspect, AI can model multiple related functional modules as a neural network and convert the complex multi-module joint problem into a simple data fitting or regression problem.

We believe, 6G will be an AI-native system where the network entities i.e., Network Management System (NMS), Core Network (CN), BS and UE, have AI resources and capabilities, and collaborate with each other to realize AI-related scenarios and use cases together with the 6G functions, e.g., user plane and control plane functions. Figure 10 shows an AI-native architecture with the following characteristics.

- All four types of network entities, i.e., NMS, CN, BS and UE, have basic AI functions and AI resources (computation, storage, etc.)
- AI resources enable Data Management Functions (DMF), Model Management Functions (MMF) and control functions.
  - ■ DMF include data collection, data pre-processing, data labeling, sample library, etc.
  - ■ MMF include basic model repository, model training, model transfer, model inference, model activation and de-activation, model monitoring, model updating, etc.
  - ■ The control function refers to the policy and parameter configuration of the DMF and MMF, which can be accomplished through the control plane function of CN or RAN.

- The AI basic functions between the four types of network entities can interact with model, data and control information. For example,
  - The AI basic function of CN collects data from the AI basic function of many UEs, trains model, and provides services for AI use cases of UE QoE (Quality of Experience) prediction
  - In the case of limited AI computing resources at BS, the AI basic function of BS can send the collected data and training control signaling to the AI basic function of NMS and request NMS to execute the training. After executing the calculation, NMS feedbacks the model to the AI basic function of BS
  - The UE can download the model from the AI basic function at BS or CN to its AI basic function, and then provide services for the AI use cases at UE.
- AI basic functions complete AI use cases independently or collaboratively.

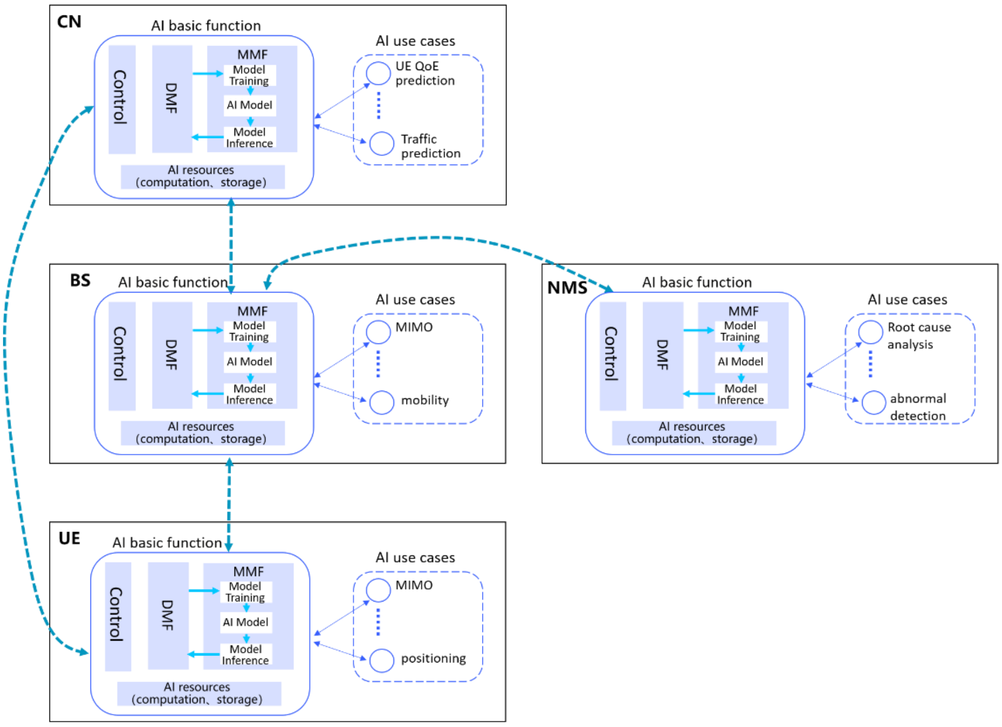

Figure 10. AI-native system architecture

As mentioned above, the AI-native system is a closely collaborated system composed of network entities such as CN, NMS, BSs and UEs. Whether an AI application requires information exchange and collaboration among network entities has a great impact on the algorithm and specification design. For example, according to the collaboration level shown in Figure 11, in signaling level collaboration (Level 1), the lifecycle management needs to be performed on one side or both sides independently, while in the case of tight collaboration (Level 3), the lifecycle management requires to be tightly coupled on both sides.

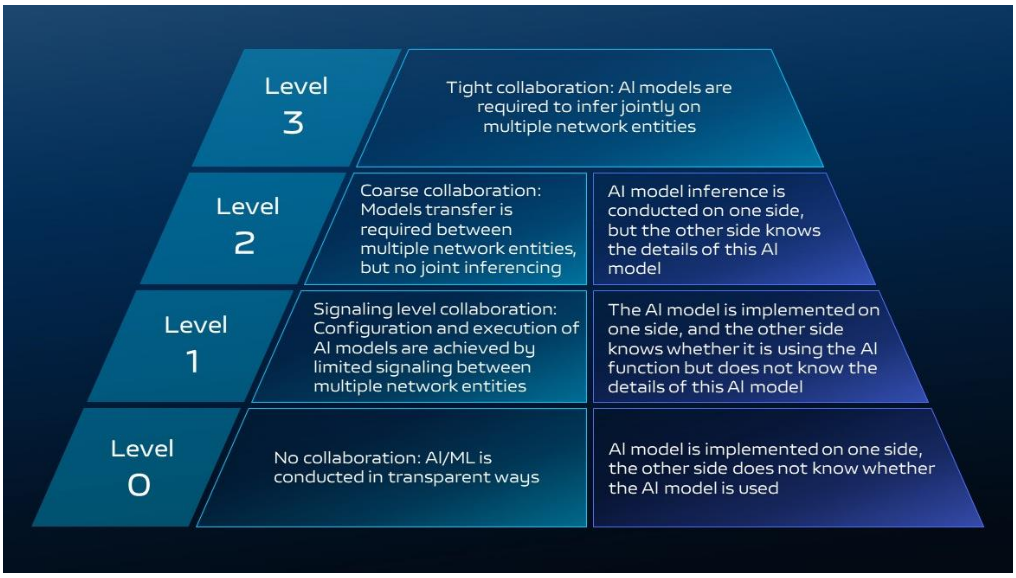

Figure 11. Collaboration levels of AI-native communication systems

Another promising feature of AI-native system is the ability of self-evolution, which is achieved by continuously collecting data, extracting knowledge, and iteratively interacting with the environment and users during the operation. The self-evolution automates the updating and elimination of old modules and the derivation of new ones, gradually building a more efficient communication system. According to the level of complexity, the self-evolution can be divided into 4 stages.

- Stage A: the parameters of the AI model can be evolved while the hyperparameters, inputs and outputs of the AI model are fixed.
- Stage B: the system can evolve and replace the structure, model, hyperparameters of the AI model, etc.
- Stage C: the system can update, combine and delete existing modules according to predefined rules, and can search and discover new modules autonomously.
- Stage D: the system can autonomously determine and modify the self-evolution rules.

There are several schemes for applying AI to specific communication use cases. The first one is AI based single-module optimization scheme. Examples include AI-based localization, beam management, precoding, channel coding, channel estimation, mobility management, resource allocation, traffic prediction [20~22]. The second one is AI based multi-module joint optimization scheme that models multiple interrelated functional modules into one AI model. For example, the processes related to MIMO signal processing such as channel estimation, channel feedback and precoding are modeled as a joint problem [23], where the spectral efficiency is used as the global loss function to obtain the optimal MIMO transmission scheme. Taking the simplified flow of physical layer signal processing as an example, Figure 12 illustrates the AI based single-module optimization and AI based multi-module joint optimization. Considering multiple factors such as industrial ecological development and standardization progress, we believe that the evolution of AI-native system is a gradually evolving process: starting from the AI based single-module optimization and then gradually realizing AI based multi-module joint optimization.

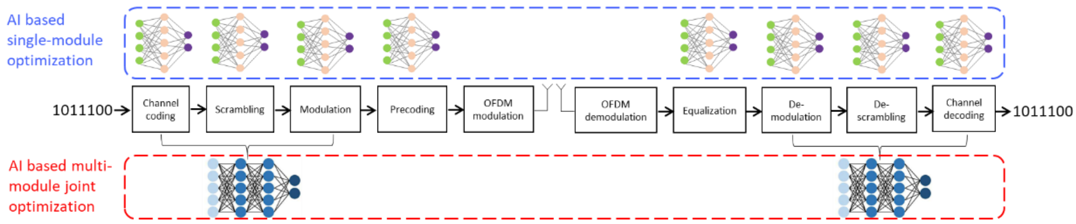

Figure 12. Examples of single-module optimization and multi-module joint optimization for physical layer signal processing

In the following, some applications of AI in communication systems are presented. The CSI feedback problem can be implemented by an auto-encoder based AI neural network [24]. Figure 13 shows the performance of AI-based CSI feedback compared to the eType II codebook-based CSI feedback (traditional non-AI scheme). The detailed simulation parameters can be found in [24]. With the same feedback overhead, the AI-based channel feedback can achieve about 10% spectral efficiency gain.

