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ICDT INTEGRATED 6G NETWORK

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Executive Summary

ICDT is the technological integration trend of mobile communications technology, information technology, artificial intelligence (AI) and big data technology. It is the extension of ICT integration and the technical driving force to promote the social economy to upgrade to intelligence and to expand from the physical space to the virtual space. ICDT will usher a large number of emerging services and application scenarios, such as AI services, immersive services and digital twin services. It will bring an explosive growth of mobile information processing demand and consequently drive 5G to ICDT integrated 6G.

ICDT integrated 6G will be an end-to-end (E2E) information processing and service system. Its fundamental functions will extend from information delivery to information acquisition, information computing and information application, and providing stronger multi-dimensional native capabilities such as communications, computing, sensing, AI and security. It will bring a beautiful vision of "digital twin, ubiquitous intelligence" for the social and economic development towards 2030.

ICDT integrated 6G will redefine the mobile network architectures, functions and performance in multiple dimensions. The new design certainly faces new problems and challenges. This white paper will focus on the following key technologies and problems, and try to give solutions to the challenges ahead.

1. ICDT integrated network architecture and protocol stack

The 6G network will further extend the 5G service-based architecture and software defined network to the E2E architecture, so as to support the space-air-ground integration, cloud-network-edge-terminal cooperation, and the underlying integration of sensing, communication and computing, as well as new native capabilities. This aims at a global resource scheduling capability that can quickly respond to the demand of E2E information processing. A 6G network will support the portability of containers, the scalability and customization based on microservice architecture, the continuous integration and delivery of DevOps, and the organizational structure meeting Conway's law. The 6G protocol stack will fully consider the capabilities of each layer of the protocol stack. In addition to the user plane and the control plane, the 6G protocol stack will introduce the computing plane and the AI plane to support computing, sensing and AI procedures.

2. Integration of sensing, communication and computing

Sensing, communication and computing will be the three essential capabilities of 6G. The integration of sensing, communication and computing refers to an end-to-end information processing framework that performs information acquisition and information computing in the process of information delivery. It has been carried out in the form of cloud-network-edge-terminal collaboration. Cloud services, edge computing, network slicing, non-public network, Internet of vehicles and other technologies have introduced such collaboration capabilities to varying degrees. The integration of perceptual communication and computing will provide a greater opportunity for 6G network performance improvement and function expansion. The key technologies and problems to be solved include: 1) unified waveform and signal design for the integration of wireless sensing and transmission; 2) deterministic information processing, including deterministic sensing, deterministic transmission and deterministic computing; 3) multidimensional resource management and scheduling algorithms; 4) service continuity, including sensing continuity, communications continuity, and computing connectivity. The challenges include: basic theories to answer the coupling relationship and the integrated function gain boundary, signal processing and device architecture for the integration of wireless sensing and transmission in the millimeter wave, visible light and terahertz bands, heterogeneous computing environment and chips, and trusted information processing.

3. Space-air-ground integrated network

6G should support the space-air-ground integrated network architecture, technical systems and control processes to achieve global coverage of on-demand information services. The radio access network (RAN) based on the microservice architecture and distributed core network are the enabling solutions of the integrated architecture. The former realizes microservice by extracting and reconstructing the functions of the RAN protocol stack. It can match the limited resources of space-based nodes, deeply integrate the access function of the ground and space-based access nodes, simplify the design of interface with the core network, and reduce the energy consumption of space-based nodes. In a distributed core network, some lightweight core network functions are deployed on the space-base nodes to form an edge core network, and some important or computing-power dependent functions are deployed on the ground to form a cloud core network. Through computing power release, real-time sensing and scheduling, fault detection and recovery, the space-air-ground computing collaboration is realized, so as to reduce service delay and ensure service robustness.

4. Native AI

6G will evolve from "AI for network" to network with native AI, providing ubiquitous AI computing power and AI services. The application of AI in the network aims to improve the network performance, reduce the complexity of algorithm and operation and maintenance (O&M), and solve the problems that cannot be modeled. AI is first applied in O&M automation, and then extended to the application layer, network layer, edge computing, air interface, physical layer and terminals, thus forming a multi-level distributed AI architecture. In addition, different machine learning (ML) algorithms, such as transfer learning, federated learning and deep reinforcement learning, need multi-node cross-domain collaborative sensing, data sharing and model sharing. This also triggers a distributed AI architecture. The Distributed AI architecture is conducive to seamless perception of global context, including attributes and states of services, network, terminals, users and environment, so as to obtain state prediction, long-term pattern and high-level semantic knowledge. This can help reduce the randomness of various problems and improve the performance of communication and computing solutions. The distributed AI architecture will also fully consider the hardware performance constraints to make the AI algorithm more practical.

5. Intent aware smart network

An intention aware network is based on the understanding of network O&M intentions and user's intentions to realize the network's adaptation to different services and scenarios without human intervention. It can realize intelligent network in various scenarios, such as multi-network operations, terminal computing, edge computing and AI enabled air interfaces. In an intention aware network, intention users use domain specific language to express their goals without describing the methods to achieve them. Intent knowledge base helps to translate an abstract intent expression to specific network configuration operations and determine whether the target can be implemented or not. An intention aware network supports cross-layer intention decomposition and collaboration to ensure the realization of the highest intention goal.

6. Deterministic network

Deterministic network technology originated from fixed networks, and was initially used in time synchronization, traffic scheduling shaping and transmission reliability on the Ethernet. With the deep application of mobile communications in vertical fields, deterministic technology is also introduced into mobile networks to ensure network quality, including bounded delay, low jitter, high reliability and high-precision time synchronization. Based on the breakthroughs of deterministic technology in both fixed and mobile networks, 6G will develop into three directions: cross domain integration, cross layer optimization and wide area determinacy, and eventually become a deterministic information processing system considering deterministic sensing, deterministic transmission and deterministic computing.

7. Digital twin body network

The digital twin body network is a body domain information processing system supporting the digital body twinning. It involves the data acquisition and transmission in vitro and in vivo with a large number of sensors, the fusion of multi-dimensional heterogeneous data, the modeling and data visualization. This requires both high real-time and reliability of communications and computing capabilities.

8. Endogenous safety and security architecture and key technologies

6G security is facing the double uncertainties of network evolution and security threats, as well as the contradiction and conflicts between openness and security, and advancement and credibility. Prying into the nature of the problem, we can find that even in the face of double uncertainty, most of the security threats come from endogenous safety and security (ESS) problems caused by intrinsic defects in 6G networks, and the two oppositions come from the lack of discovery and utilization about common origin attributes for communications/security/service. Since external factors can only function through internal factors, internal factors are the key to resolving contradictions. Only through ESS, a construction-oriented security solution, can we avoid uncertain threats, unify the two opposites, and have the ability to resist unknown security threats and endogenous integration capabilities for communications/security/service "trinity". The research work of 6G wireless ESS should include the exploration of wireless ESS mechanisms, the construction of an innovative security architecture with ESS attributes, and breakthroughs in key ESS technologies for 6G typical scenarios.

9. Open network

The open network is defined as a flexible and customizable network with capability and resource exposure functions. According to the varying degrees of openness, an open network can be classified into three levels, namely, the black-box network, the gray-box network, and the white-box network. To obtain higher openness, there are four main kinds of splitting methods to decoupling a traditional RAN, namely, hardware/software decoupling, control plane and user plane splitting, central unit and distributed unit splitting, and downlink and uplink decoupling. This facilitates 3D slicing with resource slicing, function slicing and network slicing. In addition to communication resources and capability exposure, open networks will support sensing, computing and AI resource and capability exposure and introduce sensing services, synchronization services, positioning services, ML services, as well as information sharing.

10. AI enabled air interface

An AI enabled air interface tries to optimize or reconstruct wireless transmission schemes and provide customization in different scenarios. The introduction of ML algorithms such as deep learning can help optimize the process and parameters of channel estimation and equalization, channel coding and decoding, waveform modulation and multi-antenna precoding. It can also transform the traditional transceiver structure from a modular-based framework to neural networks. With the deep sensing and AI capabilites, the wireless transmission schemes can be optimized under the constraints of spectrum environment, hardware capability, computing power and target demand.

11. Multifunctional air interface

A multifunctional air interface expands its fundamental function from wireless transmission to wireless sensing, positioning, synchronization, and computing. It introduces sensing nodes, synchronization nodes and computing nodes, and integrates synchronous networks, deterministic networks and computing aware networks with RAN, to form a multifunctional RAN. Especially, the sensor node has the ability of sensing and cooperative sensing through radar, camera and wireless sensing transceivers and other equipment. The new introduced function can not only be used to improve the wireless transmission performance, but also can be exposed to applications as a capability or provided to users as a service.

12. Space-air-ground integrated air interface

The space-air-ground integrated air interface tries to improve the radio access capability and 3D coverage capability from different aspects such as services and system architecture. Based on the on-board regeneration mode, it supports multi-satellite multi-dimensional access, inter-satellite cooperation or space-air-ground cooperation, flexible segmentation of multi-platform and intelligent reconfiguration of networks. The key technologies include carrier modulation, multiple access technology, multi satellite multi-beam cooperative transmission, satellite-ground cooperative transmission, and high-speed inter-satellite transmission. The problems of limited satellite power, high path loss, large delay, high frequency shift and high dynamic conditions are challenging the space-air-ground integrated air interface.

13. New enablers for air interface

The 6G air interface should not only expand new spectrum, but also improve the spectral efficiency of traditional spectrum to meet more KPI requirements. New enablers, such as advanced coding, modulation, waveform and multiple access schemes still play an important role. The extreme multi-antenna system (extreme-MIMO) and the related technologies or applications such as distributed MIMO, holographic radio and wireless positioning are developing rapidly. Reconfigurable intelligent surface (RIS) has been widely concerned by using large-scale device arrays to actively improve the channel environment. Terahertz and visible light communications have the advantages of ultra wideband transmission and will continue to receive attention. In addition, orbital angular momentum, transform domain precoding and cross-media relay and cooperative communication are worthy of attention. Specifically, the following key issues should be addressed: 1) the coding and modulation schemes approaching Shannon limit while with limited code length; 2) enhanced waveform based on OFDM needs to be designed to meet the diverse 6G scenarios, such as high-speed mobility and high-frequency bands; 3) the future multiple access technology will change from human-centric and scheduling based to agent-based without scheduling; 4) extreme-MIMO still needs to be further enhanced around the new antenna architectures, new deployment methods, new signal processing and new applications; 5) terahertz communication, visible light communication and RIS still need to continue to break through around key devices and system solutions.

14. Intelligent terminals

ICDT integration drives mobile terminals to be ubiquitous, intelligent, lightweight, and sharable. A large number of terminals with diversity forms are emerging, such as robots, UAVs, unmanned vehicles and other personal terminals, home terminals and industry terminals. To meet the needs of 6G emerging services, the transmission data rate of 6G terminals will be increased by 12-15 times, and the computing power will be increased by 100-1000 times compared with 5G. It supports intelligent human-machine interfaces (HMI) and immersive interactive experiences such as holographic imaging, virtual reality and 3D display. It supports high-precision sensing such as 3D positioning and super long endurance. The following key areas should be addressed: 1) semiconductor chips, development of chip design and packaging process oriented to functional requirements; 2) computing architecture, cloud-terminal cooperative computing, and multi-core heterogeneous computing; 3) OLED / LED flexible display materials to solve screen size problems; 4) electromechanical integration; 5) inertial navigation to support indoor positioning; 6) 3D positioning to achieve deep environmental perception; 7) new material batteries, energy harvesting and savings to solve the problem of battery life.

In addition to the above key technologies, 6G has inherently interdisciplinary characteristics, and the following interdisciplinary opportunities can be considered:

- Quantum information technology (QIT). QIT may have a revolutionary impact on the development of ICDT integrated 6G. It includes Quantum computing, quantum communication and quantum metrology. Quantum communication is a new communication technology that uses quantum signal to transmit information, such as quantum key distribution, quantum teleportation, quantum repeater and so on. The experimental application of quantum communication based on satellite has been realized. Quantum computing is a new computing model that follows the laws of quantum mechanics to control quantum information units. Combined with quantum parallelism, quantum computing has greater potential than classical information processing. Quantum metrology is a kind of measurement technology. It has higher resolution and sensitivity in measuring physical parameters than similar classical measurements. Quantum information technology will promote the 6G computing power innovation, bring about the great improvement of information processing capability, and usher in a new era of "quantum Internet".

- Bioinformatics: Bioinformatics technology will promote the expansion of ICDT integrated 6G into the biological field. Molecular communications, brain computer interfaces, nano robots, synesthesia Internet, etc. will bring rich service and application scenarios for 6G, and promote the improvement of human life.
- New materials and energy. Materials and energy are the bottlenecks in the development of 6G. Graphene and other nano materials, composites and metamaterials have been widely used in the ICT field, and will continue to seek opportunities in 6G equipment heat dissipation, antenna design, millimeter wave / optical / terahertz communications key device design, terminal flexible screens, battery and other fields. Ubiquitous information processing brings great energy consumption. 6G can consider new battery technology, lightweight energy harvesting and sharing technology, and the simultaneous wireless information and energy transfer.

To promote global 6G development, we propose:

- Promote global consistent 6G new spectrum planning
- Building a globally consistent technology validation environment
- Building a global open 6G technology and industrial ecosystem
- Advocate the legal use of big data and the protection of digital rights and interests
- Pay attention to the fairness and ethics of network AI.

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1. Introduction

Information technology innovation promotes social and economic development. The growing demand for information processing is driving 5G further evolution into the next frontier. Global attention has thus begun to focus on 6G.

Recently, extensive viewpoints and thoughts on 6G have been reported. These wide-ranging discussions have clearly shown that the deep integration of information technology, mobile communications technology, artificial intelligence and big data technology (ICDT) have become the development trends of mobile communications.

Traditionally, the E2E information processing is divided into three parts: information acquisition at terminals, information delivery at networks and information computing at the cloud. This inevitably limits the improvement of information service quality due to the function dissociation. Meanwhile, the emerging services, such as artificial intelligence (AI) services and immersive services show the strong coupled characteristics of sensing, communication and computing, and put forward E2E information processing requirements on mobile networks.

Therefore, 6G networks should be designed in an ICDT integrated framework, where the fundamental network capability will extend from information delivery to information acquisition, information delivery, and information computing. Such framework should aim to transform “AI/computing for network” to “AI/computing in network” and “network for AI/computing”.

Clearly, outlining such a framework solution is a rather challenging task. There are a number of questions on service, requirements, architecture and technology that we need to answer. Although a lot of architecture and function proposals have been proposed from both the academia and industry, there is still no consensus on what 6G will be.

This paper absorbs multiple viewpoints and aims to look for some deep insight into the 6G concept, feature, services, network architectures, functions, and potential technologies to help answer these questions.

2. Mobile Network Development Trends

2.1 Afterthought of 5G

5G fully embodies the ICT integration idea and cloud native concepts, introduces SDN / NFV and service based architecture (SBA), as well as technologies such as control plane/user plane separation, network slicing, edge computing and capability exposure, so as to realize the differentiated technical scenarios, and provide a powerful capability for a rapid and elastic network deployment and function upgrade.

However, with the accelerated development of ICDT, especially the penetration of AI, there's been an explosion of intelligent end-to-end information processing requirements, which highlights the bottlenecks of 5G in terms of partial SBA architectures, partial redundant network functions, patched AI capability and isolated resources.