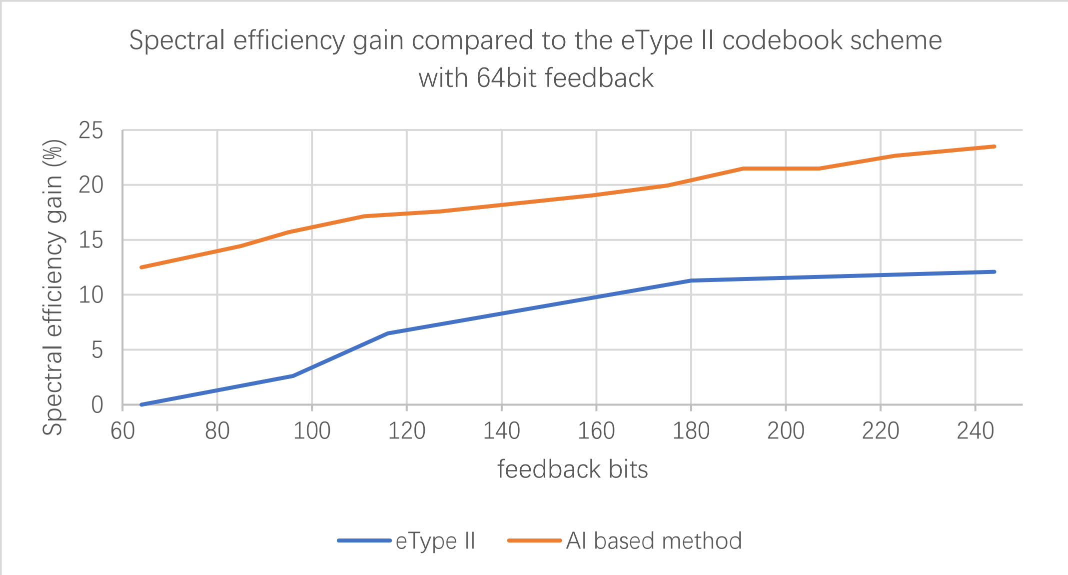

Figure 13. Spectral efficiency gains with different channel feedback schemes in Urban Micro scenario

AI can also be used in wireless signal-based positioning where AI can be utilized to exploit the hidden relationship between the reference signal and the user's location to achieve high accuracy positioning. Figure 14 shows the positioning accuracy with the various wireless signal-based positioning methods [25]. The AI-based positioning method can ensure a 90% accuracy with the positioning error of 4 meters, while all other schemes can offer a 90% accuracy with the positioning error of 20 meters or even more.

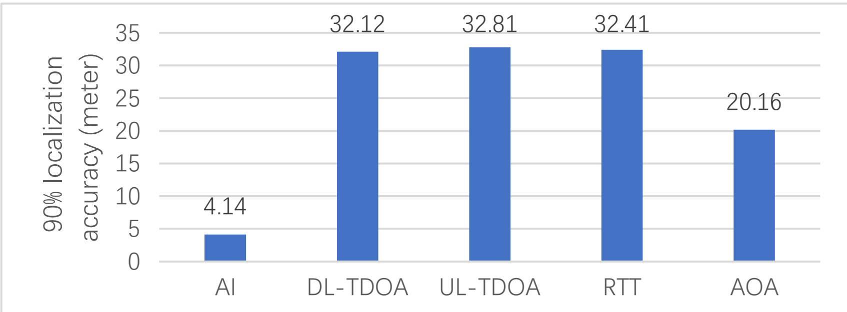

Figure 14. Positioning accuracy of various wireless signal-based positioning methods

AI can also be used to solve the Demodulation Reference Signal (DMRS) based channel estimation problem by obtaining the channel estimation results of all time-frequency resources from the channel estimation results of the time-frequency resource where the DMRS is located [26]. The prototype system developed by vivo shows that, even with half of the DMRS resource overhead, the channel estimation offered by AI-based DMRS can achieve a lower BLER and higher throughput than that by the non-AI scheme.

AI-native 6G system has to overcome lots of challenges. Firstly, the ability to efficiently collect data is crucial. AI requires large amounts of data for training, while the required data contains private information associated with users, operators and vendors that cannot be easily transferred. In this regard, federated learning [27] and swarm learning [28] could be the important directions to be considered. Secondly, AI models inherently suffer from a lack of generalization ability, which will be further aggravated by the varying wireless communication environments. Transfer learning [29], meta learning [30], and other few-shot learning can be the potential solutions to solve this problem.

The understanding of 6G AI-native system within the industry includes not only AI enabling 6G communication systems, i.e., AI as internal services, but also 6G system providing AI services for thousands of industries, i.e., AI as external services. AI resources deployed in 6G system can be provided for both internal and external services through proper orchestration. However, there are significant differences in requirements and architecture between internal and external services. From the requirement aspect, on one hand, the use cases of internal and external services are quite different in terms of problem modeling, AI collaborators, data collection and transfer, model requirement, AI inference accuracy, latency and computation requirement, etc. It is difficult to meet the personalized service requirements of AI for thousands of industries with a highly efficient system that enables the intelligence of the communication system itself. From the architecture point of view, on the other hand, external AI services are often built on top of communication bearers, hence they need to go through more layers of communication protocols, additional encryption and privacy protection, etc. Internal AI instances can collect data, transfer and manage model through AI and 6G signaling and protocol at each layer. In addition, the internal services usually do not require billing and service control. Whether the AI-native system architecture can be efficiently integrated with the external AI service architecture of mobile computing network needs further study.

4.5 Data function and data plane

Data is a common requirement for all the services of 6G, i.e., super communication service, basic information service and converged computing service. Data function is a supporting technology for enabling technologies such as AI-native system, ISAC, convergence of mobile network and computing, etc. Data function needs to efficiently fulfill the requirements of multiple services.

For super communication service, data function needs to enhance cross-domain data collaboration, data reuse efficiency and time-accumulation effect. The cross-domain data collaboration includes data collaboration among CN, RAN, UEs, external functions, etc. The data reuse shall facilitate avoidance the duplicated collection of the same or similar data in a point-to-point approach. A small amount of immediate data available at a single time instance is difficult to meet the demand of 6G AI-native system. Therefore, the persistent data at multiple time instances are beneficial for the time cumulation.

For the control optimization of new services (e.g., sensing and computing), the data function provides real-time status of network functions and resources, such as location information of sensing nodes (e.g., BSs or UEs), UE movement speed, communication load, computing load, etc. For user-level data, the generation, collection and storage of personal data are supported by the data function according to the user's requirements and authorization. The user-level data control and storage need to be done at data nodes that are owned by the individual user. Any function inside or outside the network that is not authorized by the user cannot control, access or use user-level personal data. The data function provides the technical support for personal data protection with administration and data leakage traceability.

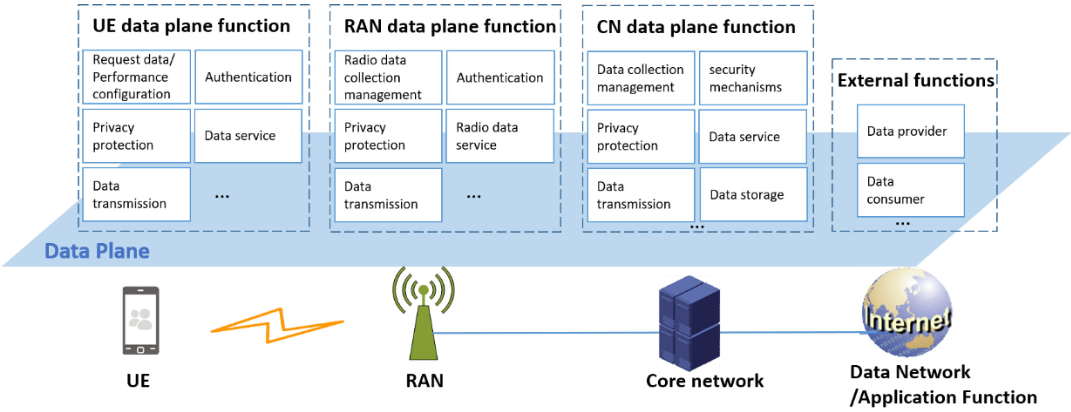

Figure 15. 6G data function and data plane

6G data function provides the common basic data required by the network, including network data, UE-level data and non-UE-level data, etc., rather than point-to-point data between application functions or communication control data. Currently, the logic of UP functions is to provide the paid data transmission, while the logic of CP (Control Plane) functions is to guarantee the high-priority and real-time transmissions of control information. However, the logic of data function needs to consider payment to the data provider, and the priority of data function is not as high as control plane functions. The data function may also be different from the existing CP/UP in terms of security and mobility, etc. The potential termination points of data may lay in CN, RAN (Radio Access Network) or UE. The equality between UE data function and network data function can be enhanced. Therefore, solutions of 6G data function need to prioritize holistic solutions that can meet the requirements of multiple services and functions, and avoid pieces of fragmented solutions that address the requirements of individual service or function.

Data plane, with end-to-end connectivity, is a potential solution consisting of CN data plane functions, RAN data plane functions and UE data plane functions. The data plane is responsible for data collection, privacy and security, data analytics, data pre-processing and data storage. The introduction of the data plane helps improve the logic of the division of responsibilities among network functions and the flexibility of UE design. The key technologies of data plane are described as follows:

- Data definition and classification: Data definition and classification are the fundamental issues of data plane. The scope of data extends from existing communication related data by means of NWDAF (Network Data Analytics

Function), SON (Self-Organizing Network), MDT (Minimization of Drive Tests) and QoE to data related to information service and computing service. Data can be classified and graded in terms of multiple dimensions, such as application scenarios, data sources, security requirements, data volumes and so on.

- Diverse data interactions: Data interactions of data plane can be single point to multipoint, multipoint to single point or multipoint to multipoint. Data termination point can be at the CN, RAN or UE. Therefore, data plane functions need to support diverse data interaction requirements efficiently.

- Mechanisms for privacy protection and security: Privacy and security are fundamental functions that must be supported by data services. Information service and computing service may increase the risk of user privacy exposure. Therefore, the security mechanisms for authorization, collection and processing of user data need to be enhanced accordingly. In addition, the trustworthiness of the UE original data is decided by the security of UEs. The authentication mechanism of data services needs to be able to prevent security issues such as malicious forged UE identity. When data is provided to the external functions, key actions of the data processing need to be recorded, which can be used as digital forensics by the regulatory departments to determine whether data usage complies with the law.

4.6 Extremely low power communication

Extremely low power communication (ELPC), with features of low cost, low power and huge number of connections, is one of the key technologies to realize ubiquitous connectivity. Compared with existing 5G IoT devices, extremely low power devices are expected to have lower deployment cost, lower power consumption with only about a hundred microwatt or even zero power required. Particularly, in addition to providing about a hundred Kbps communication data rates at the coverage of about a hundred meter, the extremely low power devices can also support positioning and sensing services, and thus eventually enable the interconnection between the physical and the digital worlds.

In broad sense, the typical use cases of ELPC can be categorized as wide-area coverage scenarios and local-area coverage scenarios. To name a few examples, wide-area coverage scenarios include logistics and warehousing, environmental monitoring, smart agriculture, railroad operation and maintenance, powerline inspection, industrial IoT, etc. Local area coverage scenarios include smart home, wearable devices, low power health monitoring, implantable medical, etc.

Extremely low power transmitting technology

Backscatter communication is the most representative technology of ELPC. In principle, backscatter communication devices modulate data bits by reflecting and modifying the signal properties, (amplitude, frequency, and phase) of incident RF signals from the environment, through the use of adjustable antenna impedances. A typical backscatter communication device is composed of the following hardware modules: antenna, energy harvesting module or battery, microcontroller, receiver, channel coding and modulation module, memory or sensor. Additionally, low power amplifier can be applied to improve receiving sensitivity and the power of backscattered signals.

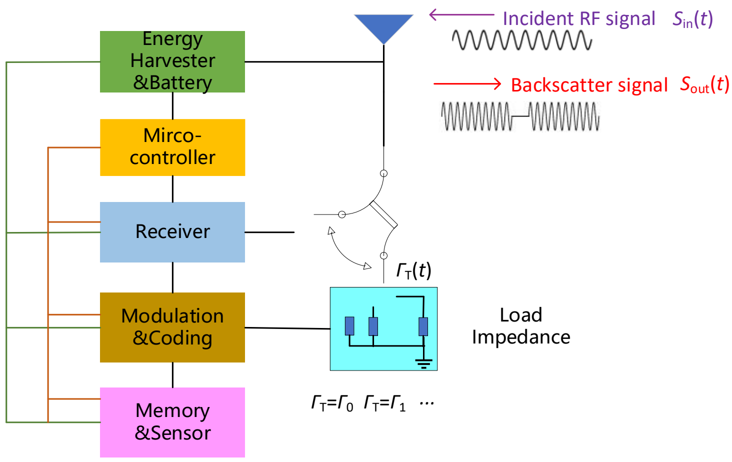

Figure 16. Backscatter communication hardware architecture and modulation principle

Limited by the hardware capability of backscatter circuits, energy storage capacity, transmit power of RF sources, double fading effects, receiving sensitivity, and antenna gain, it is highly demanding to enhance the physical layer of backscatter communication regarding date rates, coverage, connectivity, and reliability. To widen the application, the key enabler techniques of backscatter communication include:

(1) Data rate enhancement: High order modulation schemes such as APSK (Amplitude Phase Shift Keying) and QAM (Quadrature Amplitude Modulation) are shown to be effective in improving transmission data rates. Besides, millimeter wave and MIMO can also be applied to achieve high data rates in backscatter communication. vCRI has built a backscatter prototype in collaboration with Beijing Jiaotong University, which successfully achieved 2 Mbps with 4ASK (4-ary Amplitude Shift Keying) and QPSK (Quadrature Phase Shift Keying) modulation, preliminarily demonstrating the feasibility of high data rates in backscatter communication.

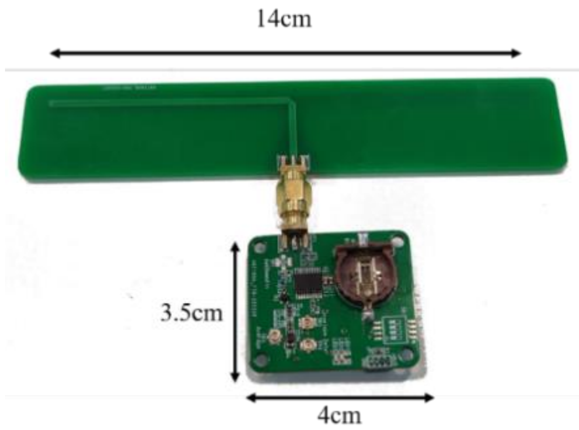

Figure 17. Backscatter communication device prototype

(2) Coverage expansion: Bistatic architecture [31], beamforming, and high-efficiency energy harvesting circuits are major techniques to improve the coverage of backscatter communication. Moreover, the introduction of low power reflection amplifier is also shown to be capable of expanding coverage by amplifying the transmit power of backscatter devices [32]. Table 9 provides some link budget of backscatter communication under some typical parameter settings. Accordingly, UE-assisted bistatic architecture and low power amplifier can significantly extend the communication range to hundreds of meters, demonstrating the feasibility of integrating backscatter communication in cellular networks.

Table 9. Comparison of coverage for different deployment scenarios and architecture

Parameters/Assumptions	ELPC Device communication with gNB directly (without amplifier)	ELPC Device communication with gNB directly (with amplifier)	UE assisted ELPC device (without amplifier)
Carrier frequency (GHz)	0.90	0.90	0.90
Tx Power (dBm)	36.00	36.00	23.00
RF Energy Source->ELPC Device Distance (m)	100.00	100.00	3.00
Path Loss (dB)	71.48	71.48	41.03
Reflection Amplifier	0.00	20.00	0.00
Return Loss (dB)	8.00	8.00	8.00
ELPC Device Antenna Gain (dB)	0.00	0.00	0.00
ELPC Device Tx EIRP (dBm)	-43.48	-23.48	-26.03
Reader Antenna Gain (dB)	6.00	6.00	6.00
Receiver Sensitivity (dBm)	-92.00	-92.00	-92.00
MCL (backscatter link) (dB)	54.52	74.52	71.97
Coverage (backscatter link) (meters)	14.17	141.75	105.78

Remark：The deployments can refer to the network architecture in Figure 19.

(3) Reliable transmission: Designing innovative channel coding schemes, e.g., code structure and low-complexity channel coding and decoding techniques, based on the service characteristics, channel conditions, and usage scenarios are the key technologies to reliable transmissions and quality of service provisioning in backscatter communication. Moreover, a joint coding and modulation scheme with high code rate can further enhance reliability while satisfying the low-cost and low power requirement of backscatter communication. In addition, the space-time block code, which is designed considering the load impedance matching characteristic, is another effective technique for reliable improvement [33].

(4) Interference cancellation: The receiving sensitivity can be greatly improved by

isolating the transmitting channel and receiving channel, e.g., separating transmitting and receiving antennas, multi-port circulators, directional couplers, and carrier leakage interference cancellation techniques, e.g., receiving dual circuit elimination, negative feedback loop, dead zone amplifier offset. In bistatic architecture, if the RF signal exhibits certain structural characteristics, e.g., the repetitive structure in time-domain or frequency-domain, those structural characteristics can be leveraged to design some special modulation scheme to effectively cancel cross-link interference [34].

Extremely low power receiving technology

Low power receiving technology is also a key factor in ELPC, including wake-up and data reception. Particularly, low power wake-up receiver technology can enable the standby power consumption at the micro watt level, and thus significantly extend the battery life of terminal devices [35]. In addition to the low power wake-up receiver, the low power data reception can be used in ELPC to achieve 10 Kbps~1000 Kbps data rate reception under the active power consumption of 10 uW~100 uW.

Non-coherent detection receiver is the key technology to achieve extremely low power reception. Particularly, the envelope detector directly transforms the RF signal to low-frequency signal, which can effectively reduce the receiver complexity, and reduce power consumption by 1/1000 - 1/100 folds, a reduction to the micro-watt level. Although, non-coherent detection receiver can effectively reduce the receiving power, it can also cause a loss of reception sensitivity. The communication range can be extended through effective transmission signal waveform design. However, when the low power receiver receives the target low power signal, it inevitably suffers from the co-channel interference and adjacent channel interference, resulting in a high false alarm detection probability and miss detection probability. Specifically, interference can also be suppressed by some techniques such as RF/IFL filters, comparator threshold adjustment and spread spectrum signal design. vCRI has built an extremely low power receiver prototype jointly with University of Electronic Science and Technology. It turns out that 10 kbps data rates can be achieved under the power consumption of only tens of microwatts according to the advanced CMOS process evaluation, and the receiving sensitivity is -73 dBm. The results validate the feasibility of high-sensitivity data reception under extremely low power consumption.

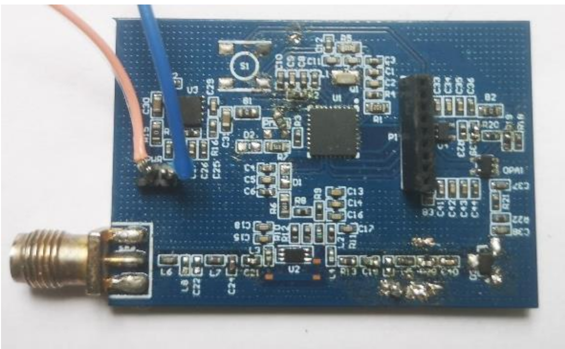

Figure 18. Prototype of extremely low power receiving technology.