2.2 ICDT integrated development trend

The key driving force for the development of information technology is to deeply understand and transform the physical world. The existing mainstream commercial technologies, such as 5G, Internet of Things, cloud native, big data, AI, digital twin (DT) are promoting the comprehensive upgrading of traditional industries and the digital transformation of the society and the economy. A large number of technology trend analysis results [1][2] show that digital virtualization and intelligence have become the emerging information technology trends. Such trends are extending the human society from the physical world into the virtual world.

From 4G to 5G, the mobile communication technology features can be identified from the field of communication technology (CT) to the field of information and communication technology (ICT) by introducing cloud/edge computing. 5G design fully demonstrates the technical characteristics of ICT integration. 5G services, such as XR-like eMBB services and IoT services also show the same ICT characteristics.

Along with the accelerated integration of ICT, AI and big data technologies are maturing rapidly and are extensively discussed for application into mobile networks. The mobile network is evolving towards the integration of IT, CT, AI and big data technologies (ICDT), as shown in Fig. 1. The primary ICDT feature expected is to provide 6G with native AI. This will transform "AI for network" to "AI in network" and concurrently upgrade "Network for AI" from pipeline to content.

Similar to AI technology, digital twin technology has shown a strong potential application ability in the expected 6G capabilities and services. In other words, 6G networks will run in twinning mode and provide digital twin services for a large number of vertical applications. So, we can foresee a large number of autonomous things (ATs) and virtual spaces are emerging and gradually becoming the elements of human life and production. AT can carry out human-like activities through the ability of environment perception and interaction, such as robots, UAVs, autonomous vehicles, virtual assistants, etc. Virtual space is a digital reconstruction, simulation or image of a physical space from the space-time dimension, such as extended reality (XR), holographic image, digital twin, intelligent space, etc.

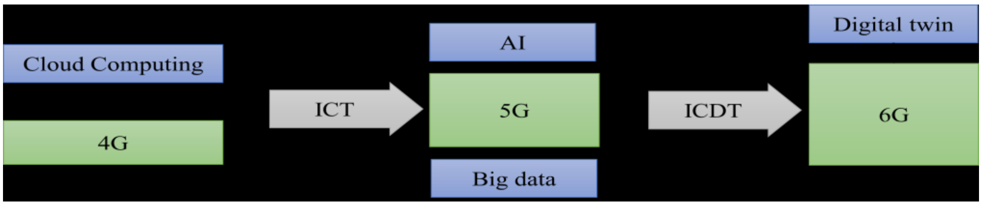

Fig. 1: Mobile network development trend towards ICDT integrated 6G

The upcoming explosion of interaction and cooperation among ATs/virtual spaces will bring about a clear shift in a mobile network from human-centric interconnections to AT-centric interconnections. Such kind of interconnection requires a mobile network to support more functions in terms of sensing, communication, computing, and machine learning (ML). Due to AI, sensing has become a fundamental interconnection means, as important as communications. In summary, ICDT integrated 6G will be an end-to-end (E2E) information processing system.

3. 6G Vision and Requirements

3.1 6G Vision

With the wide penetration of AI and digital twin technologies, 6G is expected to promote the upgrading of intelligent social and extend the human society from the physical space to the virtual space. 6G services are foreseen to be more immersive, remotely controlled, and unmanned. 6G fully supports the digitization of the world and promotes the upgrading of social and economic informatization from “Internet+” into the “AI+” and “digital twin+” age. 6G will push the world towards “Digital Twin, Ubiquitous Intelligence” and achieve the great goal that “6G will reshape the world".

3.2 6G Typical Services

A 6G service classification model is proposed in [3], which defines four elements: human, autonomous things, physical space and virtual space. According to their interaction relationships, traditional services, AI services, immersive services and digital twin services are defined respectively. The traditional services refer to the mobile Internet services, Internet of things services and integration services of broadcast and communications. The AI services refer to the assistant services based on human-machine interfaces and the unmanned services based on machine-machine interfaces. The immersive services refer to the virtual multi-sensory experience and control services based on holographic communications or XR. The digital twin services refer to the simulation and control services based on the interactive mapping ability between the physical space and virtual space. These four types of services have a wide range of application possibilities in personal and vertical scenarios.

3.2.1 AI services

It is expected that AI services will provide intelligence and capabilities of AI computing which will be empowered by 6G. In order to implement such services, the machine-machine interface (MMI) and the human-machine interface (HMI) will be required for access. Then, AI services are mainly divided into two categories: unmanned services based on MMI and assisted services based on HMI.

Along with advances in sensing, positioning, computer vision, and other machine intelligent techniques, more human-involved activities will evolve to unmanned services such as autonomous driving, unmanned manufacturing and unmanned logistics. Unmanned service refers to the service capability of completing a task through one AT or multi-AT cooperation without human intervention.

An assisted service refers to the dedicated action of an AT to help human achieve his target. These services include virtual doctors, virtual teachers, virtual guides, virtual scientists, etc.

3.2.2 Immersive services

Immersive services aims to promote the interaction manners of humans from audio, video, AR/VR to extended reality (XR) and hologram, enabling immersive experience in terms of senses of vision, hearing, touch, smell, taste and even emotion, without constraints of time and space.

Immersive services mainly include holographic type communications (HTC) and interactive extended reality (XR). HTC is expected to digitally deliver 3D images from one or multiple sources to one or multiple destination nodes in an interactive manner. XR refers to all real-and-virtual combined environments and HMIs generated by computer technology and terminals. Both of them can be applied into remote driving, remote surgery, remote teaching, remote inspection, remote meeting, virtual classroom, virtual shopping, virtual tourism, virtual concert, virtual museum etc.

3.2.3 Digital twin services

Digital twin (DT) refers to interactive mapping between physical space and virtual space and the ability to clone physical objects into virtual objects. It uses sensing, computing, modeling, etc., through software definition to describe, diagnose, predict and make decisions on physical objects. The virtual objects reflect all the important properties and characteristics of the original objects. It consists of five elements: physical objects, virtual objects, DT platform, DT data and DT models. Support technologies such as sensing and AI, as well as sensors and actuators equipped within physical objects are needed. This kind of services includes digital twin city, digital twin network, digital workshop, digital twin body, etc.

3.3 Requirements on 6G

The services discussed above have the high coupling characteristics of sensing, communication and computing, and put forward the general requirements of end-to-end information processing capabilities for 6G networks. This requires a 6G network to have a high scheduling ability of global resources and underlying capabilities.

3.3.1 Architecture requirements

To support the emerging services efficiency, the following suggestions should be considered:

- The 6G network should have an E2E micro service architecture and software defined network architecture to support rapid network function reconfigurations and upgrading, and rapid resource and function scheduling to match dynamic service requirements

- The 6G network should have a distributed AI architecture to support ubiquitous AI computing resources scheduling and guarantee ubiquitous AI applications and services.
- The 6G network should have an integrated space ground architecture to support global service deployment and operations
- The 6G network should have an cloud-network-edge-terminal integration architecture to support the global balance of traffic and computing power and E2E information processing capabilities, and ensure the E2E service quality

3.3.2 Capability requirements

Besides the inherited capabilities from 5G, 6G is expected to have more powerful native capabilities as follows.

- 6G networks should have enhanced communications and coverage capabilities, further improve the data rate, reduce delay, improve reliability, and ensure global coverage and body-like micro space coverage;
- The 6G network should have the ability of native sensing to realize the global perception of the attributes and states of services, networks, users, terminals and environments;
- The 6G network should have the ability of native computing, where the distributed, multi-level and heterogeneous computing power of the whole network can be perceived, encapsulated and schedulable.
- The 6G network should have native AI to realize both "network for AI" and "AI for/in network".
- The 6G network should have the ability of deterministic information processing to support sensing, transmission and computing on time and in time;
- The 6G network should have the capability exposure function to realize the opening of the underlying sensing, communication and computing resources and capabilities, and realize the capability as a service;
- The 6G network should have the ability of native security to achieve zero trust, active defense and self-immunity, and can introduce blockchain to realize

resource sharing and multi-party cooperation

3.3.3 Key performance requirements

The emerging services will put forward many key performance challenges for mobile communications network from the following aspects:

- Data rate: holographic communication has peak data rate requirements at the Tbps level, digital twin services demand 10~100Gbps peak data rate, and the experience rate is correspondingly 100Gbps and 1~10Gbps.
- Synchronization accuracy: the synchronization accuracy will reach ns level regarding unmanned field services and remote-control services needs.
- Positioning accuracy: indoor positioning accuracy and vertical positioning accuracy will be improved from meter level to sub-meter level, and unmanned manufacturing demands 3D positioning accuracy at millimeter level;
- Determinacy: The E2E delay will reach ms level, the delay jitter will reach μs level, and the reliability requirement of unmanned manufacturing is 99.999999%;
- Mobility and service continuity: The aircraft-like terminal speed will reach 1000 km/h, and the availability of sensing, communication and computing reaches 99.999%
- Computing power: holographic services demand peak computing power at the 100TOPS level.

4. ICDT Integrated Network Architecture and Technologies

4.1 Integrated Network Architecture

There are still shortcomings and potential enhancements in the existing network architecture and protocol stack functions. From the perspective of network architecture, CU/DU cloudification is insufficient, and RAN slicing also faces problems. From the perspective of the protocol stack, the problems such as functional redundancy and cell definition redundancy need to be further explored.

In response to the above-mentioned problems, we focus on three perspectives on the next-generation RAN architecture: service-based architecture for RAN, component-based forwarding plane architecture, and intelligence-based RAN architecture.

（1）As the perspective of service-based architecture for RAN, the End-to-End SBA and the integration of DN, CN and RAN are not only technical trend, but also pulled by new business mode of the future network. Different from the traditional To C-Native network, future network will be a To B-Native network and To C will be supported on the basis of To B, so as to provide customized network driven by the demands from enterprises, governments, and social organizations. Based on the public platforms, private platforms operated or owned by enterprises, government and social organizations, or hybrid platforms, person, organizations and autonomous things can be fully connected and enabled.

（2）Regarding component-based forwarding plane architecture, forwarding plane can forward user data and signaling. Thus, forwarding plane can be considered as a more general plane than user plane. Functions of forwarding plane should meet the basic requirements of security, efficiency, reliability, and QoS control. To support MEC, verticals, space-air-ground integration, integrated access and backhaul, dual connectivity, carrier aggregation, URLLC, and interworking, forwarding plane should also meet the advanced requirements of generality, independence, compatibility, extensibility, portability and openness. For this purpose, component-based design is recommended for the forwarding plane. With the consideration of basic and advanced requirements, protocol stacks of forwarding plane can be partitioned into orchestratable modularized components, in order to achieve the balance of basic requirements and advanced requirements.

（3）Regarding intelligence-based RAN architecture, intelligence is an important driven-force and enabler of next generation RAN. It impacts all RAN functions. Intelligence can be acted as a micro-scopic enabler within RAN functions, mesoscopic enabler by the side of RAN functions, and macroscopic enabler on the top of all RAN functions. Intelligence-based architecture will appear in different forms at different scales. One of the evolution directions of achieving intelligence-based RAN is deep combination of existing mobile communication systems and AI.

4.1.1 Network Architecture

The characteristics of softness for the next generation network is aligned with the cloudification trend in the network evolution. Here cloudification not only means the deployment in the cloud, but also means the network design based on Cloud-Native guideline, including portability via container, scalability, extensibility and customization based on micro-service architecture, continuous integration and delivery with DevOps, and the organization structure supporting the network architecture with Conway's Law.

With NFV or Platform as a Service (PaaS) in 6G, portability can be supported. The direction of future network is to further enhance the capability of scalability, extensibility, customization, and continuous integration. Specifically, 6G should extend the service-based architecture from core network to E2E service-based architecture. For that purpose, the radio access network should be rebuilt with SBA to support SBA-RAN. The UE and air interface should also be redesigned from certain aspects with the basic guideline of SBA (please note that it is not suitable to directly copy the service-based interface to the air interface from the efficiency perspective).

4.1.2 Protocol Stack

The emerging services pose new challenges on the 6G networks, such as how to avoid network load imbalance, improve spectrum efficiency, and decrease power consumption. To address these challenges, a jointly-optimized transmission strategy can be considered, which involves all layers of the protocol stack, such as the application layer, the RRC layer, as well as the PHY layer. Currently, the 5G protocol architecture is still based on the traditional layered protocol model, which prevents effective interaction among different layers.

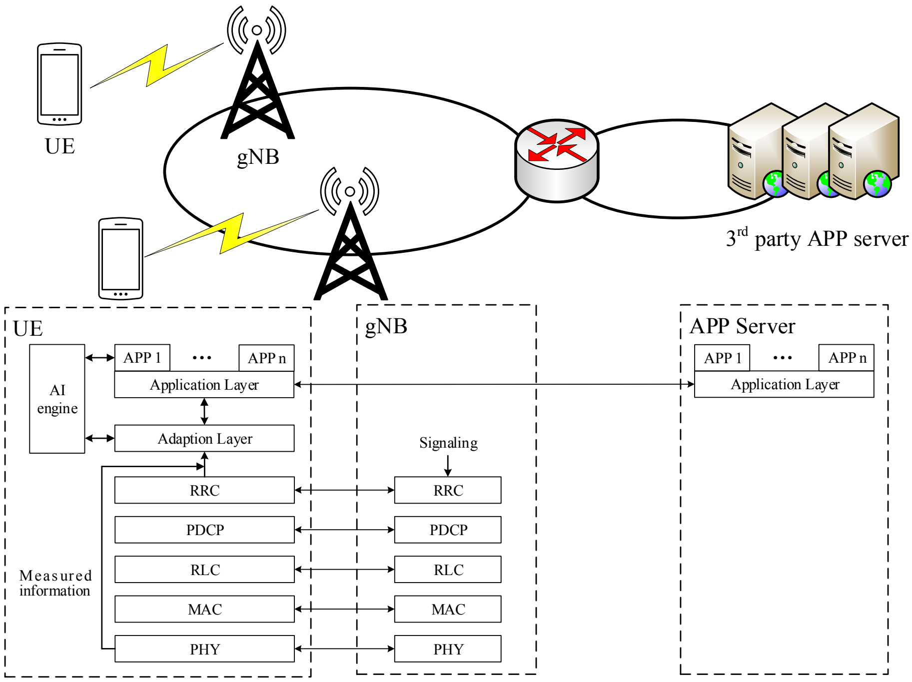

Fig. 2: Overall architecture of adaptive transmission manager

To make the 6G networks become an intention network, some enhancements on the NR control plane protocol stack are required. As shown in Fig. 2, the main modification is to introduce an adaption layer in UE and signaling to indicate the information about transmission condition obtained at the gNB side (i.e. UL radio channel condition and network congestion status).

4.2 Integration of sensing, communication and computing

With the accelerated development of ICDT, sensing, communication and computing have become the three essential functions to provide mobile information services. The emerging services, such as AI services, unmanned services, digital twin services and immersive services [3], are showing stronger coupling characteristics of sensing, communication and computing, which then bring the technical requirements on functional integration.

4.2.1 Basic concept and features

The integration of sensing, communication and computing refers to an E2E information processing framework that performs information acquisition and information computing during the information delivery. Sensing refers to the behavior of information acquisition from sensing objects through sensing devices, data interface, and/or the ability of data analysis. Communication refers to the information delivery behavior through certain methods and media. Computing refers to the calculation behavior for a specific task through special or general hardware and software.