System Design of Extremely Low Power Communication

The cellular based ELPC system has two basic modes. Mode 1 is the BS direct link mode, where the BS and the extremely low power device are directly connected for the transmission and the reception of both the uplink and the downlink data. This network deployment architecture in Mode 1 is simple, yet requires high receiving sensitivity in both BSs and ELPC devices. Mode 2 is UE/relay assisted mode, where at least one of uplink or downlink of the extremely low power device involves the UE or relay. This mode can effectively reduce the receiving sensitivity and power consumption requirements of extremely low power devices but introduces a little complexity in system design.

A complicated network architecture brings new challenges to operation costs, power consumption, and device costs. Thus, it is necessary to design a simplified network architecture suitable for ELPC. In general, there are two possible network architectures for cellular based ELPC system. In option 1, extremely low power devices do not access core network. Instead, the core network only provides data transfer between the extremely low power devices and an application server. The application server records the entity which transfers data to the extremely low power device and forwards the downlink data that is destined to the low power device to the entity. In option 2, network operator provides a reader and proxies the extremely low power device to access the core network. Conclusively, it is not necessary for extremely low power devices to support NAS protocol stacks, which helps to reduce the power consumption and costs. On the other hand, the core network can authenticate extremely low power devices, perform mobility management and provide secure and fine-grained services for the application.

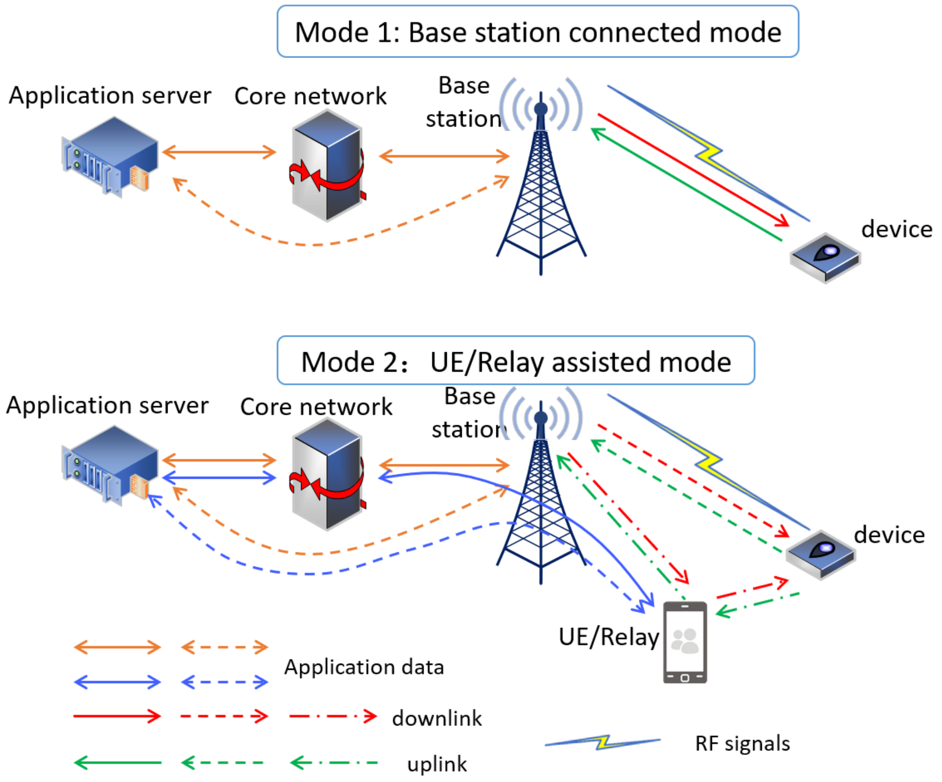

Figure 19. Network architecture for cellular extremely low power communication.

In addition to the key technologies mentioned above, a few open issues remain to be solved in order for cellular based ELPC to come true.

- Poor synchronization: Limited by the costs and power consumption of ELPC devices, the internal passive oscillation exhibits inaccurate sampling time and random drifts in time, dramatically degrading the communication performance and network capacity. Therefore, it is important and critical to address the synchronization issue without increasing the cost and power consumption of the device.

- Massive access technology: 6G is expected to support massive IoT devices with connection densities 10-100 times higher than in 5G. Conventional multiple access techniques based on collision management or grant-based orthogonal multiple access are not suitable for extremely low power devices. Thus, development of new multiple access techniques to meet the connectivity requirement of extremely low power devices is the key.

- Lightweight protocol stack: Considering the limitations regarding the costs, the power consumption and the complexity of ELPC devices, lightweight protocol stacks and simplified security mechanisms should be studied and designed to satisfy the service requirements.

4.7 MIMO evolution

The convergence of multi-antenna technology and OFDM technology improves the performance of 5G communication systems. 6G system is expected to achieve not only higher data rates, higher frequency and energy efficiency, but also focus on user experience in specific areas, such as coverage performance at the cell edge and communication performance in ultra-dense areas of hotspots. The evolution of multi-antenna technology in 6G includes centralized MIMO technology supporting higher frequency bands and large-scale distributed MIMO technology like cell free MIMO networking technology, etc.

The number of antenna units integrated in the same size antenna panel will increase when a higher frequency band is used in the communication system. 6G BSs, especially in the higher frequency bands, will be equipped with larger antenna arrays to provide finer beamforming. As the wavelength of the high band shrinks to the millimeter or sub-millimeter level, the area near the antenna panel of the high frequency band BS can be regarded as under the near-field channel condition [36]. The near-field range of the wireless device, $D_{NF} = \frac{2d^2}{\lambda}$, depends on the aperture of the device antenna array d and the wavelength of the wireless signal λ. Under the near-field channel condition, beamforming no longer targets just a beam direction, but specific locations of the users. Therefore, MIMO technologies of 6G may evolve from far-field beamforming to near-field beamforming, and eventually toward the holographic MIMO technology that precisely generates an arbitrarily shaped beam.

In interference-limited scenarios, distributed MIMO technology can reduce the impact of inter-cell interference for the cell edge users. The distributed MIMO deployment can be achieved through the jointly beamforming of multiple BSs or multiple TRPs, or the cooperation between the BS and other devices such as RIS or beamforming relays. Distributed MIMO could provide different transmission schemes depending on the capabilities of the wireless devices. For distributed transmitters with high accuracy synchronization, the coherent MIMO transmission scheme could be used to improve multiplexing gain, while for distributed transmitters with limited accuracy synchronization, the non-coherent MIMO transmission scheme could be adopted to achieve diversity gain. Differently distributed MIMO schemes are suitable for different communication scenarios. For example, multi-TRP beamforming scheme is suitable for enhancing the throughput in the hotspot scenario; the cooperation transmission of BS and RIS/ relays can be used to improve the hotspot throughput and extend the cell coverage.

Cell free MIMO technology [37] is suitable for the densely deployed networks. Cell free MIMO systems dynamically schedule multiple BSs or network nodes to form a distributed MIMO network to provide services for UEs according to the current wireless channel conditions. Cell free MIMO technology breaks the traditional cell boundary and transforms the mutual interferences from multiple cells into a distributed MIMO network that collaborates with each other, greatly enhancing the coverage performance of the wireless system and improving the UE mobility performance. In order to balance the spectral efficiency per unit area and UE mobility, cell free MIMO technology can be applied based on a two-layer networking scheme decoupling the control plane and data plane. The control plane network is mainly responsible for the signaling and process of the control plane including mobility management, etc. It provides a ubiquitous coverage and highly reliable links for the control plane functions by means of SFN (Single Frequency Network) involving multiple network nodes or low-frequency-band macro station transmission. The data plane network is responsible for serving user plane processes such as data transmission, dynamic node scheduling, and data services provisioning to the users in a distributed MIMO transmission mode.

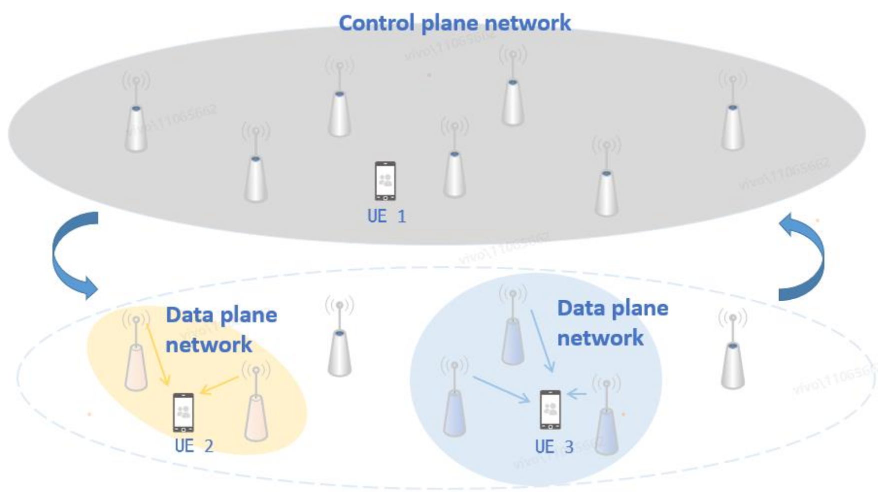

Figure 20. An example of cell free MIMO network deployment

There are several challenges for 6G ultra large-scale MIMO technology, including the hardware requirements and the algorithm designs.

- One of the key challenges is the hardware complexity and power consumption in ultra large-scale MIMO systems. With the increase in the number of antennas at BSs, especially the high-frequency-band BSs, the hardware complexity and power consumption of the BSs will increase significantly. To address this problem, a sparsely selected or sparsely distributed antenna array can be used to reduce the cost and power consumption of the BS.
- Distributed MIMO technology leads to higher requirement on the hardware performance at the BS. On the RF aspect, the distributed MIMO systems needs to ensure high-precision time-frequency synchronization between the nodes to realize a distributed MIMO transmission; on the baseband aspect, the networks need to flexibly configure baseband computing resources according to the network node grouping, including merging the baseband signals according to the scheduled node grouping, and the joint transmission/reception and processing of broadcast channels without knowing channel conditions.
- The 6G MIMO system requires allocation of more time and frequency resources for channel measurement and channel information feedback. There is a motivation to provide an efficient channel measurement and feedback mechanism to keep a balance between the data rate and the channel measurement accuracy. Considering the poorer penetration performance of high-frequency signals, 6G high-frequency communication is likely to be used for the high data rate transmission in LOS environments. 6G MIMO system can utilize the signal characteristics of orbital angular momentum (OAM) to design antenna arrays and codebooks to achieve multi-stream data transmission in the LOS channel environment [38].

4.8 Reconfigurable intelligent surface

Reconfigurable Intelligent Surface (RIS) [39] is a low-cost, low power, flexibly deployable hardware technology. RIS device can manipulate the electromagnetic parameters (amplitude, phase, polarization direction, etc.) of the reflected or reradiated signal by independently controlling the variable element (variable capacitors, PINs, etc.)

of the RIS unit. The reradiated modulated signals from many RIS units are superimposed on each other to form the desired spatial beam at a macroscopic scale, realizing the manipulation of the electromagnetic environment. Integrating RIS technology with the wireless communication system can further enhance the flexibility and transmission efficiency of the wireless communication system.

RIS technology can be deployed as an independent node in the communication system to enhance the communication performance. The coverage performance of the wireless networks can be improved by providing RIS-based reflection paths in poor coverage scenarios. Independently deployed RIS nodes can also manipulate the wireless signal propagation environment and improve the signal quality according to the requirement of the wireless network, such as increasing the transmission rank of MIMO in multipath environments or suppressing interference signals from other cells.

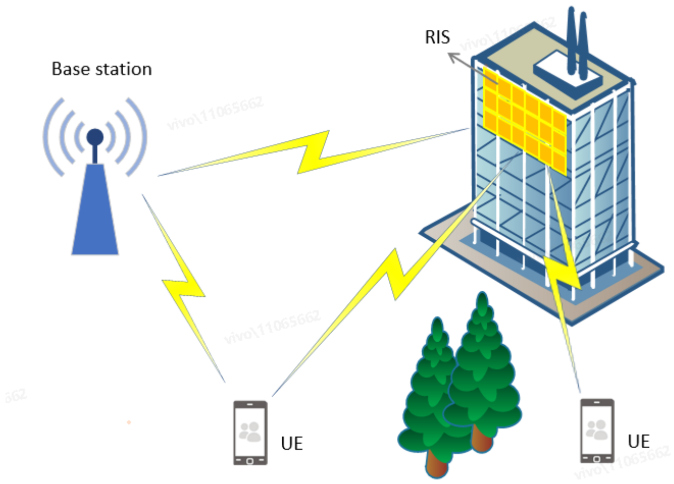

Figure 21. Improving the network performance via RIS

RIS technology can be applied in BSs or terminal equipment to form a new transceiver architecture. Considering the limitation on the number of RF units in BS, RIS module can be used as a further extension to the BS antennas acting as virtual antennas to provide a finer beam manipulation. Furthermore, with the help of the index modulation technique, the data bit stream to be transmitted are sequentially mapped by the control module into RIS states of different time domain resources, which converts the wireless signal into a modulated signal carrying data information.

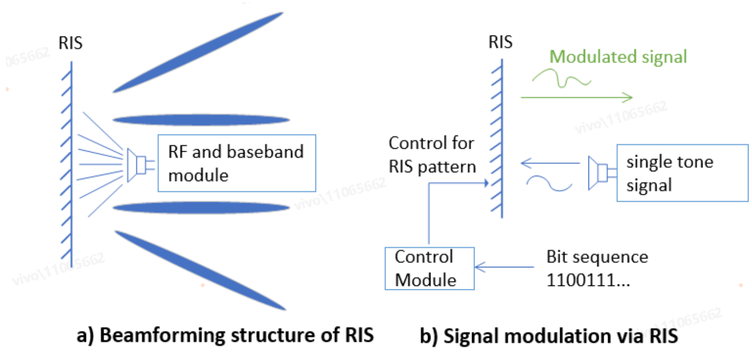

Figure 22. Novel transceiver architecture via RIS

RIS technology has brought up new research issues while improving system performance, including the hardware design issues and the network deployment issues for RIS and communication convergence.

In the aspect of hardware design, the hardware parameters of the RIS device shall match the working parameters of the wireless communication system. In a practical deployment scenario with multiple operators and multiple cells, the RIS device will receive wireless signals from multiple cells in different directions of different frequency bands. In order not to impact the properties of the unrelated cells or signals on unrelated frequencies, the working bandwidth of the RIS devices should match the working bandwidth of the serving cells. The working bandwidth of the RIS device can be approximated to that of the wireless communication system by optimizing the hardware structure of the RIS unit. For example, for a RIS unit constructed with four square patches, the working bandwidth could be reduced from 10 GHz to 1 GHz after attaching the additional delay line structure, as shown in Figure 23 and Figure 24 [40]. In addition, the working bandwidth of the RIS device can be further reduced by adding frequency filter modules, such as frequency selective surfaces or filter elements.

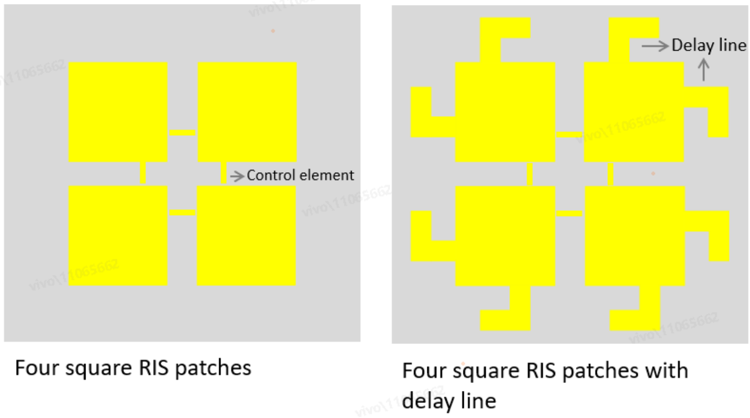

Figure 23. Optimizing RIS unit structure by adding delay line

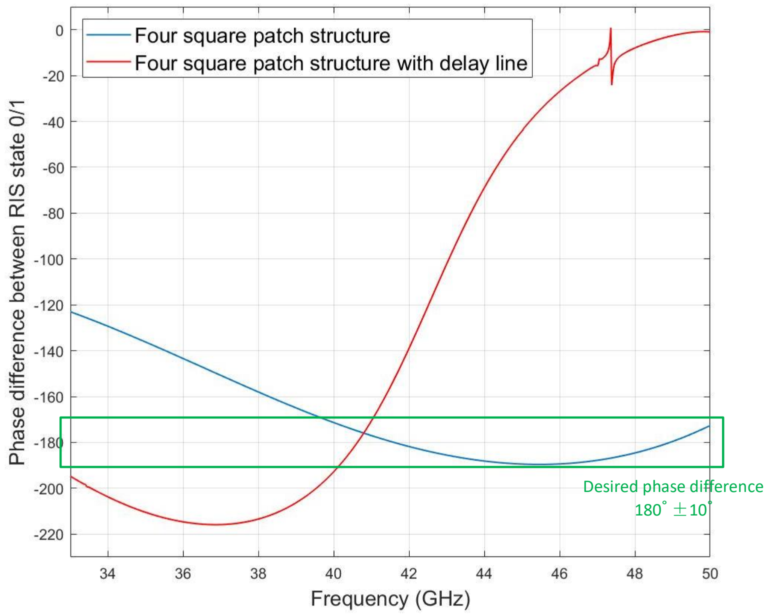

Figure 24. Restricting RIS working bandwidth by optimizing RIS unit structure.

In terms of the network deployment, new channel measurement and scheduling strategies should be designed based on the passive operating characteristics of RIS devices. Considering the passive RIS devices do not have the capability of independent channel estimation, RIS-based cascaded channel estimation and the corresponding RIS beamforming are necessary for the integration of RIS in the communication systems. When RIS technology in future wireless networks evolves from fixed-point deployments to large-scale distributed deployments, the 6G system shall consider the collaboration of RIS and BS to form the cell free MIMO networks instead of deploying base stations to reduce the cost and power consumption.

4.9 Delay-Doppler domain waveforms

The new waveform techniques considered by the industry or academia in recent years can be categorized as follow. One category is the evolution of the CP-OFDM (Cyclic Prefix Orthogonal Frequency Division Multiplexing) waveform adopted in existing 3GPP NR (New Radio) protocols, which was originally intended to overcome the sub-band/subcarrier interference problem of OFDM. The representative waveforms are f-OFDM (Filtered OFDM), W-OFDM (Windowed OFDM), UFMC (Universal Filtered Multi-Carrier), GFDM (Generalized Frequency Division Multiplexing), etc. [41~44]. There is also a class of waveforms based on QAM modulation techniques such as FBMC-OQAM (Filter Bank Multi-Carrier with Offset QAM), FBMC-QAM, WCC-FBMC-OQAM (Weighted Circular Convolution FBMC with Offset QAM) [45~47] that aim to mitigate the out-of-band leakage of OFDM waveform while reducing the complexity compared to the aforementioned filter-based techniques. There is also a class of techniques that seek to further improve spectral efficiency by artificially introducing inter carrier interference, inter symbol interference and corresponding non-linear receiver algorithms, such as MC-FTN (Multi-Carrier Faster than Nyquist) [48].