Integration of sensing, communication, and computing can work under function cooperation, function fusion and function reconfiguration models, and support cloud-network-edge-terminal cooperation and convergence. Cloud services, edge computing, network slicing, non-public network, Internet of vehicles and other technologies have introduced cloud-network-edge-terminal cooperation capabilities to varying degrees.

Integration of sensing, communication, and computing is believed to introduce more essential functions for 6G, such as cooperative sensing, cooperative ML, deterministic transmission with higher reliability and data rate. It is expected to be applied to different technology scenarios, such as human-machine interaction, inter-AT interaction, and virtual-physical space interaction.

4.1.2 Key issues

Integration of sensing, communication, and computing should address the following key issues:

1) Integration of wireless sensing and transmission

The natural idea for the integration of wireless sensing and transmission is to design a unified waveform to enable them to work on the same spectrum bands. They can share the radio resources and hardware resources and can effectively realize wireless sensing and transmission functions through interference cancellation, interference isolation and other technical means.

2) Deterministic information processing

Deterministic information processing is an end-to-end task-centric information processing technology, including deterministic sensing, deterministic transmission and deterministic computing. It is expected to ensure service experience from system level by jointly reducing sensing delay, transmission delay and computing delay, and jointly improving sensing reliability, transmission reliability and computing reliability.

The key issue is to solve the problem of ultra-high precision synchronization and joint resource scheduling.

3) Multi-dimensional resource management and scheduling

Sensing resources refer to the radio and hardware resources such as radar, camera, various sensors and detectors. Communication resources refer to the radio and hardware resources of access, forwarding, routing and synchronization. Computing resources refer to special or general software and hardware resources such as computing and storage. These resources inside or outside the network can form a resource pool through virtualization for multi-party sharing. This can improve resource utilization and provide new capabilities such as cooperative sensing, cooperative communication and cooperative computing. Blockchain is a better tool for resource sharing. The key problem is how to perform modeling, optimization, decomposition and allocation for a sensing task, a communication task and a computing task according to the service requirements.

4) Service continuity

Service continuity refers to the functional continuity of sensing, communication, computing, and application. Sensing continuity refers to the ability of continuous information collection, positioning and tracking for the sensing objective, which requires sufficient sensing coverage of base station or mobile terminal. Communication continuity traditionally refers to the handover of access points, which can be achieved by multiple-connection over high and low frequency bands and increasing base station density. Computing continuity refers to the ability to decompose and migrate computing tasks in real time due to the dynamic changes of computing resources. Application continuity refers to the ability of real-time migration from local platform to another platform due to the change of service environment.

5) Capability exposure

The capability exposure of sensing, communication and computing can further enhance the information service ability of 6G. The capability exposure framework architecture can be divided into resource layer, capability layer and application layer. The resource layer includes all kinds of sensing resources, communication resources, computing resources and various data resources. The capability layer is the core layer, being responsible for capability modeling and encapsulation, capability arrangement and operation and maintenance, and capability announcement. The application layer is the underlying capability demander, which requirements are proposed to the capability layer through API interface.

6) The challenges

The primary challenge for the integration of sensing, communication and computing is to answer the coupling relationship between them and the integrated function gain boundary. Secondly, the integration of wireless sensing and transmission in the millimeter wave, visible light and terahertz bands faces the challenge of signal processing and devices challenges. Thirdly, the integration of sensing, communication and computing faces the challenge of heterogeneous computing environment and chips. Fourthly, resource scheduling and collaborative machine learning meet the challenges of algorithms. Finally, trusted information processing should be addressed to create a trustable sensing, communication and computing environments.

4.3 Space-air-ground integrated network

The future space-air-ground integrated communication network will be a three-dimensional layered, integrated and cooperative network based on the ground network, air-based network and space-based network. Satellites (including high, medium and low orbit), near space platforms (such as hot-air balloons, UAVs, etc.) and ground nodes form multiple coverage. Global service coverage, on-demand service, security and credibility will be achieved by adopting a unified network architecture, unified technical system and unified system management and control.

In terms of logical architecture, the space-air-ground integrated communication network is divided into access network, bearer network and core network. The access network is composed of all layers of non-terrestrial network nodes and terrestrial cellular access nodes, forming a global wireless access network to meet the service access needs of large numbers of users distributed among land, sea, air and space. The bearing network includes two parts: ground bearing network and satellite bearing network. Ground bearing network is the carrier network in traditional terrestrial cellular communication system. Satellite bearing network is composed of various orbit satellites and high-altitude platform nodes. Each node has the ability of broadband transmission, routing and switching, and completes the fast forwarding of various service data in the air network through the link between nodes. The core network is distributed, which is composed of edge core network deployed in non-terrestrial network nodes and cloud core network deployed in ground nodes. Edge core network and cloud core network realize edge-cloud cooperation through computing power scheduling.

4.3.1 Micro-service-based RAN

At present, 5G core network based on service architecture has achieved good results in network efficiency and flexibility. Using the idea of core network micro-service for reference, the service-oriented design of access network can be realized by extracting the protocol stack of access network and redefining the function modules of access network. The access network based on service architecture breaks the solidification of the traditional protocol stack hierarchy, and provides the possibility to further reduce the access network delay and simplify the interface with the core network elements. For example, the retransmission function originally distributed in MAC layer, RLC layer and RRC layer can be extracted and re encapsulated as "retransmission control service". The resource configuration function originally distributed in MAC layer and RRC layer can be extracted and re encapsulated into "resource configuration service". In the same principle, "session control service", "connection control service" and "signal processing service" can also be encapsulated.

Compared with the traditional access network protocol stack partition mechanism, the access network function micro-service can better adapt to the characteristics of limited space node resources. With the micro-service granularity, the access network control plane and user interface functions are deployed on the ground or space node platform as required, forming an access network function flexible segmentation mechanism, improving the flexibility of network function satellite ground partition mode. From the perspective of development, micro-service can improve the agility of access network software development and adapt to the development needs of future global application scenarios; in addition, through the micro-service of access network function, it is consistent with the core network function micro-service, which is easier to realize the integration design of access network and core network, and reduce the energy consumption of space nodes.

4.3.2 Distributed CORE network

In the space-air-ground integrated communication system, the distributed core network architecture is adopted, where some core network functions are deployed in the space nodes to establish the edge core network, and the cloud core network is established on the ground. Such architecture can effectively reduce the service transmission delay and improve the system robustness. The edge core network deployed in the space node is a functional entity with simple and cohesive functions and no obvious network element boundary. The cloud core network deployed in the ground node is mainly responsible for resource scheduling, policy arrangement, complex signaling processing and deep message processing. The dynamic deployment of core network functions is realized by network function reconfiguration to adapt to the changes of future application scenarios and network operation requirements.

Edge core network needs to carry access management, authentication management, policy management, session management, mobility management, paging management and other logical functions. If all the functions are deployed in a single edge core network, it is difficult to realize the lightweight calculation of the edge core network, which makes the resource constrained satellite payload face challenges. If these logic functions are deployed on multiple satellites in a fixed way, the resource utilization rate will be low due to the difference of computing power requirements of each logical function. The edge core network is an effective way to improve the efficiency of satellite load computing capacity, which adopts the computing architecture of fully distributed deployment of satellite nodes and dynamic intelligent adjustment of computing role. For example, in busy business areas and insufficient on-board computing power, authentication management and policy management functions with small demand for computing power can be dynamically enabled; in service free areas, mobility management and paging management functions with large demand for computing power can be dynamically enabled.

Due to the characteristics of high-speed movement and uneven business distribution of space nodes, if the static planning method is adopted for space node computing power deployment, the problems of mismatch between space node computing power and service demand and low utilization rate will appear.

In the space-air-ground integrated communication system, the computing power scheduling architecture is introduced to accurately allocate and schedule the computing power of cloud core network and edge core network. According to the terminal characteristics, service quality requirements and service characteristics, the computing power dispatching center can allocate the real-time computing power of edge core network and cloud core network, adapt to the non-uniform distribution of services, and improve the utilization rate of computing resources. The technical difficulty of computing power collaboration lies in the development of a set of computing power release mechanism, real-time sensing mechanism, scheduling mechanism, recovery mechanism, and fault-tolerant processing mechanism of computing power node anomalies.

4.4 Native AI architecture and technologies

6G should introduce new architecture to move from AI ‘for’ 5G to AI ‘in’ 6G as fundamental of 6G and provide ubiquitous AI capability for intelligent network and new service operation. So far, the mobile network provides mainly the connectivity of the world for information exchange. As AI becomes more powerful and widespread, the mobile network is expected to provide intelligence not just information. The intelligence refers to the human-like capabilities, such as sensing/cognitive to the world, data analysis, and making decision /reaction to the worlds, no matter in physical world or digital world.

In general, AI/ML application in mobile network aims for performance improvement, complexity reduction, or solving problems difficult to model. It will involve almost each network element and layer. It first focuses on network automation and then on RAN/air interface enhancement, optimization and reconstruction, with user cases including AI/ML “orchestration” for network slicing, “platform” for analytics application, location and MEC for emerging services, anomaly detection / correction for RAN optimization algorithms, RRM/Scheduler/PHY/BF optimization, RRM (control plane) in network layer, UP /QoE optimization in network & transport layer, scheduler in MAC layer, receiver / channel estimation in L1 high layer, digital beamforming in L1 low layer, DPD and analog BF in RF, and AI/ML cross-layer optimization involving RAN and edge cloud. Thus, accurate service personalization down to the lower layers can be achieved. A distributed multi-level AI architecture is then required to enable application layer AI, network AI, edge AI, radio AI, physical AI and terminal AI, as shown in Fig. 3.

Besides multi-level AI architecture, various forms of ML, such as transfer learning, federated learning and deep reinforcement learning, will need to be used across different nodes or environments. AI/ML function, such as cooperative sensing, data set sharing, model sharing, cooperative learning and operation between various nodes needs distributed manner.

5G has introduced AI/ML function in its network structure, such as RAN intelligence controller (RIC) function with E2 and A1 interface in O-RAN and network data analytics function with specification of structured data in 3GPP 5G core network. Both of them employ centralized architecture, although RIC introduces two-level architecture.

Fig. 3: Distributed computing/AI/ML in 6G network

The distributed AI architecture facilitates seamless integration of context awareness into the optimization of transmission and computing schemes under the AI/ML framework, as shown in Fig. 3. The context may include the attribute and state of services, network, terminals, users and environment. State prediction, long term pattern and higher-level semantic knowledge can be derived from the context with AI/ML technology, and then used for several different use cases. Essentially, this can reduce the randomness in the communication links.

Finally, the distributed AI architecture should be designed taking into account the capabilities of the hardware, which are distributed in each network elements for transmission computing or AI/ML computing. Both the ML algorithm performance and the transmission scheme performance optimized by the ML algorithm are limited by hardware capabilities.

Moving from AI 'for' 5G to AI 'in' 6G as fundamental of 6G, we expect various forms of learning will be employed to realize the above applications. Transfer learning and federated learning will play critical roles. Systems will have to be trained offline in simulation environments to a sufficient extent first so that basic communications can be established and then subsequently trained in the field to optimize performance. So there will be transfer of learning from the simulation to the field environment. Devices and network infrastructure have to co-learn to incorporate to end to end operations and here, federated learning will play a role.

Rather than sharing large data sets between various devices and the network, models will be shared. At the higher layers, deep reinforcement learning will be necessary for optimization of resource allocation and control of various parameters. Hierarchical and multi-agent reinforcement learning will need to be used across different nodes.

4.5 Intent Aware Smart Network

To accommodate a wide range of scenarios and service requirements, 6G is expected to become more agile, and inevitably, more complicated, thus posing great challenges to network management and radio resource optimization. Intelligence is expected to be introduced in wireless network for all the domains and all levels, from terminal, local, edge to the cloud. Data analytics, machine learning, AI and intent expression are identified as the key drivers for the intelligence evolution and revolution in the wireless network. Data driven and intent aware smart wireless network usage scenarios and key technologies (see Fig. 4) are being heatedly discussed and investigated recently both in the wireless network industry and academia. "Smart and Simplicity" become the industry consensus for 5G and future network. "Smart" requires the network to dynamically adapt to the diversified scenarios and services to efficiently boost both spectrum efficiency, energy efficiency and offer the consistency the user experience according to the network intents of network operators or the business intents of vertical users. “Simplicity” poses the requirements of network automation and autonomy to significantly reduce the network operation and maintenance human labor and cost by applying a concise intent expression model.

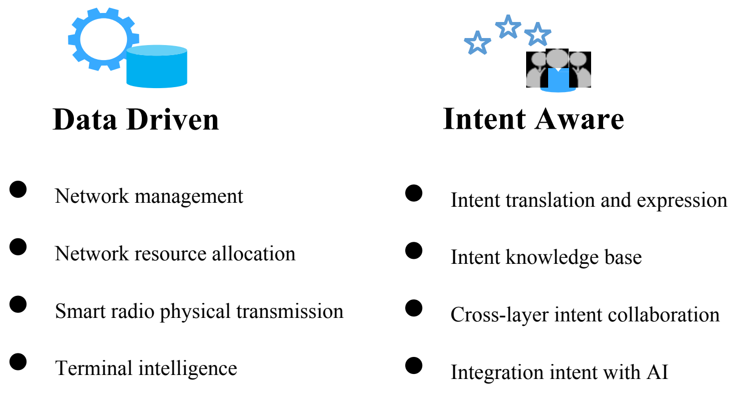

Fig. 4: Key areas of Intent Aware Smart Network

Currently diverse multiple networks have co-existed, e.g. 2G, 3G, 4G, 5G, and network management and optimization is a huge burden for operators, for example, exponentially increasing number of parameters need to be optimized and adjusted timely not only for new base station planning, coverage optimization, but also for anomaly detection and root cause analysis. The introduction of AI related technologies have demonstrated great benefits to improve efficiency and relieve human efforts.

With increasing capabilities of mobile terminals, for example, integration of GPU or NPU in Terminal, mobile terminals is evolved from a smart phone to an intelligent phone. Part of AI processing can be offloaded from network to terminals not only to reduce cloud processing cost, but also to achieve more accurate or efficient processing since user terminals have better understanding user specific radio channel. With the assistance of user terminal, network can better configure and control resource allocation.

Mobile edge computing is a vitally important use case for 5G and even 6G. By utilizing powerful AI processing capabilities on edge, the user plane content can be analyzed in a timely manner to help achieve accurate edge caching policy.

AI applications have also been experimented in PHY layer optimization and will play an important role in 6G. AI enabled radio transmission technologies, e.g. deep learning aided channel estimation, MIMO detection, have been explored and experimented by academics and positive results have been achieved.

Furthermore, intent aware wireless network is proposed and investigated to achieve the network “smart” and “simplicity” leveraging the data driven network intelligence. In intent aware wireless network, the intent users (e.g. BSS/OSS) uses a controlled language (e.g. domain specific language, DSL) to express the business/network goals, without describing how to accomplish the goals. Such an intent aware wireless network could help the network operators to simply the network management and improve the network automatic capability (e.g. close loop). In case of 5G vertical industry, intent aware wireless network could be introduced to meet with the business intents of the vertical industry operators without deeply understanding the wireless network details. Such vertical industry system or user submit a business intent which describes the specific business goals using the dedicated vertical industry business terms, without having to use network-related language. Then the intent system of the intent aware wireless network translates the business intent to one or more network commands and delivers them to the wireless network entities ensuring the business intent goal to be achieved.