In recent years, OTFS modulation techniques [49] have attracted much attention. As a typical delay-Doppler domain waveform, OTFS migrates the digital signal processing and analysis from the time-frequency domain to the delay-Doppler domain. By exploiting the sparsity of the delay-Doppler channel, the OTFS can obtain more diversity gain by two-dimensional spreading from the delay-Doppler domain to the time-frequency domain, which shows excellent performance against Doppler-induced inter carrier interference. Furthermore, the CP-free design in each symbol overwhelms the OFDM waveform in spectral efficiency.

The OTFS waveform design in [49] requires a high complexity ISFFT transform, and its OFDM-alike waveform suffers the off-grid interferences in delay-Doppler domain. Alternative waveforms are being considered in the academia. For example, two alternative single-carrier-like waveforms are respectively based on continuous and discrete Zak transforms [50,51], and ODDM [52].

There are some key points in the research of practical OTFS waveform. Firstly, since OFDM is still a very competitive waveform, the coexistence of OFDM and OTFS in 6G system design needs to be considered. Secondly, the current pulse pilot design results in high PAPR (Peak to Average Power Ratio) in time-domain signals, which has limitation on the hardware implementation. Therefore, a low PAPR design needs to be considered. Thirdly, the combination of OTFS and MIMO is a guarantee of high transmission rates in high-speed scenarios. It is essential to design an efficient pre-coding mechanism for MIMO-OTFS systems.

- OTFS and OFDM waveforms coexistence

Follow the principle of ISFFT transform and signal sampling, we can replicate the modulated symbols in the delay-Doppler domain, which is equivalent to leave empty carriers or empty OFDM symbols between the transformed symbols in the time-frequency domain. These vacant time-frequency resources can be used to send OFDM signals to achieve coexistence of the two and improve the efficiency of resource utilization, as shown in Figure 25.

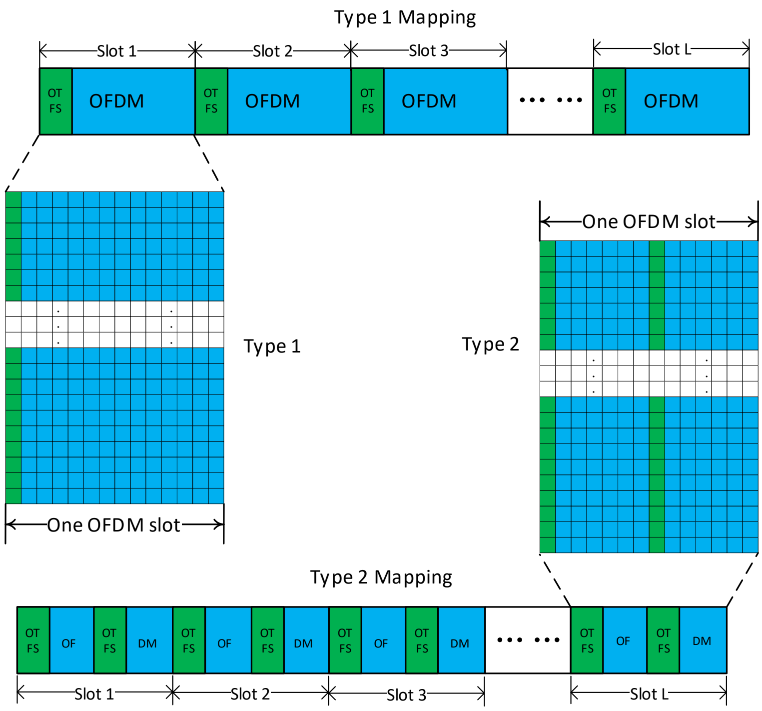

Figure 25. OTFS and OFDM hybrid frame

- Low PAPR pilot design

A sequence pilot design shown in Figure 26 effectively balances the power in each delay dimension, thus fundamentally solving the high PAPR problem.

With this novel pilot sequence design, the improvement in PAPR performance is evident as depicted in the CCDF plot in Figure 27. Meanwhile, the diversity gain in this dimension is obtained as the pilot sequence spreads in the delay dimension, resulting in a better channel estimation performance.

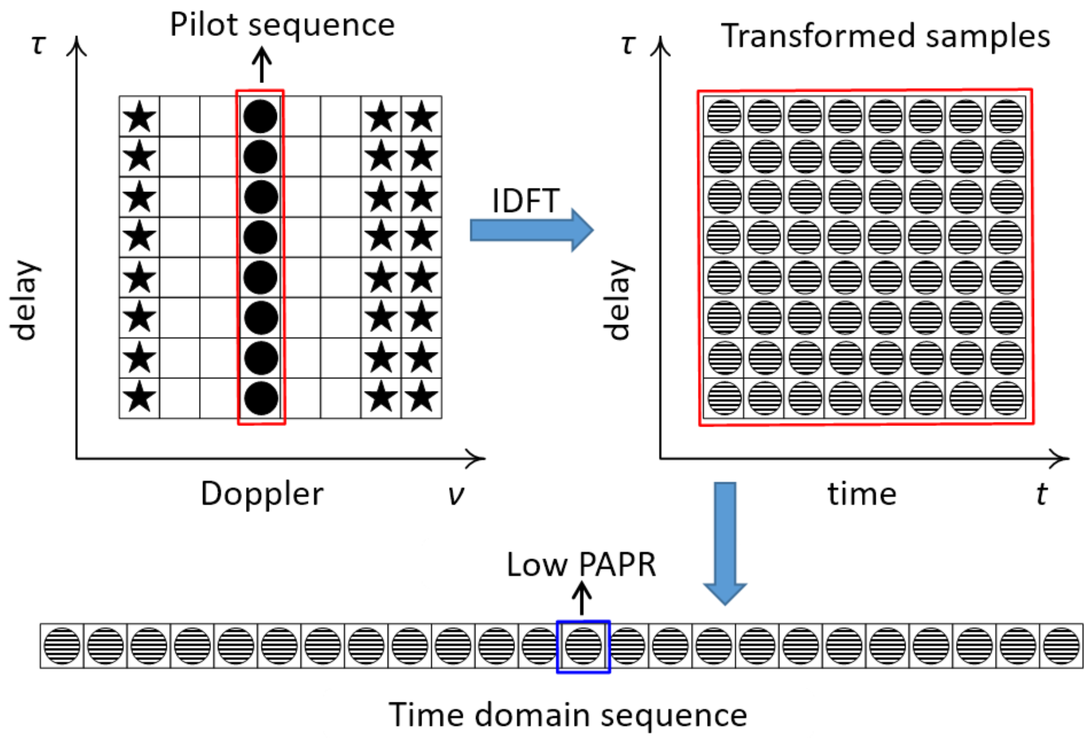

Figure 26. Low PAPR pilot design

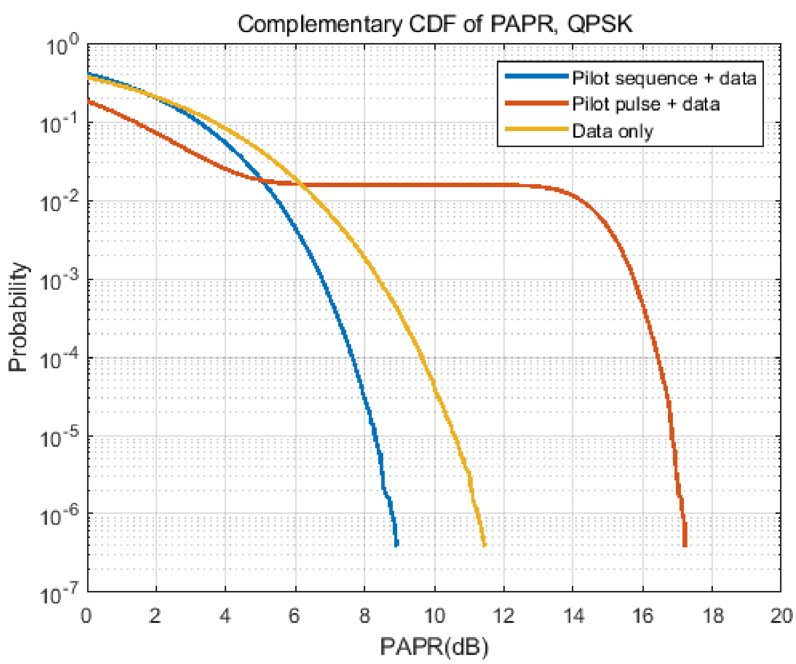

Figure 27. PAPR performance of different schemes

- OTFS-MIMO Technique

An open-loop diversity precoding scheme for MIMO-OTFS is shown in Figure 28, where the frame in the delay-Doppler domain at each antenna is equally divided into two half-frames along the Doppler dimension, each mapped with a data layer. The problem of inter-half-frame interference and channel phase offsets are solved by a specific protective spacing design.

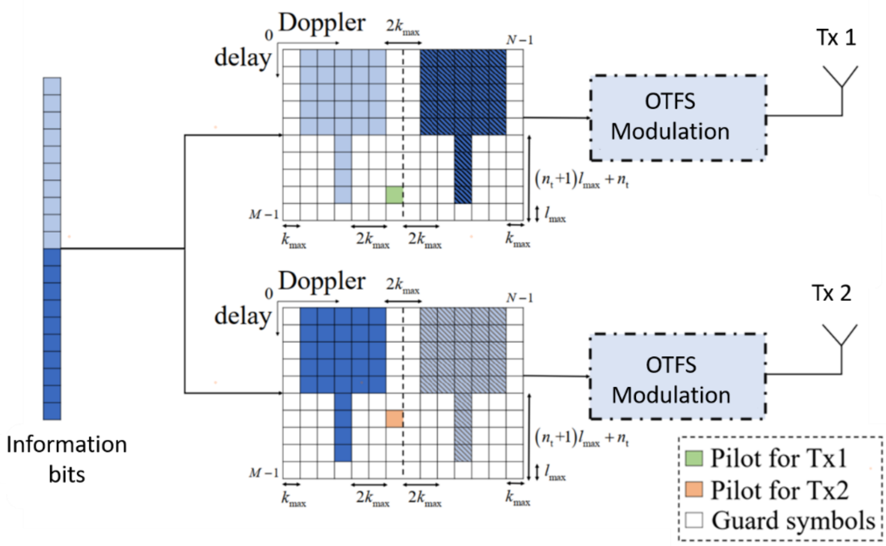

Figure 28. OTFS-MIMO open-loop precoding

The BER (Bit Error Ratio) performance of the proposed scheme outperforms the OTFS-MIMO using CDD (Cyclic Delay Diversity), as well as the OFDM-MIMO using STC (Space Time Code). More detailed simulation assumptions and performance analysis can be found in [53].