Intent knowledge base helps to translate an abstract intent expression to specific network configuration operations. The operation could be a command with specific/dynamic parameter values, an optimization problem or a sub-intent. In addition, translated operations may be different in different network scenarios, so the applicable conditions of the operations should be provided. Besides, since an intent only describes the network goals that need to be achieved and does not involve specific implementation details, the criteria for determining whether the intent is achieved or not that can be understood by the network should be also provided in the intent knowledge base.

When a high-level intent system receives an intent from the operator or higher-level system, it decomposes the intent to sub-intents and send them to multiple low-level intent systems (e.g. NMS sends sub-intents to multiple EMS). For intents with specified measurement target (e.g. throughput, loss rate), the high-level intent system only needs to ensure that the statistical measurement (e.g. average throughput, total loss rate) meets the intent target and there is no need for each low-level systems to achieve the same target. In this case, cross-layer intent collaboration should be taken into consideration.

4.6 Deterministic network technologies

Deterministic network technology was initially used in Ethernet for time synchronization, traffic scheduling shaping and transmission reliability. It is then extended to the mobile communication network, mainly for the network quality guarantee, including bounded delay, low jitter, high reliability and high precision time synchronization. With the continuous emergence of 6G new services, 6G network will gradually evolve into a quality assurance network providing coverage determinacy, connection determinacy, perception determinacy, delay determinacy, calculation determinacy and security determinacy, and will gradually become the technical basis for the upgrading and development of vertical industries.

From IEEE, IETF to 3GPP, various standard organizations have different definitions for deterministic transmission. Typical service requirements mainly focus on bounded delay and low jitter, high reliability, and end-to-end high-precision time synchronization.

The concept of determinacy was first proposed and standardized in IEEE. In 2007, the IEEE 802.1 working group created the AVB audio and video bridging task force. In 2012, IEEE 802.1avb task group was renamed time sensitive network (TSN) task group. TSN standard extends AVB technology and becomes a new generation Ethernet protocol. IEEE has released 13 basic protocols, including the combination of synchronization, reliability, delay and management to ensure low delay, low jitter and extremely low packet loss rate of data transmission, and realize deterministic network transmission.

In 2015, IETF set up Deterministic Networking (DetNet) working group, focusing on determining the transmission path on IP (layer 3), so as to provide deterministic delay of E2E network across LAN. At present, DetNet mainly focuses on the scenarios of single network domain or closely related networks, excluding large-scale networks. The DetNet working group has published standards including problem statement, use cases and architecture. However, DetNet only provides reliability guarantee mechanism based on IP (layer 3), without forwarding delay control, and cannot be well applied to large-scale networks.

In view of the problems existing in TSN and DetNet, IETF is studying large-scale deterministic network technology DIP. DIP is based on deterministic packet scheduling and E2E delay guarantee mechanism to achieve E2E delay determinacy and large-scale scalability of IP networks. In 2018, IETF DetNet working group has completed technical solutions such as network architecture and workflow.

3GPP started the research of vertical LAN project in R16 phase in July 2018, in which 5G supporting IEEE TSN protocol research and standardization were carried out for industrial manufacturing scenarios. 3GPP R16 is an adaptive IEEE TSN protocol, which supports five basic protocols: traffic scheduling, time synchronization, traffic filtering, network topology discovery and resource reservation. 5G system is integrated into TSN system as a transparent TSN bridge. It uses URLLC's "guaranteed bit rate bearing" mechanism, and uses TSN network parameters including periodicity, flow direction and flow arrival time to assist in wireless resource reservation.

3GPP will further improve 5G, support IEEE TSN protocol, realize native determinacy of 5G network, support 5G system as clock source to synchronize other nodes of the whole network to support deterministic transmission, simplify system requirements and configuration process, expand application scenarios, optimize routing between terminals and enhance clock synchronization.

In June 2019, 5G Deterministic Networking Alliance was established with the purpose of creating differentiated and deterministic network capabilities and jointly building an industrial innovation platform for 5G. At present, the cooperation of the organization mainly focuses on slicing and edge computing technology. With the maturity of R16 standard and the development of equipment, the prototype construction based on 5G + TSN technology will be started in the future to carry out test verification.

Deterministic network is considered as one of the key technologies of 6G network. It is however facing some technical bottlenecks, which need to be addressed.

TSN is mainly designed for local area network, and its scalability is not good in large-scale scenarios. The deterministic demand indicators of some vertical industries are not clear. Due to the complexity of overall scheme, it is unable to achieve a unified and standardized implementation scheme to meet all scenarios and requirements. DetNet mainly focuses on the layer 3 network based on TSN. This leads to limited applicability and poor scalability. DIP is for large-scale, long-distance network by enhancing the existing TSN mechanism. But the assumption of time synchronization and stream scheduling of some forwarding devices in TSN cannot be established.

In the mobile network, the quality of wireless transmission is more difficult to guarantee. The essence of QoS in mobile network is resource preemption. Setting high priority QoS only improves the probability of resource preemption and cannot guarantee stable service experience. At the same time, cross-layer real-time fault location and repair capabilities need to be improved.

We need to continue to explore new technology combined with practice, having a focus on the high reliability of clock synchronization mechanism, the clock synchronization accuracy requirements and constraints in different scenarios, as well as the asynchronous traffic shaping technology. A unified YANG model is conducive to the automation of deterministic mechanism.

It mobile network, precise time synchronization among nodes can achieve the time synchronization in underlying infrastructure, network element and gateway. Radio resource reservation is a solution for wireless deterministic transmission in case of radio resource shortage. At the same time, programmable network technology can be introduced to simplify protocol to ensure determinacy.

6G is expected to be an extensive deterministic network, which will change from the independent development mode of mobile and fixed networks to the integration mode. Mobile network needs to absorb the existing fixed network two-layer and three-layer deterministic transmission protocol to realize the integration with fixed network deterministic mechanism, namely protocol support, collaborative scheduling and deployment integration.

6G is expected to be a large-scale wide area deterministic network. In the initial large-scale deterministic network, the proportion of strictly deterministic traffic may not be high, and there are some transition schemes. It is necessary to study the cross layer deterministic mechanism, break through the technical difficulties related to the mobility and IP forwarding, and realize the E2E node-by-node deterministic transmission; In addition, it is necessary to strengthen the cross domain deterministic mechanism, such as cross domain time synchronization to reduce accuracy drift in a larger range, and can integrate various deterministic technical solutions.

6G is expected to be a E2E deterministic information processing network. To meet the requirements of mission-critical services on determinacy, 6G should take into account deterministic sensing, deterministic transmission, and deterministic computing. Deterministic sensing mainly focuses on the sensing response time with a certain sensing accuracy and range. Deterministic computing refers to the information computing on time and in time within a task process. Computing task assignment and computing resource allocation algorithms are needed to ensure deterministic computing. The features of deterministic sensing, deterministic transmission and deterministic computing are respectively field-level processing, E2E processing and distributed processing.

4.7 Digital twin body network

The future 6G network will not only develop towards the more macro space-air-ground-sea integrated network, but also extend to the field of micro-communication in living bodies. The wireless body area network (WBAN) is more sophisticated than current network which is a communication network built around human bodies and consists of various related network devices. It integrates various technologies including wireless sensor network, short-range wireless communication and distributed information processing, which is essential to the interaction between personal data and core network. In addition, WBAN is the key component of network connection which lays the foundation for implementing the personalized services of future network.

The new terminal for WBAN is an extension of traditional base stations which may be a module embedded in a smart belt or portable device. Mass data from body area can be converged to the data center of WBAN through multi-dimensional and heterogeneous network, containing 4 communication-related technical procedures which are acquisition, transmission and convergence, computing and display, as shown in Fig. 5. In detail, it consists of 4 steps: 1) data acquisition and access from mass sensors in body area. Sensors, cameras and other devices are used to collect data on human physiological information; 2) transmission and convergence of multi-dimensional and heterogeneous data to the new terminal. The collected data is aggregated in the data center by molecular communication or traditional electromagnetic communication; 3) collaborative computing and digital twining.

Collaborative computing, digital twining, holographic display and other technologies are used to calculate and analyze the aggregated data; 4) communication and interaction with base stations and core network. The data can be transmitted to the network for storage or further screening and analysis.

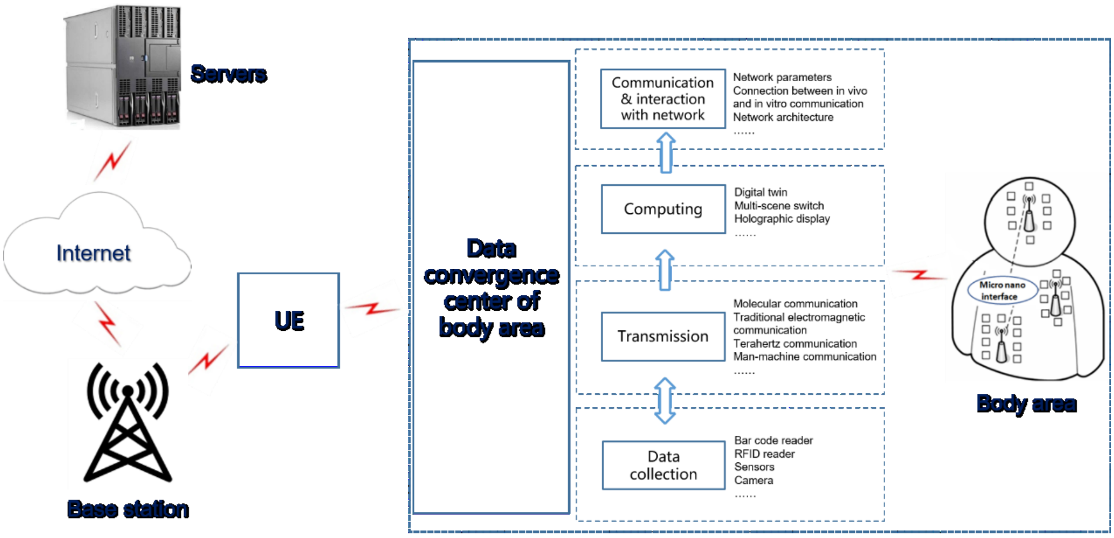

Fig. 5: Key technical procedures of digital twin body network

4.8 Endogenous safety and security architecture and key technologies

6G security is facing a huge realistic dilemma. On the one hand, the 6G vision is initially formed, key technologies are still being identified, and standard formulation is about to start. This leads to double uncertainties faced by 6G security, namely, uncertain network evolution and uncertain security threats. On the other hand, 6G is characterized by open integration, heterogeneous coexistence, and ubiquitous IoT. This leads to two contradictions to be resolved by 6G security, namely, the opposition between openness and security, and the opposition between advancement and credibility. In the face of double uncertainty and two oppositions, what is the way out for 6G security? Prying into the nature of the problem, we can find that even in the face of double uncertainty, most of the security threats come from endogenous safety and security (ESS) problems caused by intrinsic defects in 6G networks, and the two oppositions come from the lack of discovery and utilization about common origin attributes for communication/security/service. Since external factors can only function through internal factors, internal factors are the key to resolving contradictions. Only through ESS, a construction-oriented security solution, can we avoid uncertain threats, unify the two opposites, and have the ability to resist unknown security threats and endogenous integration capability for communication/security/service "trinity". The research work of 6G wireless ESS should include the mechanism and architecture of wireless ESS, as well as key ESS technologies for 6G typical scenarios.

4.8.1 Wireless ESS mechanism and architecture

(1) Wireless ESS mechanism

6G ESS uses dynamic, heterogeneous, and redundant (DHR) constructions to achieve the uncertainty effect of changes in the current defense scenario from any "detection" or "trial and error" attacks by mining ESS attributes, which can fight against man-made attacks and random failures using the axiom of "construction determines security". It uses untrustworthy and low-reliability components to construct a secure and reliable system and can simultaneously deal with uncertain security threats and uncertain random disturbances. The wireless ESS problem refers to the generalized uncertain disturbance caused by the endogenous defects of electromagnetic environment, which can only be solved by the ESS construction based on the wireless ESS attributes. A typical wireless communication system can be regarded as a natural and artificial DHR construction. The heterogeneous, dynamic, and redundant characteristics of wireless environment are the endogenous attributes to achieve wireless communication security.

(2) Communication and security integration theory approaching Shannon's "one-time-pad"

The complexity and randomness of the wireless propagation environment are inherently related to the "one-time-pad" security capability, and the wireless channel entropy determines the "one-time-pad" security capability. By mining ESS genes and using ESS attributes and metamaterial empowerment to encode channels, the channel capacity and the one-time-pad security capacity can be approached simultaneously, and the two limits can be unified. It provides the existence conditions for the security capability approaching Shannon's one-time-pad in 6G wireless application scenarios, and provides a theoretical basis for the realization of "one-time-pad".

(3) 6G wireless network ESS architecture

The 6G wireless network ESS architecture is based on the ESS mechanism and model of the 6G wireless network, and it is an architecture with a complete system and an evolutionary development centered on ESS functions and strategies. It includes key technologies such as 6G ESS feature extraction and ESS function construction. Driven by communication/service/security requirements, it supports the "three layers"(security resource layer, security function layer, and security service layer), "three layers"(control signaling security plane, user data security plane and intelligent drive security plane), and “four domains”(terminal domain, wireless access domain, terrestrial network domain and on-board system domain), as shown in Fig. 6.

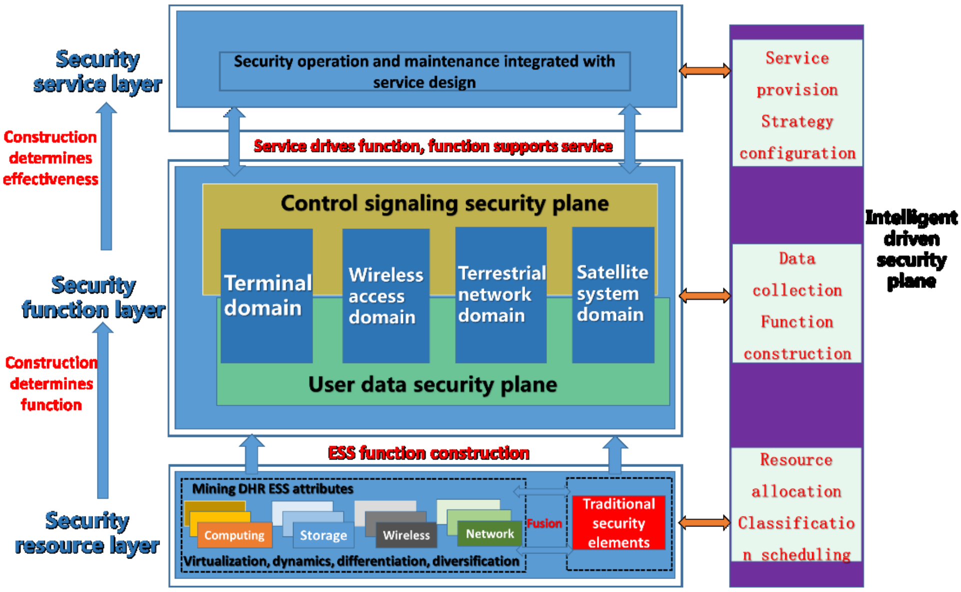

Fig. 6: 6G wireless network ESS logic architecture

4.8.2 Key ESS technologies for 6G typical scenarios

(1) Key ESS technologies for 6G further-eMBB scenarios

In response to the ultra-high communication rate requirements of 6G further-eMBB scenarios, it is necessary to break the bottleneck of the channel key rate and realize the high-speed key generation that matches 6G high-speed communication. The high-speed ESS key generation technology based on the reconfigurable intelligent surface can be used, where the magnitude, phase, direction, and polarization of the electromagnetic wave can be efficiently, quickly and flexibly controlled by the reconfigurable intelligent surface to refine the channel perception capabilities and customize the channel generation capabilities to achieve high-speed ESS key generation. Specifically, the ESS key generation technology based on random space multipath is adopted to maximize the refinement of channel feature extraction and obtain a high output ratio of channel keys by accurately observing the signal multipath. Further, by reconstructing the channel on demand, increasing the heterogeneous complexity and random time variability of the electromagnetic environment, expanding the channel key space, and refining channel perception capabilities, a key rate matching the ultra-high communication rate can be achievd.

(2) Key ESS technologies for 6G IoT scenarios

For 6G IoT scenario with massive low-power terminals, the use of traditional encryption algorithms will face the problems of difficult key distribution management. In response to the above problems, a lightweight encryption technology based on wireless channel fingerprint construction can be used. The channel fingerprint has the characteristics of dissimilarity, random time-varying and third-party uncertainty, which can greatly reduce the burden of key distribution management and achieve light weight key generation. Aiming at the quasi-static channel scenario of IoT, the reconfigurable intelligent surface can be used to realize real-time reconfiguration of the electromagnetic environment and the dynamic programming of wireless channels to improve the dynamic and randomness of the original channel, which can provide conditions for the key generation approaching "one-time-pad"" under slowly changing channels. In addition to encryption, there are also huge challenges in the authentication of massive devices. The differentiated construction of RF fingerprints for massive terminals can be adopted. On the one hand, the uniqueness and non-counterfeiting of RF fingerprints can be used for authentication, which can greatly reduce the difficulty and time delay of distribution and management of authentication keys and realize lightweight authentication. On the other hand, the use of fingerprint differential construction technology by amplifying fingerprint differences can increase the distinction of devices and reduce recognition complexity to realize efficient and secure lightweight authentication.

(3) Key ESS technologies for 6G space-air-ground integrated scenarios

In view of the characteristics of global coverage and heterogeneous coexistence in 6G network, it is necessary to study the ESS technology of the space-air-ground link. Currently, the security requirements of the satellite-to-ground network are higher than that of the terrestrial network, but the protection capability of the satellite-to-ground network is weaker than that of the terrestrial network. The top priority of 6G space-air-ground integrated security is urgently to strengthen shortcomings and bridge the gap. In view of the problems existing on the space-air-ground link side, it is necessary to study how to use the ESS attributes of the satellite-ground network to achieve authentication and encryption at the edge of the network. In terms of authentication, a two-way authentication technology that integrates physical fingerprints of the satellite-ground link can be used. The RF fingerprints can be simultaneously extracted and used for subsequent authentication with the authentication information that is the first access to the satellite network. Then, combining predictable channel characteristics for multi-dimensional authentication can reduce time delay, resist counterfeiting, and realize endogenous unity of communication and authentication. In terms of encryption, the key generation technology based on multi-satellite random sources can be used to generate shared random sources using multi-satellite cooperation and space/time/frequency/track composite channel characteristics, and a key that cannot be stolen by a third party is generated internally to realize encryption transmission.

4.9 Open network architecture and technologies

4.9.1 Basic concept

Open network is defined as a flexible and customizable network with capability and resource exposure function. According to the varying degrees of openness, open network can be classified into three levels, namely, black-box network, gray-box network, and white-box network. Black-box network provides the underlying capability or resource through open application programming interface (API) or a universal platform. Gray-box network is a compromise proposal fallen in between black-box and white-box network. White-box network takes fully openness on both hardware and software. It aims at utilization improvement of general-purpose hardware and fully use the open source software.

In addition to the open service capabilities defined in 3GPP R15/R16, 6G is expected to introduce sensing services, synchronization services, positioning services, ML services, as well as the information sharing of user/service/network/terminal attribute and status.

4.9.2 Open RAN

To obtain higher openness of future networks, there are four main kinds of splitting methods to decoupling traditional RAN, namely, hardware/software decoupling, control plane (CP) and user plane (UP) splitting (CUPS), central unit (CU) and distributed unit (DU) splitting, and downlink (DL) and uplink (UL) decoupling (DUDe). It is worth noting that hardware/software splitting and CUPS are the basis of open source wireless networks, while CU/DU splitting and DUDe further exploit the flexibility and openness of wireless networks.

Hardware/software decoupling is the fundamental of building open source networks. Through mature virtualization technologies, network resources is abstracted and shared among different users, and different services can run on a same infrastructure, thus separating functionalities from physical infrastructure.

The idea of CUPS stems from SDN, which decouples the control signaling from the data transmission. Then, it further expands to cellular networks by deploying two kinds of BSs. To be specific, the control base stations (CBSs) which are normally made up of macro base stations (BSs) form the CP, providing continuous and reliable control coverage at low frequency bands. By contrast, the data base stations (DBSs) (which are normally small BSs (SBSs)) in the UP have the priority of high data-rate transmission at high frequency bands.

CU/DU splitting is the key technology for next generation cloud RAN, which focuses on functional separation by carrying out the real time functions (RTFs) at the radio transceiver and non-real time functions (nRTFs) at a logical center.

The tight couple DL and UL transmission hampers the flexibility of a user's connection, thus cutting down the throughput of RAN. Upon adopting DUDe via dual-connectivity, where a TN connects a MBS and a SBS for its DL and UL delivery respectively, flexible association and high energy efficiency can be achieved.

Upon hardware/software decoupling, CUPS, CU/DU split and DUDe, SDN and NFV assist reconstructing on-demand virtual RANs (namely, RAN slices) for diverse applications with different QoS requirements. To be specific, NFV abstracts network infrastructure and specific function into independent virtual network functions (VNFs). Computing, storage, sensing and communication resources are abstracted in the virtual resource pool. After virtualizing network infrastructure and resources, Hypervisors pick up VNFs and orchestrate them into isolated slices with on-demand virtual resources, based on the requirements of individual services. Then, virtual SDN controllers will manage the operation of each slice.

To realize the RAN re-construction, we devise a hierarchical SDN control plane to achieve an easy management, where the CN controller and the RAN controllers form a two-level hierarchical control plane of the network. Supported by the hierarchical SDN control plane, network virtualization is performed in three abstract dimensions: resource slicing, network function slicing, and network slicing. Through the SDN based 3-dimensional slicing, function blocks of the open architecture can be assembled dynamically according to user requirements, thus providing customized network slicing.

MEC facilitates RAN with local computing and storage resources, which can be incorporated into the open RAN to provide users with optimal or low-latency local services and reduce transport network burden.

5. ICDT Integrated Wireless Transmission

In the diverse service scenarios, a large amount of data and information need real-time or non-real-time transmission over the radio. The 6G radio should support the following essential functions:

- Stronger wireless transmission: Support enhanced eMBB and URLLC on uplink, downlink and sidelink with the sensing ability and potential technologies.
- Deterministic transmission: Support integration of synchronization network and RAN, and coexistence with other TSNs. Support high-precision timing and positioning message delivery. Support integrated traffic and computing resource scheduling.
- Distributed computing: The computing resources at edge and terminal should be easily perceived and scheduled, even in the heterogeneous computing case.
- Multidimensional sensing and 3D positioning: Support multi-sensor operation and cooperative positioning with the help of wireless transmission. Support camera, Lidar, mmWave Radar, ultrasonic, and other sensors. Support wireless positioning, GNSS, and local positioning.

5.1 AI enabled air interface

Big data and AI techniques are playing increasingly important roles in air interface enhancement and air interface extension. The major difference of 6G AI/ML usage than 5G is that 6G will use E2E AI to optimize the transmission schemes itself and customize the air-interface to specific scenarios. One concrete example is the probabilistic and geometric shaping of the constellation. AI can help optimize the choice of the waveform or the constellation, the pilot structure and coding of the control signals. Comparing to the traditional receiver, an AI/ML based 6G receiver's architecture is illustrated in Fig. 7. In this case, Channel Estimation, Equalization and Demapper functions will be replaced and handled by Deep Learning receiver. Generally, various learning frameworks can be explored for future air interface.

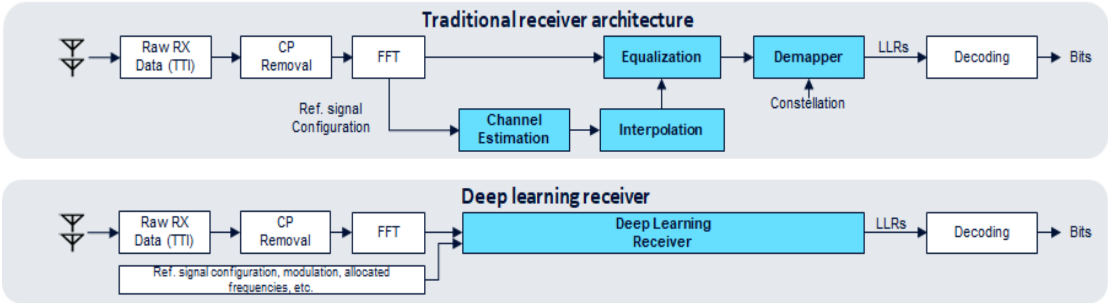

Fig. 7: 6G receiver's architecture based on Deep Learning

In AI/ML implementation design, 6G AI native air interface Layer 1 and Layer 2 shall consider the following cases:

- Optimize the framework using E2E learning – waveform, pilot structure, control signaling
- Custom solution for specialized environments
- Learn traffic patterns and adapt signaling framework
- Adapt to hardware limitations

Ongoing research has demonstrated that deep learning systems can learn to communicate over quasi-static links more efficiently than model-based system design. No explicit design of waveform, constellation, or reference signals is required.

Through extensive training, a single DL network at the transmitter and one at the receiver learn to pick the best design for these parameters as illustrated in Fig. 8.

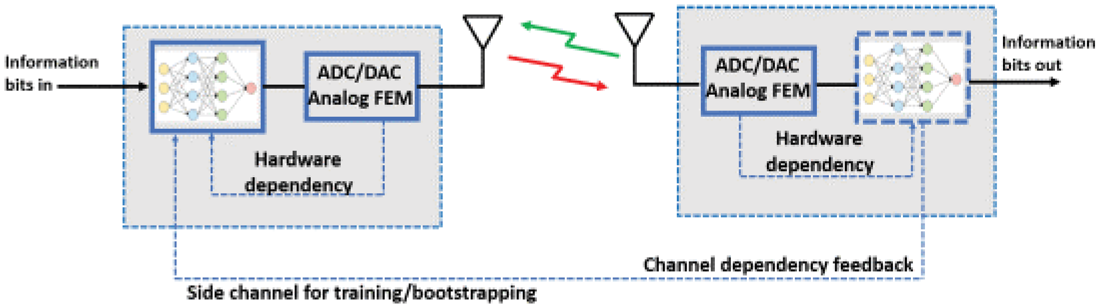

Fig. 8. 6G E2E learning system adapting to hardware and channel

In order to handle complex, dynamically changing multi-user environments, the 6G communication framework with E2E learning approach will be designed in such a way as to allow learning in field to make some design choices. This will enable optimization of the air-interface characteristics based on the choice of the spectrum, environment, hardware deployed and target requirements. One important shift will be to include the capabilities of the hardware in the optimization of the communication framework. In the current approach, the air interface is designed taking into account some practical limits on implementation. But after the design phase, it is expected that all implementations will have the hardware required for the chosen air-interface design. In the future, we can expect the air-interface to adapt to the capabilities of the hardware. For example, a certain implementation may have a limited number of analog to digital conversion (ADC) or digital to analog conversion (DAC) resolution, which can be taken into account by the learning systems to determine the optimal signaling choice.

5.2 Multifunctional air interface

5.2.1 Basic concept and framework

Multifunctional radio is proposed as a potential solution for 6G air interface, as shown Fig. 9. It is a conceptual framework aiming to extend radio function from wireless transmission to computing, sensing and positioning. It is expected to achieve the following objectives:

- Enhance radio resource management. The RAN state space and resource allocation space will be redefined by the perception and prediction ability of sensors. This benefits network capacity improvement.
- Reduce E2E transmission latency. The proposed radio covers both HMI and MMI, as well as the traditional air interface (up / down / sidelink). This will reduce the latency interval between information acquisition and transmission. The transmission latency and computing time will be further reduced when data dimensionality reduction is performed over the radio.

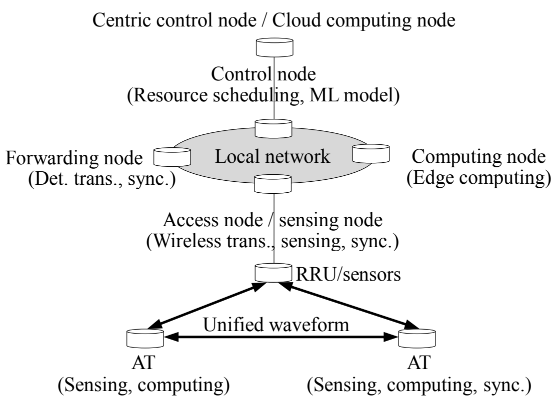

Fig. 9. Multifunctional radio framework

From a functional point of view, 5G NR have four kinds of functions (nodes): access function, transport function, control function and computing function. The corresponding nodes form RAN, transport network and core network, respectively.

In addition to 5G NR, multifunctional radio introduces new functional nodes: sensing nodes, synchronization nodes, and computing nodes. These new nodes form synchronization network, deterministic transport network, and computing-aware network, respectively, and then form a multifunctional RAN, rather than the traditional RAN supporting only wireless transmission.

The sensing nodes support multidimensional sensing with multi-sensor operation, such as camera, ultrasonic, Lidar, Radar, other sensors, and other wireless detection devices. These sensing nodes also support positioning, such as GNSS, wireless positioning and cooperative positioning with ATs. They can be deployed independently, or be located with the access nodes. An access node equipped with both RRU and sensors can be considered as a super AT.

Similarly, a synchronization node may be an access node or a forwarding node. It delivers the crucial timing messages through the local network to enable local deterministic transmission. One of ATs associated with one task should be selected to receive the timing messages and forward them to other ATs.

Multifunctional radio adopts two-level multi-domain distributed architecture for the control function, where the centric control node and local ones cooperatively manage information acquisition, delivery and computing. These control nodes will take part in cooperative sensing and ML to do computing task scheduling. Such operation is defined as cloud-network-terminal cooperation. For example, the model training task will be assigned to cloud and edge, while the reasoning and decision making tasks may be handled at ATs.

Furthermore, multifunctional radio extends from air interface to MMI and even HMI. The design of unified waveform is needed to support the convergence of wireless communication and sensing, not only for uplink/downlink, but also for sidelink. This can help reduce the E2E latency, improve the spectrum utilization, enhance radio resource management, improve network capacity and simplify the hardware architecture.