As an emerging technology, OTFS technology has some real technical challenges, mainly in the following areas.

- In some cases, the OTFS may be limited in the delay and Doppler resolutions, and the presence of fractional delay and fractional Doppler scenarios will lead to inaccurate channel estimation. As a result, BER error flooring exists in symbol detection, particularly the case with higher order modulation and continuous Doppler-shift channels. With better design methods and channel estimation algorithms, the channel estimation gain of OTFS over OFDM systems can be further improved.
- How to better integrate OTFS with MIMO is yet to be studied. The current

open-loop MIMO scheme is simple to implement, but does not make full use of the channel information and thus brings limited performance improvement. The implementation of closed-loop MIMO in the delay-Doppler domain, on the other hand, suffers from the problem that complexity and performance cannot be reconciled due to the double convolutional nature of the delay-Doppler domain channel. Therefore, new designs of OTFS-MIMO need to be further explored to approach the performance upper bound.

- OTFS receiver adopts a non-linear iterative equalizer which has a higher complexity than the widely used linear equalizer in current communication systems. The currently proposed OTFS low-complexity receivers [54] suffer from degraded performance or high overhead, and better design solutions are needed.

4.10 Other technologies

6G spectrum technologies

The demand for 6G peak data rate and user experienced data rate requires larger system bandwidth and more spectrum resources. Spectrum band from 6GHz to 7GHz has more than 1GHz continuous frequency resources and will be an important potential candidate band for 6G. Flexible spectrum use that aggregates more licensed and unlicensed frequency resources is an important technical means to achieve large bandwidth and high throughput in low frequency bands. In addition, millimeter wave and sub-THz are effective means to achieve "busy and hot" local hotspot coverage.

Channel coding and decoding

Potential channel coding and decoding schemes for 6G include:

- Channel coding for new scenarios: channel coding schemes for data rates above 100 Gbps, channel coding schemes for ultra-high reliability and ultra-low latency, and low-complexity channel coding schemes for very low power communications, such as short code designs based on Polar, LDPC (Low Density Parity Check Code), etc.
- Joint design and optimization of the channel coding module with other modules: joint design of coding and modulation, joint design of detection and

decoding, joint source-channel coding, etc.

- AI-based channel coding techniques: AI-based code construction, model-driven or data-driven AI channel coding schemes, AI-assisted decoding schemes, etc.

Energy-efficient communication technologies for terminals

The energy efficiency of 6G terminals will be 10 to 100 times (i.e. 10^{-10}-10^{-9} J/bit in magnitude) better compared to 5G, where the power consumption needed to achieve data rates above 100Mbps is about 1000 mW (i.e. energy efficiency of 10^{-8} J/bit in magnitude). This means that the power consumption to achieve 1Gbps data rates can reach 1000 mW or even less than 100 mW, which will greatly enhance the user experience of high-data rate services such as XR.

Transmissions with ultra-high bandwidths and design of extremely simple waveforms are potential solutions for energy-efficient communication at the terminal. On the one hand, extremely simple waveforms enable low complexity transceiver, thereby reducing or eliminating the power consumption of terminal hardware (e.g., digital-to-analogue converters, inverters, etc.); on the other hand, transmission with ultra-high bandwidths ensures high data rate requirements at low transmitting power. Pulse radio is one of the candidates for extremely simple waveforms. It uses baseband pulses of very short duration to transmit information and has the following advantages: 1) The pulse signal is generated in baseband without the need of complicated frequency-domain processing, saving hardware such as inverters and frequency-domain equalization filters compared to 5G devices; 2) The pulse signal is transmitted intermittently at the RF front-end, requiring very little power; and 3) The reception of pulsed signals can effectively mitigate multipath effects while suppressing interference among multiple users. Terminal transceiver design, modulation coding scheme design, and the coexistence of extremely simple waveforms with conventional waveforms are all key points to be considered in future.

5 Conclusion

6G will provide super communication service, basic information service, and converged computing service, and become the network information cornerstone for building a freely connected physical and digital integrated world.

6G service capability definition requires comprehensive consideration of demand, technology and cost, balancing performance indicators and efficiency indicators. Super communication performance indicators will improve several times or even orders of magnitude compared to 5G, and will further expand coverage. The service content of basic information is richer, including wireless sensing, enhanced network information provision, and public information of industries. Converged computing services will provide users with end-to-end latency and performance-guaranteed computing, storage or intelligent services.

The expansion of service content and the improvement of service capability require the redesign of system architecture to support communication, sensing, computing, information, data and other functions and services. The convergence of mobile network and computing realizes the capabilities of computing and intelligence, all of which is contingent on establishing reliable signal and data communication. ISAC opens another door for cellular wireless networks. 6G native-AI system will improve network and air interface efficiency, enhance system flexibility and reduce O&M costs. The introduction of an end-to-end cross-layer data plane is particularly necessary to support native-AI system, ISAC, and basic information services. ELPC will reduce the barrier to terminal access, enabling truly ubiquitous connectivity. MIMO evolution, RIS technology, new waveforms and other technologies will be introduced to make 6G network be more spectral efficient, more flexible in diverse scenarios, and more supportive for sensing functions.

The research and development of 6G technologies are still in the early stage. vCRI will continue to refine 6G usage scenarios, use cases and the related capability indicators, carry out in-depth research and experimental verification of potential technologies of 6G, and contribute to the development of a globally unified 6G technology standard.

References

[1] vivo, *Digital Life 2030+*, October 2020.

[2] vivo, *6G Vision, Requirements and Challenges*, October 2020.

[3] NGMN, *6G use cases and analysis*, February 2022.

[4] IMT-2030(6G) Promotion Group, *6G Typical Scenarios and Key Capabilities*, July 2022.

[5] Next G Alliance, *6G Applications and Use Cases.*

[6] Hexa-X, 6G Vision, *Use Cases and Key Societal Values*, February 2021.

[7] IMT-2030(6G) Promotion Group, *6G Network Architecture Vision and Key Technology Outlook*, September 2021.

[8] ITU-R Recommendation M.2083，"Framework and overall objectives of the future development of IMT for 2020 and beyond", Sep. 2015.

[9] 3GPP TR 38.913 V14.3.0 (2017-06), Study on Scenarios and Requirements for Next Generation Access Technologies.

[10] Hexa-X, Targets and requirements for 6G - initial E2E architecture.

[11] S. Kingsley, S. Quegan, *Understanding radar systems*, SciTech Publishing, 1999.

[12] Dinh C. Nguyen, P. Cheng, M. Ding, D. Lopez-Perez, P. N. Pathirana, J. Li, A. Seneviratne, Y. Li, and H. V. Poor, "Enabling AI in Future Wireless Networks: A Data Life Cycle Perspective," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 553-595, September 2020.

[13] O. Poursaeed, T. Jiang, H. Yang, S. Belongie and S. -N. Lim, "Robustness and Generalization via Generative Adversarial Training," in *2021 IEEE/CVF International Conference on Computer Vision (ICCV)*, 2021, pp. 15691-15700.

[14] H. Feng, S. Huang and D. -X. Zhou, "Generalization Analysis of CNNs for Classification on Spheres," *IEEE Transactions on Neural Networks and Learning Systems*, pp. 1-14, December 2021.

[15] U. Challita, H. Ryden and H. Tullberg, "When Machine Learning Meets Wireless Cellular Networks: Deployment, Challenges, and Applications," *IEEE*

Communications Magazine, vol. 58, no. 6, pp. 12-18, June 2020.

[16] GSMA, Exploring the metaverse and the digital future, 2022.

[17] A. Ali, N. Gonzalez-Prelcic, R. W. Heath and A. Ghosh, "Leveraging Sensing at the Infrastructure for mmWave Communication," *IEEE Communications Magazine*, vol. 58, no. 7, pp. 84-89, July 2020.

[18] J, Li, and P. Stoica, "MIMO Radar with Colocated antennas Antennas," *IEEE Signal Processing Magazine*, vol. 24, no. 5, pp. 106-114, September 2007.

[19] Y. Zhuo, H. Zhu, H. Xue and S. Chang, "Perceiving accurate CSI phases with commodity WiFi devices," in *IEEE INFOCOM 2017 - IEEE Conference on Computer Communications*, 2017, pp. 1-9.

[20] K. B. Letaief, W. Chen, Y. Shi, J. Zhang and Y. A. Zhang, "The Roadmap to 6G: AI Empowered Wireless Networks," *IEEE Communications Magazine*, vol. 57, no. 8, pp. 84-90, August 2019.

[21] G. Zhu, D. Liu, Y. Du, C. You, J. Zhang and K. Huang, "Toward an Intelligent Edge: Wireless Communication Meets Machine Learning," *IEEE Communications Magazine*, vol. 58, no. 1, pp. 19-25, January 2020.

[22] N. Kato, B. Mao, F. Tang, Y. Kawamoto and J. Liu, "Ten Challenges in Advancing Machine Learning Technologies toward 6G," *IEEE Wireless Communications*, vol. 27, no. 3, pp. 96-103, June 2020.

[23] F. Sohrabi, K. M. Attiah and W. Yu, "Deep Learning for Distributed Channel Feedback and Multiuser Precoding in FDD Massive MIMO," *IEEE Transactions on Wireless Communications*, vol. 20, no. 7, pp. 4044-4057, July 2021.

[24] R1-2203550, Evaluation on AI/ML for CSI feedback enhancement, vivo, RAN1 #109e, 2022.

[25] 3GPP R1-2203554, Evaluation on AI/ML for positioning accuracy enhancement, vivo, RAN1 #109e, 2022.

[26] 3GPP R1-2203556, Discussions on AI/ML for DMRS, vivo, RAN1 #109e, 2022.

[27] S. Niknam, H. S. Dhillon and J. H. Reed, "Federated Learning for Wireless Communications: Motivation, Opportunities, and Challenges," *IEEE Communications*

Magazine, vol. 58, no. 6, pp. 46-51, June 2020.

[28] S. Warnat-Herresthal, H. Schultze, K. L. Shastry, et al. "Swarm learning for decentralized and confidential clinical machine learning," *Nature*, vol. 594, no. 7862, pp. 265-270, 2021.

[29] M. Wang, Y. Lin, Q. Tian and G. Si, "Transfer Learning Promotes 6G Wireless Communications: Recent Advances and Future Challenges," in IEEE Transactions on Reliability, vol. 70, no. 2, pp. 790-807, June 2021.

[30] T. M. Hospedales, A. Antoniou, P. Micaelli and A. J. Storkey, "Meta-Learning in Neural Networks: A Survey," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, May 2021.

[31] N. Van Huynh, D. T. Hoang, X. Lu, D. Niyato, P. Wang and D. I. Kim, "Ambient Backscatter Communications: A Contemporary Survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 2889-2922, May 2018.

[32] F. Amato, C. W. Peterson, M. B. Akbar and G. D. Durgin, "Long range and low powered RFID tags with tunnel diode," in *2015 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2015, pp. 182-187.

[33] H. Liu, W. Lin, M. Lin and M. Hsu, "Passive UHF RFID Tag With Backscatter Diversity," *IEEE Antennas and Wireless Propagation Letters*, vol. 10, pp. 415-418, May 2011.

[34] G. Yang, Y. -C. Liang, R. Zhang and Y. Pei, "Modulation in the Air: Backscatter Communication Over Ambient OFDM Carrier," *IEEE Transactions on Communications*, vol. 66, no. 3, pp. 1219-1233, March 2018.

[35] 3GPP, RP-213645, New SID: Study on low-power Wake-up Signal and Receiver for NR.

[36] M. Cui, L. Dai, R. Schober, and L. Hanzo, “Near-field wideband beamforming for extremely large antenna array,” arxiv:2109.10054, 2021.

[37] J. Zhang, S. Chen, Y. Lin, J. Zheng, B. Ai and L. Hanzo, "Cell-Free Massive MIMO: A New Next-Generation Paradigm," *IEEE Access*, vol. 7, pp. 99878-99888, July 2019.

[38] T. Hu, Y. Wang, X. Liao, J. Zhang, and Q. Song, “OFDM-OAM modulation for future wireless communications,” *IEEE Access*, vol. 7, pp. 59114-59125, May 2019.

[39] M. D. Renzo, A. Zappone, M. Debbah, et al. “Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead,” *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 11, November 2020.

[40] Q. Wu, X. Long, J. Yin, C. Yu, H. Wang, and W. Hong, “Single-layer 1-bit prephased single-beam metasurface using true time delayed unit cells,” *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 6, pp. 1095-1099, June 2022.

[41] J. Abdoli, M. Jia and J. Ma, "Filtered OFDM: A new waveform for future wireless systems," in *2015 IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, 2015, pp. 66-70.

[42] R. Zayani, Y. Medjahdi, H. Shaiek and D. Roviras, "WOLA-OFDM: A Potential Candidate for Asynchronous 5G," in *2016 IEEE Globecom Workshops (GC Wkshps)*, 2016, pp. 1-5.

[43] F. Schaich and T. Wild, "Waveform contenders for 5G — OFDM vs. FBMC vs. UFMC," in *2014 6th International Symposium on Communications, Control and Signal Processing (ISCCSP)*, 2014, pp. 457-460.

[44] N. Michailow et al., "Generalized Frequency Division Multiplexing for 5th Generation Cellular Networks," *IEEE Transactions on Communications*, vol. 62, no. 9, pp. 3045-3061, September 2014.

[45] F. Schaich, "Filterbank based multi carrier transmission (FBMC) — evolving OFDM: FBMC in the context of WiMAX," in *2010 European Wireless Conference (EW)*, 2010, pp. 1051-1058.

[46] C. Kim, K. Kim, Y. H. Yun, Z. Ho, B. Lee and J. Seol, "QAM-FBMC: A New Multi-Carrier System for Post-OFDM Wireless Communications," in *2015 IEEE Global Communications Conference (GLOBECOM)*, 2015, pp. 1-6.

[47] M. J. Abdoli, M. Jia and J. Ma, "Weighted circularly convolved filtering in OFDM/OQAM," in *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*, 2013, pp. 657-661.

[48] J. B. Anderson, F. Rusek and V. Öwall, "Faster-Than-Nyquist Signaling," *Proceedings of the IEEE*, vol. 101, no. 8, pp. 1817-1830, August. 2013.

[49] R. Hadani and A. Monk, “OTFS: A new generation of modulation addressing the challenges of 5G,” arXiv preprint arXiv:1802.02623, 2018.

[50] S. K. Mohammed, "Derivation of OTFS Modulation From First Principles," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 8, pp. 7619-7636, August. 2021.

[51] F. Lampel, A. Alvarado, F. M. J. Willems, "Orthogonal Time Frequency Space Modulation: A Discrete Zak Transform Approach," in *2022 IEEE International Conference on Communications (ICC)*, 2022, pp. 1-6.

[52] H. Lin, J. H. Yuan, " Multicarrier Modulation on Delay-Doppler Plane: Achieving Orthogonality with Fine Resolutions," in *2022 IEEE International Conference on Communications (ICC)*, 2022, pp. 1-6.

[53] D. Wang, B. Sun, F. Wang, X. Li, P. Yuan and D. Jiang, "Transmit diversity scheme design for rectangular pulse shaping based OTFS," *China Communications*, vol. 19, no. 3, pp. 116-128, March 2022.

[54] P. Raviteja, K. T. Phan, Q. Jin, Y. Hong and E. Viterbo, "Low-complexity iterative detection for orthogonal time frequency space modulation," in *2018 IEEE Wireless Communications and Networking Conference (WCNC)*, 2018, pp. 1-6.

Abbreviations

4ASK	4-ary Amplitude Shift Keying
AI	Artificial Intelligence
API	Application Program Interface
APN6	Application-aware IPv6 Networking
APSK	Amplitude Phase Shift Keying
BER	Bit Error Ratio
BS	Base Station
CDD	Cyclic Delay Diversity
CFN	Compute First Networking
CFO	Carrier Frequency Offset
CN	Core Network
CP	Control Plane

CP-OFDM	Cyclic Prefix OFDM
CSI	Channel State Information
DC	Direct Current
DMF	Data Management Functions
DMRS	Demodulation Reference Signal
ELPC	Extremely Low Power Communication
eMBB	Enhanced Mobile Broadband
ESPRIT	Estimation of Signal Parameters via Rotational Invariance Techniques
FBMC-OQAM	Filter Bank Multi-Carrier with Offset Quadrature Amplitude Modulation
FBMC-QAM	Filter Bank Multi-Carrier Quadrature Amplitude Modulation
FLOPS	FLoating-point Operations Per Second
FMCW	Frequency Modulated Continuous Wave
f-OFDM	Filtered OFDM
GFDM	Generalized Frequency Division Multiplexing
GIS	Geographic Information System
IETF	Internet Engineering Task Force
IMS	IP Multimedia Subsystem
IoT	Internet of Things
ISAC	Integrated Sensing And Communication
ISFFT	Inverse Symplectic Finite Fourier Transform
LDPC	Low Density Parity Check Code
LMF	Location Management Function
LNA	Low Noise Amplifier
LOS	Line of Sight
MC-FTN	Multi-Carrier Faster than Nyquist
MDT	Minimization of Drive Tests
MEC	Multi-Access Edge Computing
MMF	Model Management Functions
mMTC	Massive Machine Type Communication

MUSIC	Multiple Signal Classification
NAS	Non-Access Stratum
NEF	Network Exposure Function
NMS	Network Management System
NR	New Radio
NWDAF	Network Data Analytics Function
OAM	Orbital Angular Momentum
ODDM	Orthogonal Delay-Doppler Division Multiplexing
OFDM	Orthogonal Frequency Division Multiplexing
OTFS	Orthogonal Time Frequency Shift
PAPR	Peak to Average Power Ratio
PGA	Programmable Gain Amplifier
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RCS	Radar Cross Section
SC-FDE	Single Carrier Frequency Domain Equalization
SFO	Sampling Frequency Offset
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Network
SRv6	Segment Routing over IPv6
STC	Space Time Code
STO	Symbol Timing Offset
TOPS	Tera Operations Per Second
TRP	Transmission Reception Point
UFMC	Universal Filtered Multi-Carrier
URLLC	Ultra-Reliable Low-Latency Communications

VoNR	Voice over New Radio
WCC-FBMC-OQAM	Weighted Circular Convolution Filter Bank Multi-Carrier with Offset Quadrature Amplitude Modulation
W-OFDM	Windowed OFDM
XR	Extended Reality