5.2.2 Key issues

To further clarify the concept of multifunctional radio, a transceiver design example is given in Fig. 10, where the AT (BS) is equipped with a communication device, a camera, and a sensor (e.g. Radar). Camera is used for target recognition, such as the behavior feature of a interactive target. It can run the machine vision algorithm on GPU. Radar such as mmWave Radar is used for target location and even for target tracking. Communication device is for wireless transmission, which is divided into two parts: remote radio unit (RRU) and baseband unit (BBU). In the proposed design example, the RRU is shared with Radar. This is for the purpose of unified waveform design, which will be described in the subsection B. The key feature of the transceiver is the ability to optimize radio resource management (RRM) for wireless transmission with the help of sensing feature information. For this purpose, the receiving and transmitting procedures should support ML model training and in turn benefit from ML model.

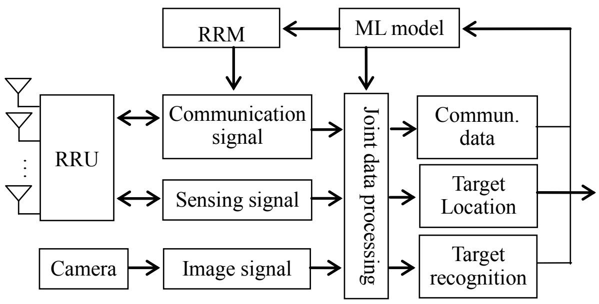

Fig. 10. Transceiver architecture example for multifunctional radio

A unified waveform is one of the key technologies for the multifunctional radio. It enables sensing, wireless positioning and wireless transmission to work on the same spectrum band. It is natural to design the waveform with orthogonal components in time, space, or the beam domain. However, it is a quite challenging task when taking into account the number of antennas, frequency bands and multicarrier modulation. Wireless reference signal for positioning within wireless communication signal is well defined in 3GPP R16 version. The waveform designs to achieve integration of Radar and communication have attracted more attention. A signal processing scheme using massive MIMO arrays for joint communication and sensing is proposed in [4]. Millimeter-wave transceivers for wireless communication, Radar, and sensing are proposed in [5]. Although wireless communication technologies on THz bands [6][7] and visible light bands are recently developed as potential for 6G, there are no concerns on the integration of communication and sensing on THz bands and visible light bands.

The challenges of a unified waveform are the joint wireless signal processing algorithms and the hardware designs of integrated signal processors, RFs and antennas.

A typical cooperative ML involves a sequence of wireless communication and sensing. The joint data processing is actually an underlying ML procedure aiming to support upper-layer cooperative ML. All the lifecycle state of cooperative ML and network state form the state space of the joint data processing. According to the state space, training-based methods use a trained ML model to make decision while knowledge-driven methods use a knowledge base.

Similar to the various level of data fuse, the joint data processing can be performed in signal detection, feature extraction, or decision-making. For practical purpose, the communication context information can assist target feature extraction, while the target recognition results can in turn optimize the radio resource allocation for communication.

5.3 Space-air-ground integrated air interface

The space-air-ground integrated communication system has the characteristics of heterogeneous network, highly dynamic space nodes, time-varying topology, large space-time scale, limited space node resources, and satellite broadcast transmission chain being attacked. These characteristics put forward higher requirements for the design of satellite ground integrated communication system.

5.3.1 Generalized frequency division multiplexing

At present, orthogonal frequency division multiplexing (OFDM) is widely used, OFDM technology is the most mature multi carrier modulation technology. However, OFDM is very sensitive to frequency offset. Firstly, Doppler frequency offset caused by high-speed relative movement between satellite and ground will make accurate frequency synchronization more difficult. Secondly, the nonlinear characteristics of satellite power amplifier will aggravate the impact of high peak to average power ratio (PAPR) of OFDM. Meanwhile, the out of band attenuation of OFDM is slow, which will further restrict the spectrum allocation and sharing capabilities in the intergrated network. In the space ground integrated communication system, it is necessary to develop new carrier modulation technology to counter the nonlinear characteristics of high-power RF devices in satellite payload and the non ideal characteristics of satellite ground link transmission, to improve the transmission performance and efficiency of the whole system.

Generalized frequency division multiplexing (GFDM) is an improved non orthogonal multi carrier modulation scheme. At the transmitter, the binary sequence to be transmitted is first encoded and symbol mapped, and then converted into k × M data block by serial parallel, where k is the number of carriers in the system and M is the number of symbols contained in each carrier. After the data block on each subcarrier is up-sampled, each channel of complex data symbols is circularly convoluted with the shaping filter, and the channel complex data symbols are dispersed over M different time slots. Each channel of complex data symbols will then modulate the corresponding subcarriers; the receiver first carries out synchronization processing to remove the CP in the receiving sequence to obtain the received sequence, and then equalizes the received sequence to eliminate the influence of fading channel on the signal, and finally performs GFDM demodulation, symbol inverse mapping and decoding to obtain binary receiving sequence.

5.3.2 New multiple access technology

The available physical resource blocks of the existing orthogonal multiple access schemes are limited, and the spectrum utilization is not high enough, so it is difficult to meet the ubiquitous access requirements of massive terminals. Therefore, it is necessary to develop new multiple access technology. Based on orthogonal division of resources, non-orthogonal multiple access technology is introduced to meet the requirements of space-air-integrated communication system.

Non orthogonal multiple access technology allows different users to occupy the same spectrum, time slot and code word resources through power reuse or signature codebook design. The receiver eliminates interference through multi-user detection, which has a high overload rate and improves the spectrum efficiency and throughput of the system.

The essential idea of non-orthogonal multiple access technology is to use the complexity of receiver in exchange for the improvement of system spectrum efficiency. However, in the space-air-ground integrated system, from the satellite side, whether using point beam or hop beam mode, the power difference of each terminal is not obvious, so it is difficult to realize non orthogonal multiple access in power domain. In addition, the satellite is a typical resource constrained system, the onboard power and processing capacity are limited, and the receiver complexity should not be too high. In comparison, SCMA and MUSA will be potential multiple access technologies for space-air-ground integrated system.

5.3.3 Multi satellite multi beam cooperative transmission

In the space-air-ground integrated communication system, the deployment mode of constellation satellites will provide the basis for the application of MIMO technology. Through inter satellite cooperation, virtual multi antenna system will be established to realize multi satellite and multi beam cooperative transmission. Multi beam cooperative transmission realizes data transmission by multiple beams from the same orbit or different orbit. Though multiplex diversity technology, the capacity of the satellite ground transmission can be effectively improved, and the BER of the system will be reduced. This will satisfy the needs of the future space-air-ground integrated communication system to achieve the capacity and reliability of the global seamless access system.

Compared with the inter cell cooperative transmission of terrestrial cellular communication system, multi satellite and multi beam cooperative transmission is facing great challenges due to the highly dynamic space-time scale of space nodes in space-air-ground integrated communication system. As the core technology of multi satellite and multi beam cooperative transmission, adaptive beamforming needs to select the best forming pattern according to the highly dynamic and accurate virtual MIMO channel model, to form the narrow beam to alignment user signals in real time and suppress the side lobe to obtain the maximum gain. However, the satellite has high mobility and long transmission distance, and the channel is always in dynamic change. It is difficult to establish a high-precision mobile channel model, which will affect the multi satellite multi beam cooperation gain. The rapid movement of space nodes and large space-time scale cause great difficulties in the synchronization of multi satellite and multi beam. It is necessary to explore the effective synchronization mechanism between large constellation satellites and the receiving algorithm under asynchronous conditions. On the other hand, the interference between multi satellites and multi beams is more complicated for the three-dimensional space network composed of large constellation satellites, so it is necessary to develop effective inter satellite interference suppression technology.

5.3.4 Satellite-ground cooperative transmission

With the development of resource intensive demand and new application demand, breaking the boundaries between the two networks of satellite communication and terrestrial cellular communication network, and realizing satellites and ground cooperation transmission has become an inevitable trend of communication system development.

Typical integrated space-air-ground network deployment includes ground cellular communication network, LEO satellite communication network and high orbit satellite communication network. The cooperation transmission of satellites and earth can occur between multiple satellites at the same orbit height, or between satellites and ground mobile communication systems with different tracks. Different satellite to ground cooperation transmission modes can be adopted for different business needs. Satellite ground collaboration can realize the wide area distribution of massive hot content and relieve the transmission pressure of ground backbone network. Ground mobile communication network and LEO satellite communication network can also provide double layer network data communication services for ground terminal. For example, LEO satellite is used to provide signaling wide coverage, while terrestrial mobile communication network is used for high-speed data transmission.

The difficulties of satellite-ground cooperative transmission include system synchronization control and satellite ground interference suppression. The difference between the space-time scale of the satellite and the ground is large, which leads to the difficulty of the satellite ground cooperative transmission synchronization. The key to improve the efficiency of cooperative transmission is to study the cause of the formation of satellite ground interference, and develop the technologies such as interference prediction and interference avoidance. In addition, improving access efficiency, reducing access overhead, reducing delay and other issues also need to be further studied. The cooperative transmission of satellite and ground will inevitably lead to increase the system overhead. Hence, it is necessary to study how to balance performance gain and system overhead.

5.3.5 Space high speed transmission technology

Inter satellite link is a wireless link, the microwave band, millimeter wave band or laser can be used for inter satellite communication. However, for the traditional microwave communication, due to the limitation of spectrum and orbit resources, it is difficult to improve the transmission capacity of the whole system by increasing the number of space nodes and improving the single node capacity.

Both terahertz communication technology and space laser communication technology have obvious advantages, such as large transmission capacity, small terminal volume, good transmission security and rich frequency resources. They are very suitable for space high-speed information transmission, and become an important means to solve the space high-speed transmission.

However, space terahertz communication has some problems, such as low power of terahertz source, low energy conversion efficiency, weak received signal and low signal-to-noise ratio at the receiving end. In order to construct space terahertz communication network and realize large capacity and high-speed interconnection between satellites and ground, it is necessary to develop high-performance devices and receiving and processing technologies. In the aspect of high-performance devices, it is necessary to develop high-power continuous terahertz wave or pulse terahertz wave generation technology, so as to overcome the interference of background terahertz wave. At the same time, it is necessary to further improve the performance of terahertz modulation devices, and design precise and reliable antenna with high gain and high directivity to overcome the shortcomings of low radiation power of existing terahertz sources. In the aspect of receiving and processing technology, it is necessary to study the receiver with high sensitivity, consider the processing process of terahertz signal, and study the appropriate and efficient space borne terahertz signal processing technology.

In the practical process of space laser communication technology, the influence of the earth atmosphere channel on satellite ground laser communication can not be underestimated. Although the atmospheric channel accounts for a small proportion in the satellite to ground links from hundreds of kilometers to tens of thousands of kilometers, when the laser is transmitted in the atmospheric channel, the atmospheric attenuation effect and atmospheric turbulence effect will affect the quality of optical communication in varying degrees, and measures should be taken to overcome or suppress them. The solution to the atmospheric channel influence problem includes choosing the communication wavelength in the "window" of atmosphere, optimizing the location of ground station, increasing the transmitting optical power, adopting large aperture receiving, high sensitivity receiving, ground multi-point station layout, and adaptive optics technology.

In addition, in the complex space environment (heat, radiation, vibration of satellite platform, etc.), how to improve the space environment adaptability of satellite borne laser communication terminal and maintain long-term and stable communication performance is also a problem should be solved.

5.4 New enablers for air interface

5.4.1 New waveform & multi-access

There will be more scenarios for different services in 6G. Different scenarios have different requirements. Enhanced waveform design will be crucial in specific scenarios to guarantee the performance. No single waveform solution addresses the requirements of all scenarios. For example, high frequency scenario is faced with some challenges, such as higher phase noise, larger propagation loss due to high atmospheric absorption and lower power amplifier efficiency. Waveform based on single carrier form may be a good selection for high frequency scenario to overcome these challenges. For indoor hotspot, the requirements include larger capacity, higher data rate and flexible user scheduling. Waveform based on CP-OFDM form may be a good selection for the scenario. For higher Doppler frequency shifts scenarios, the transformed domain waveform based on OTFS may be an effective approach to harvest the gain of Doppler domain diversity. So multiple waveform schemes will be designed to satisfy different requirements in 6G. Case-by-case system optimization will be needed and compatibility across different waveforms must also be redefined.

Multiple access technology has played an important role in wireless communication in the last decades. It can increase the capacity of the channel and allow different users to access the system simultaneously. Generally, multiple access can be classified as grant-based multiple access and grant-free multiple access. Grant-based multiple access requires dedicated multiple access protocols to coordinate the communication of the accessible users in the systems. Grant-based multiple access technology has become mature and been adopted by various wireless communication standards. However, the grant-based multiple access technology, designed for current human-centric wireless networks, is not appropriate for future autonomous thing-centric wireless networks. To support millions of devices in the future cellular network, a fundamental rethink of the conventional multiple access technologies is required in favor of grant-free schemes suited for massive random access. Grant-free multiple access does not need to perform a sufficient coordination among the users, and can more efficiently handle the low latency requirement, global scheduling information deficiency, or the bursty and random-access pattern of user activity, etc. Grant-free multiple access technology has been used in the initial access process of both cellular terrestrial and satellite communication networks. There are also some challenges for grant-free multiple access, for example, the performance limit for massive bursty devices simultaneously transmitting short packets; the low complexity and energy-efficient channel coding and communication schemes for massive access; efficient detection methods for a small number of active users with sporadic transmission.

5.4.2 New channel coding & modulation

From 4G to 5G, the peak rate of uplink and downlink increases by 10-100 times, and this trend is likely to continue to 6G. It is predicted that the throughput of a single decoder may reach hundreds of Gbps. It is difficult to achieve such a high throughput goal only depends on the progress of IC manufacturing technology in 10 years. Solutions must be found from the algorithm aspect as well. Compared with polar code and turbo code, quasi-cyclic LDPC code has a very high degree of parallelism, and is very suitable for high-throughput services. New designed ultra-high speed LDPC codes are expected to meet the requirements of 6G data channel. Both new parity matrices design and corresponding encoding/decoding algorithms need to be taken into account to reduce the decoding iterations and improve decoder's parallelism level. It is also vital for a decoder to keep a reasonable power consumption level. Considering dramatically increased throughput requirement, the energy consumption per bit needs to be further reduced by at least 1~2 orders of magnitude.

Modulation is another technique that 6G can re-examine. High order QAM constellation modulation has been used to improve spectral efficiency. However, because of the non-linearity of transmission medium, the marginal benefits obtained in higher-order QAM constellations are gradually disappearing. New modulation methods, for example, schemes based on signal shaping, have been proved to be effective in wired communication or broadcast system. However, whether they are also applicable to wireless communication is worth careful study.

Reducing the peak-to-average-power-ratio (PAPR) is an important technology direction in order to enable IoT with low-cost devices, edge coverage in THz communications, industrial-IoT applications with high reliability, etc. Some low PAPR modulation schemes, such as FDSS+pi/2 BPSK, 8-BPSK and CPM, were proposed, but which had some loss in the demodulation performance when obtaining the lower PAPR. So more research is still need for low PAPR modulation schemes with good performance. The phase noise is very high in TeraHertz band. Although the receiver can compensate the most, the residual phase noise will still impact the performance. So new modulation scheme with good suppressing phase noise capability is another important technology direction in THz band. New demodulation algorithm also need to be researched due to the different characteristic between phase noise and AWGN.

Furthermore, to meet the dramatically increased throughput requirement of 6G, there are only two solutions. One is to use wider spectrum, the other is to increase spectral efficiency. THz communication and visible light communication can provide wide spectrum, but are limited by coverage. Thus, it is urgent to increase spectral efficiency. Some high spectral efficiency modulation technologies, such as FTN (faster-than-Nyquist)) and SEFDM (spectrally efficient frequency division multiplexing), has been proposed for several years, which are worthy of being studied further to investigate their performance.

5.4.3 Extreme-MIMO

In order to meet the ultra-high requirements in spectrum efficiency and peak rate, extreme MIMO is one of the most important key technologies in 6G and beyond systems. Extreme-MIMO is more than the evolution of massive MIMO. As shown in Fig.11, the trend of extreme-MIMO includes new antenna structure, distributed MIMO, new signal processing and new application.

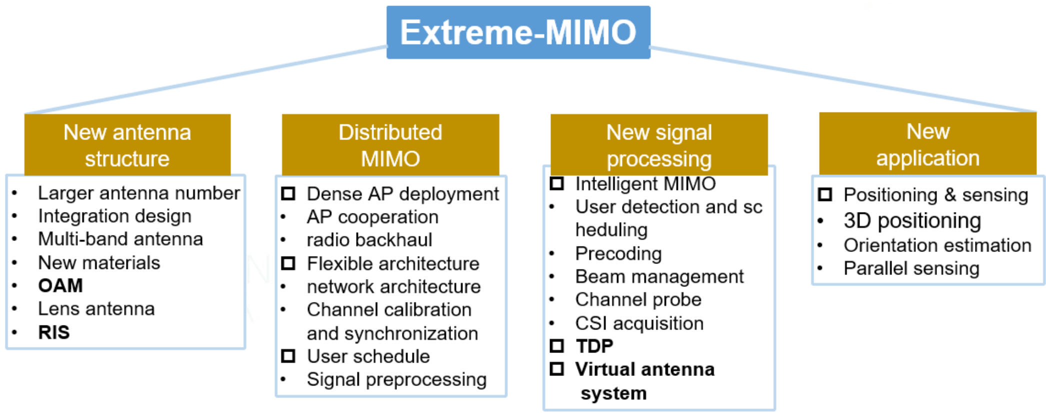

Fig.11. The trend of extreme MIMO

The realization of extreme-MIMO depends on the development of antenna technology. The development of extremely large scale antenna array follows the trend towards larger array scale, smaller array size, higher integration, higher frequency band and higher capability on multi-band transmission. The key technologies of extremely large-scale antenna array include: new antenna structures and new antenna modes. The new antenna structures involve antenna designs of larger scale array in limited space, integration design of active antenna, antenna design based on new materials, multi-band antenna design, etc. The new antenna modes include lens antenna, RIS and OAM, etc.

Distributed extreme-MIMO deployment is an important trend of extreme MIMO. Compared to the centralized extreme-MIMO, distributed extreme MIMO system can provide higher spatial resolution and better performance. The key technologies of distributed extreme-MIMO system include: network architecture design, access point cooperation technology, radio backhaul, synchronization and calibration, channel modeling, channel state information acquisition, signal preprocessing and signal processing technologies, etc.

Intelligence is another important trend of extreme-MIMO. The implementation of extreme-MIMO system requires a lot of decision-making and a lot of beam scanning. Through AI technology, the relevant information of time, frequency, space and other dimensions can be used effectively. In the future, in order to make MIMO more efficiently and more intelligent, AI may be applied in the following modules of extreme MIMO system: channel probing, beam management, precoding, user detection and MU-MIMO scheduling, signal processing and CSI acquisition, access point allocation for distributed extreme-MIMO systems, etc.

The application of high-precision beamforming for extreme-MIMO includes the application of extreme-high frequency band, three-dimensional coverage, high-dimensional positioning, sensing technology and so on. By forming high-precision vertical beamforming and applying distributed MIMO deployment, extreme MIMO can realize high-precision three-dimensional coverage. The high-dimensional positioning of extreme-MIMO evolves high-precision 3-dimensional geographical positioning and UE orientation estimation (i.e. roll, pitch and jaw). Estimation of the orientation in addition to geographical positioning has benefits for several applications, extreme MIMO can also achieve UE orientation estimation (i.e. roll, pitch and jaw). In the aspect of sensing, with the high spatial freedom, high spatial diversity gain and high spatial multiplexing gain provided by extreme-MIMO, the performance of target sensing can be significantly improved.

Although the extreme MIMO has lots of advanced characteristics compared with the massive MIMO, it faces many challenges: high cost, difficulty in channel modeling, high complexity of signal processing, large amount of computation, large delay of beam management, high pilot overhead, high pressure of fronthual and backhaul transmission, high power consumption, etc.

5.4.4 Reconfigurable intelligent surface

Reconfigurable intelligent surface (RIS) consists of a large number of nearly passive elements with ultra-low power consumption [8]. Each element is capable of electronically controlling the phase of the incident electromagnetic waves. It does so with unnatural properties, such as, negative refraction, perfect absorption, and anomalous reflection. Moreover, the spatial feeding mechanism of RIS avoids the excessive power loss caused by the bulky feeding networks of phased arrays. Therefore, RISs significantly reduce both the power consumption and hardware cost. To ensure the antenna gain of the conventional phased arrays, it may be necessary to install a larger number of antenna elements.

RIS has complex discontinuous electromagnetic structures, which is usually much smaller than the wavelength in thickness and much larger than the wavelength in the transverse dimension. Simply, a RIS consists of a large-scale two-dimensional array of subwavelength metal or dielectric scattering particles, and a large-scale device array and a brain, namely array control module. RIS can convert the electromagnetic waves incident on it in different ways. As shown in Fig. 12, these parameters can be modified through array control module by human operations.

Therefore, the adjustable RIS can effectively control the waveform of the incident signal, such as phase, amplitude, frequency and polarization mode, without complicated coding and decoding and RF processing.

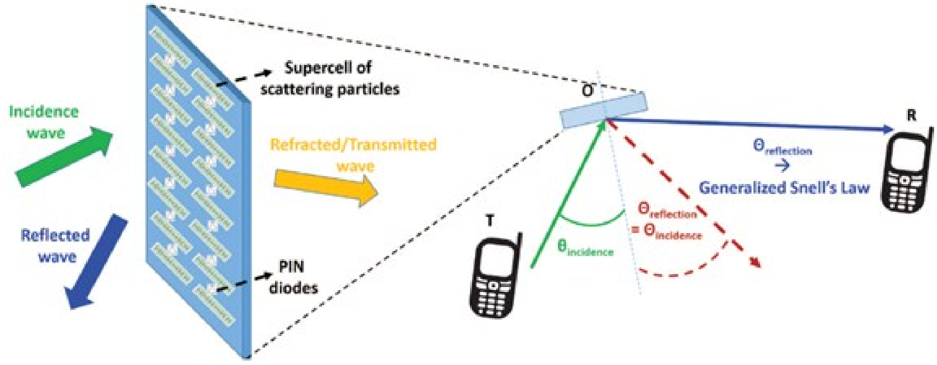

Fig.12. Working principle of reconfigurable metasurfaces

There are many names for the concept of controlling the transmission of electromagnetic waves, such as large intelligent surface (LIS), programmable metasurface (PMS), Reconfigurable Intelligent surface (RIS), and intelligent reflecting surface (IRS) and dynamic metasurface antennas (DMA).

The existing research on RIS can be roughly divided into two directions. The first is to simplify wireless communication by transferring the information modulation to the metasurface, so as to reduce the transceiver hardware complexity. The second is to create an intelligent wireless communication environment to enhance wireless transmission, such as coverage enhancement and energy efficiency improvement. Its basic idea is to use optimized and software adjusted entities to realize continuous enhancement of wireless connection, without the need to generate new signals. For example, with the help of metasurface magnets, electromagnetic waves can be effectively redesigned, including steering to any desired direction, complete absorption, polarization operation, etc. In indoor and outdoor environments, multiple RISs can be used to cover different objects, such as walls, furniture, and other objects.

RIS combined with potential 6G technologies such as THz communication and extreme-MIMO can improve the performance of communication system in many practical application scenarios.

- It provides the transmitted signal beam for the terminal in signal blind areas to expand the cell coverage.
- It provides additional signal propagation path for hot traffic to improve the throughput.
- It overcomes the problems of cost and power consumption for extreme-

MIMO.

5.4.5 THz communication

With the rapid development of communication technology, there are some new applications, such as AR/VR, Drone network, Intelligent Driving, Smart Factory/City, Holographic Communication, etc., Therefore, the performance of 6G communication network in the future is facing higher requirements. The utilization of terahertz (THz) frequency band can greatly expand the available spectrum resources and break through the capacity limitation of the current wireless communication system.

THz waves are electromagnetic waves with a frequency of 0.1 THz~10 THz and a wavelength of 3 mm~30μm, whose frequency range is between millimeter wave and far-infrared optical wave. The availability of THz continuous large bandwidth provides data rates up to Tbps for ultra-high throughput, low latency, and new 6G application scenarios. THz wave also has the following advantages: small antenna size, large number, narrow beam, good directivity, Small scattering, high penetrability to clouds and plasma penetrating ability; Good confidentiality, strong anti-interference ability, the photon energy is between millimeter wave and light wave, which is safe. According to the characteristics of THz wave, its potencial communication scenarios include:

- Wireless backhaul/fronthaul. Using THz wireless transceiver equipment to replace optical fiber or cable to realize high speed data transmission.
- Ultra-wideband coverage in hot spots, providing ultra-high-speed network coverage through the deployment of THz communication systems as a supplement to the macro cellular network.
- Micro-scale communication, used in nano-network and inter-chip communication and other scenarios;
- Space communication: THz waves can be used for high-speed data communication between satellites and spacecraft or space probes with low loss in the outer space path.
- Realize the coexistence of THz communication and perception system to further

improve user experience.

- In addition to communication, THz wave can also be used in imaging, security detection, radio astronomy and high-precision positioning, etc.

THz communication has a broad application prospect, but it is still in the research and exploration stage at present. To realize extensive application, the development of hardware devices and related technologies is needed to promote. The difficulties and challenges are mainly reflected in the following aspects:

- Generation of THz source: There are two main methods to generate THz wave, photoelectric combination method and electronic method. The former method uses optoelectronic technology to convert optical frequency to THz frequency, but the difficulty is limited by optical absorption rate and photoelectric device conversion efficiency, low power, large volume, high energy consumption, and not easy to integrate. The latter method is the use of frequency multiplier devices from microwave frequency multiplier to THz frequency band, but there are problems of high frequency loss and serious deterioration of phase noise.
- THz channel modeling: THz free space transmission has a high loss and is easily absorbed by water and oxygen in the air, so the traditional channel model cannot be used in the THz frequency band. How to establish a more accurate and universal THz channel model is still a problem
- Baseband signal processing: THz communication baseband processing rate is required to reach at least hundreds of GSamples/s, which has A high requirement for the sampling rate of D/A and A/D converter. At the same time, waveform design and high performance modulation coding scheme are also the key research direction of THz baseband processing.
- Antennas and RF systems: Due to the limitation of core device performance, especially the power efficiency of amplifier above 100GHz is low. In order to compensate for the transmission loss, very large antenna arrays are needed to achieve high gain, while the problems of beam management, shape and high energy consumption remain to be solved.

5.4.6 Visible light communication

The demand for wireless connectivity would be increasing at a frenetic speed when networks evolve into the 6G era. With congested radio spectrum and rapid development of solid-state lighting industry, Visible Light Communication (VLC) has received much attention as one of the most promising technologies in the 6G era.

VLC utilizes the visible light band to achieve high data rate. Light Emitting Diode is typically used as high speed modulator. The electrical signal which carries information can be transformed into optical signal, propagating through space and captured by optical receivers in the form of photodiodes or image sensors. The received signal is then demodulated to recover the original information.

As a merger of lighting and communication functions, VLC enjoys several advantages such as ultra-high bandwidth, high security, effective spatial reuse, high energy efficiency, low cost and does not generate any electromagnetic interference.

Some of the typical application scenarios are high data rate wireless access, communication in RF-constrained environments and newly emerged applications such as smart transportation, indoor localization and machine-to-machine communication.

Due to the non-negative and real signal restriction, traditional communication technologies need to be modified before used in VLC. This includes an improved channel model and modified physical layer technologies. Other novel schemes including dimming control, RF/VLC networking, are also extensively investigated.

Despite its many advantages, several key challenges such as limited LED modulation bandwidth, device nonlinearity, coverage issue, background light interference and uplink scheme need to be further studied.

VLC research is in active progress globally. China has initiated its own effect of VLC research and standardization in different projects, especially for VLC in 6G. Other countries including Japan, the European Union and the United States of America have also launched various projects focusing on VLC. IEEE has already established several task groups and published standards for VLC as well.

With joint effort from different parties in the industry and academia, VLC can serve as a bridge that connects communication, lighting, sensing and imaging technologies in the ICDT integrated 6G network.

5.4.7 Holographic radio

Holographic radio is a full-dimensional coherence in space-time-frequency domain, and a linear coherence described by Fourier Transformation. Therefore, the wireless communication evolution leading to 6G will face a "Coherence Transition" as shown in Fig. 13. At present, as one of three major prospective technologies for the 6G physical layer, holographic radio is considered to greatly improve spatial multiplexing, resulting in holographic imaging level, ultra-high density and pixelated ultra-high resolution spatial multiplexing.

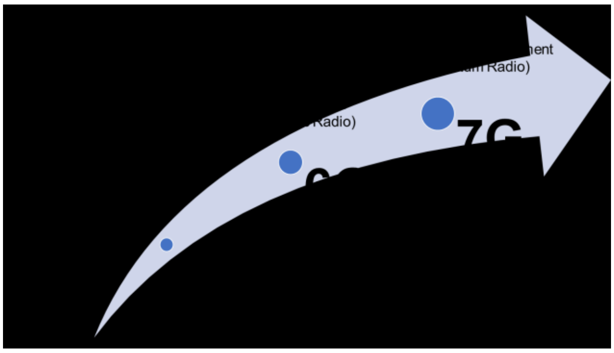

Fig. 13. The inherent logic and coherence transition of wireless evolution

In principle, holography records the electromagnetic field in space based on the interference principle of electromagnetic waves. The target electromagnetic field is reconstructed by the information recorded by the interference of reference and signal waves. The core of holography is that the reference wave must be strictly coherent as a reference, and the holographic recording sensor must be able to record the continuous wave-front phase of the signal wave so as to accurately record the high-resolution holographic electromagnetic field. Another solution is to integrate a large number of antenna elements into a compact space in the form of a spatially continuous electromagnetic aperture, a so-called meta-surface. However, this method is limited to passive reflective meta-surfaces, because for a continuous-aperture active antenna array, the RF feed network is simply impossible to achieve due to the ultra-dense elements. HR can not only realize the RF holography, spatial spectral holography and spatial wave field synthesis, but also precisely modulate and regulate the electromagnetic field of the entire physical space in a fully closed loop, which greatly improves the spectral efficiency and network capacity, and realizes RF convergence of imaging, positioning and wireless communications.

Although HR greatly improves spectral efficiency and network capacity, and helps the integration of imaging, sensing and wireless communication, how to realize HR is a widely open area. Due to lack of existing models, in future work, HR will need a featured theory and modeling, converging the communication and electromagnetic theories. Moreover, performance estimation of communication requires dedicated electromagnetic numerical computation, such as the algorithms and tools related to computational electromagnetics and computer holography. By using spatial correlation model instead of traditional Rayleigh propagation model, the HR space need to be modeled and computed in future researches.

In general, the HR technology can achieve holographic imaging level, ultra-high density and pixelated ultra-high-resolution spatial multiplexing. Fig. 14 shows the main difference between the HR and the conventional massive MIMO. It has the key features in terms of fully closed loop control, interference exploitation and photonics-defined system, which are should be built on heterogeneous optoelectronic computing architecture, seamless integration between photonics-based continuous-aperture active antenna and high-performance optical computing. In addition, meta-surface aided HR, and convergence of imaging, positioning, sensing as well as communication over HR will show a more promising mobile network.

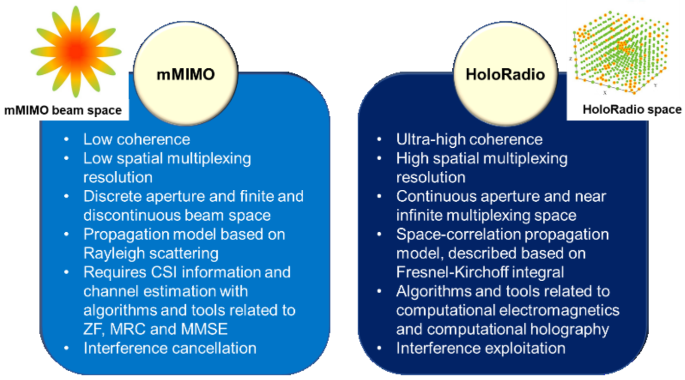

Fig. 14 mMIMO beam space vs. holographic radio space

5.4.8 Other enabler technologies

1) Transform domain precoding (TDP)

With the increase of antenna ports and bandwidth, existing subband-level precoding in 5G NR consumes high feedback overhead and restricts the precoding granularity. However, channel sparsity can be observed in transformed angular-delay domain in mmWave systems with massive antennas. To utilize the channel sparsity in transform domains, a transform domain precoding (TDP) in practical system with hybrid beamforming and frequency domain windowing is proposed to design precoder and feedback.

For example, thanks to characteristics of multi-path channels in mmWave massive

MISO systems, large-dimensional channels in space-frequency domain can be represented by small number of parameters in angular-delay domain. Due to limited scattering environments, channels in angular-delay domain are sparse. Motivated by channel sparsity in transform domains, precoders should also be designed in transform domains to reduce the design complexity and feedback overhead. TDP is composed of three parts, i.e., angles, delays and corresponding coefficients. Due to the discrete-time signal processing, quantized angles and delays are used in TDP, which results in an integer optimization problem. To solve this problem, greedy searching algorithms in compressed sensing techniques, e.g., orthogonal matching pursuit, can be used.

2. Orbital angular momentum (OAM)

OAM is another important physical quantity besides the strength of electromagnetic waves. It provides another dimension for electromagnetic waves besides frequency, phase and space. The OAM multiplexing technology uses different orthogonal OAM modes to transmit multiple signals at the same frequency to achieve the improvement of spectrum efficiency and channel capacity.

When a phase rotation factor is added to the normal electromagnetic wave, the phase wavefront will no longer be a planar structure, but will rotate around the beam propagation direction. The physical feature of OAM makes the isophase plane of electromagnetic waves spiral in the direction of propagation, and the phase changes by $2\pi l$ for one rotation. The intensity of the field strength at the center of the wavefront is zero. Electromagnetic vortex waves with different eigenvalues are orthogonal to each other, therefore OAM vortex waves with different eigenvalues can be transmitted in parallel within the same bandwidth. Common methods to generate OAM wave are: uniform annular array, spiral phase plate, spiral parabolic antenna and cyclic traveling wave antenna. The propagation of vortex electromagnetic waves has three major features: hollow, divergence and phase rotation.

3. Cross-media relay and cooperation

Optical-and quantum-domain wireless communications is less developed than radio frequency wireless communication. However, the requirement for the large data volume and ultra-high speed on mobile network will impossibly be satisfied by only developing radio frequency wireless communication technologies. Thus, it is urgent to find a promising cross-media technology. For example, a base station has multi-media capabilities that allow simultaneous transmission to the two receivers in different media, which are visible light and microwave bands, respectively.

4. Multi-dimensional Positioning

With the development of massive MIMO technology, its potential in positioning is gaining increased attention. By increasing the antenna scale and communication frequency, it is expected to realize the detection of user equipment's orientation (such as roll angle, pitch angle, and yaw angle) based on three-dimensional positioning in space. The antenna array on the base station side can detect the angle of arrival and angle of departure of the user's uplink or downlink signal to complete the user's two-dimensional positioning. Achieving high-precision positioning is of great significance in indoor application scenarios such as industrial robots, games, social networks, and virtual/augmented reality.

6. Intelligent Terminals

6.1 Terminal trends and features

An improvement in the connectivity of the cellular communication system has resulted in a gradual expansion and change in the terminal form. It is expected that in the era of B5G/6G, mobile phones will no longer be the most numerous terminals in a cellular system. In the future, the development of B5G/6G terminals will present the following trends: ubiquity, intelligence, lightweight, sharing, and convergence.

- Ubiquity: In addition to mobile phones, wearable devices such as AR/VR glasses and smart watches will emerge. Gateway products such as home/community gateway devices will become important devices for connecting everything. In the future, a large number of low-cost, low-power and small-size IoT terminals will be scattered around us, delivering various functions such as smart home, environmental monitoring, public services, and asset monitoring.
- Intelligence: By means of edge computing, cloud computing, local CPU/GPU as well as dedicated AI acceleration hardware and technology, the future terminals will become more intelligent while being ubiquitous. The future terminals will have powerful intelligence and wisdom to improve service experience, increase production efficiency and complete more tasks.

- Lightweight: Limited by many mobile and field scenarios, strict requirements have been applied to the weight, volume, power consumption and cost of terminals. Therefore, lightweight has become an important direction for B5G/6G terminals, while terminal technologies are being developed to increase the number of antennas, bandwidth and transmission power. Lightweight aims to enable lightweight terminals without sacrificing the user experience such as data rate and delay, by means of an enhanced system design and optimized link budget.
- Sharing: Development of the sharing economic model and the interconnection-of-all-thing capability enabled by B5G/6G will lead to an increasingly mature sharing capability on B5G/6G terminals. Shared B5G/6G terminals may include rented cars, rented hotel dwellings with smart furniture, or other terminal devices with display and computing capabilities that can be rented in public areas.
- Convergence: The application scope of B5G/6G has been continuously expanded, from ground cellular mobile communication to the broadcast communication system, airspace UAV/high-altitude airship platform communication system, or space satellite communication system. In addition, the device functions are continuously enriched and the performance is continuously improved. B5G/6G terminals will experience a further convergence trend. A single terminal in the B5G/6G era will be competent for the capabilities of several different types of terminals before B5G/6G, including the convergence of terminals that do not have the communication capability and those that have the communication capability, as well as the convergence of terminals that have different communication capabilities.

6.2 Capability requirements

1) Communication Capability

Generally speaking, the B5G/6G requires the terminal to have the communication capability corresponding to the realization of the relevant vision. For digital cinema with resolution up to 64K, the communication capability of 256Gbps is required. For holographic images, the data volume should reach 1GByte/cm3, and the ultra-high definition VR requires the communication capability of 13.6Gbps. Correspondingly, the communication capability of the B5G/6G should be increased by 12-15 times compared with the peak rate of 20Gbps in 5G technology and the requirement of user's data experience of 100M-1Gbps [ITU-R Document 5D/TEMP/625].

2) Computing Capability

Major technological developments in ICT fields such as the Internet, mobile Internet, cloud computing, big data, Internet of Things, artificial intelligence, automatic driving, VR/AR, next generation mobile communication and so on accelerate the society to enter the era of interconnection of everything, perception of everything, intelligence of everything, and gradually gather and activate massive data resources. At the same time, the data structure tends to be diversified, expanding from structured data such as traditional text to irregular and unstructured data such as images and audio. Nearly one third of the data will have the value of big data development, and consequently, the terminal computing demand shows a rapidly increasing trend, which puts forward higher requirements on the terminal computing technology.

3) Display/Interaction/Sensing Capability

The B5G/6G terminals should have a more user-friendly interface. Users can enjoy the pleasure of being on the scenario and can realize the system functions through simple operation. Specifically, the user interface of the B5G/6G terminal should support experiences including but are not limited to the following: Holographic imaging, True 3D, Somato sensory and gesture recognition, Natural language interaction, Augmented reality, Virtual reality, Personal identity verification, Multi-dimensional multi-touch.

4) Battery Life

The B5G/6G terminal needs to support extremely high data processing and transmission speed, which will further increase the power consumption of the terminal. In order to ensure a good user experience, the B5G/6G terminal should have better battery life. Specific technologies that are used to enhance terminal battery life may include, but are not limited to the following technologies: the use of new battery materials, the use of new charging technologies, power saving in communication process, and more advanced terminal hardware and design.

6.3 General terminal Technologies

In order to meet with the requirements of future terminal forms and capability, generally the following technologies could be considered for future terminals:

- Semiconductor Technology: Semiconductor scaling seems to have reached the physical limitation. Function requirement-oriented design and packaging technologies are expected to further improve chip integration, reduce overall power consumption, and promote the development of multi-functional heterogeneous structures.
- Computing Architecture technology: Although the Moore's Law approaches the physical limit, by integrating on mobile platforms with system-wide, converged, and optimized multi-core heterogeneous computing cores, such as DSP vector processor, GPU visual processor, NPU neural network processing unit and CPU, more efficient computing solutions are provided based on various functions, different types of data, and different computing accuracy levels.
- Flexible display material: The flexible display material, e.g., OLED/LED, can be bent freely in a certain range without compromising its normal functions. It has the advantages of impact resistance, light weight, durable, and flexible rolling. Flexible display material will greatly relieve the contradiction between users' demand for high screen resolution and the portability of display devices.
- Electromechanical integration: The electromechanical integration technology combines mechanical technology, electrical and electronic technology, microelectronic technology, information technology, sensor technology, interface technology, and signal conversion technology. Currently the technology is developing towards the direction of intelligentization, modularization, miniaturization, networkization and humanization.

- Inertial navigation: The greatest feature of inertial navigation technology is offline calculation, which can assist traditional positioning technologies, greatly improve the accuracy of indoor positioning and support for 3D positioning.
- 3D sensing technology: Human-machine interaction has evolved from the traditional mode of mouse and keyboard to a more agile and simple mode involving voices and handier mode involving voices and motions, e.g., Gesture recognition/body recognition, Facial recognition, and Brain wave, to improve the life experience of people.
- New material batteries: The introduction of many new materials, including carbon-based materials such as graphene, nano-metal oxides such as zirconia and alumina, inorganic non-metallic materials such as nano-ceramic particles, and polymer with macromolecule such as polycarbonate, as well as the innovation of many methods, including coating technology, preparation technology and doping technology, will impose an important impact on the improvement of battery performance of B5G/6G terminals.
- New charging technology: The application of new charging technology also requires the corresponding materials to enable B5G/6G terminals to recover energy, e.g., solar energy, power generation by pressing, motion power generation, and so on.
- Terminal power saving technology: Further energy saving consideration can be taken from the communication process of power consumption and software and hardware design of the terminals to further improve the life of the terminals.

7. Opportunities from Interdisciplinary Fields

7.1 Quantum Information Technology

The beginning of quantum information technologies (QITs) can be traced back to the 1970s, thanks to a few pioneering scientists who initiated reformulating information theory in the framework of quantum mechanics. The vision of QITs is to provide a radically new information processing paradigm by exploiting quantum mechanics. Nowadays, the rapidly developing QITs has become a class of emerging technologies including quantum communication, computing, and sensing & metrology，as structured by Fig. 15, which will impose profound impacts on ICDT, and finally, forge the so-called “quantum internet”.

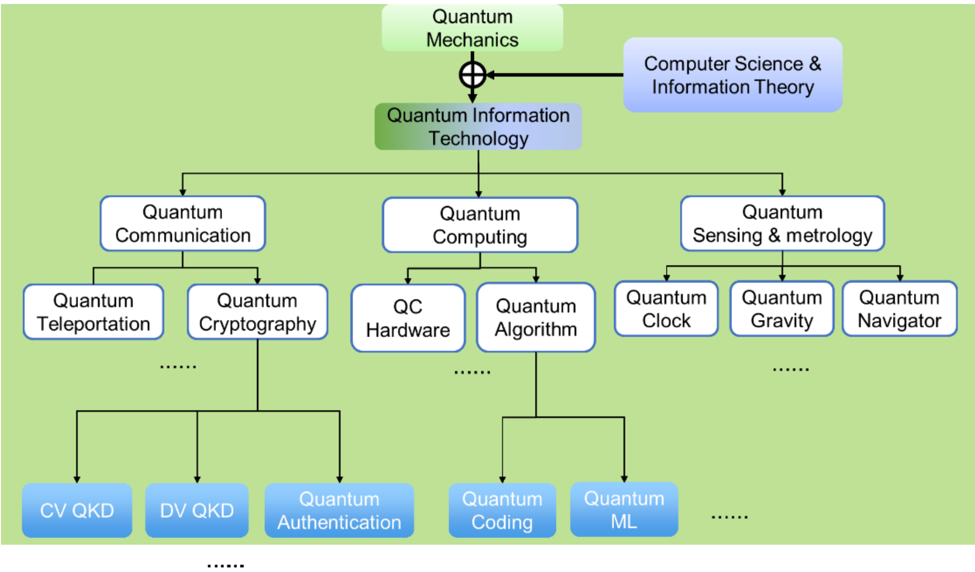

Fig. 15. Concepts of QITs

1) Quantum Communication:

Quantum communication includes a class of novel communication technologies that exploit the transmission of quantum signals, such as quantum key distribution (QKD), quantum teleportation, quantum repeater and so on. QKD is one of the most mature QIT applications at the moment. Different from the traditional key distribution technology, QKD provides long-term security based on principles of quantum mechanics. The security of QKD still holds even under the attack of unbounded computation power, which includes quantum computer. Metropolitan and backbone

QKD networks have been constructed worldwide, satellite-based quantum communication experimental applications have been realized in last decade. In the future, quantum repeater would be an essential building block in constructing distributed quantum computing.

2) **Quantum Computing:**

Quantum computing is a new computation model that follows the laws of quantum mechanics to control quantum information units. Combined with the quantum parallelism, quantum information processing has greater potential than classical information processing. Quantum computers represent a breakthrough in Moore's Law that is limited by the nanoscale, implying enormous computing power potential. Quantum computer has potential applications in many fields, such as optimization over huge data sets and design of new materials and molecular functions. The computational power brought by quantum computing will not only improve the performance of signal processing, but also become a threat to security of existing ICT networks.

3) Quantum Metrology:

Quantum metrology is the study of measurement techniques that gives higher resolutions and sensibilities in measurements of physical parameters than the similar measurement performed in a classical framework. At this stage, quantum metrology is mainly used in the fields of navigation, lidar and time-frequency transmission.

In the last decade, the development of QIT research and application have been accelerated globally. QIT has become the center of focus not only in academia, but also in industry and standardization communities. QKD-based secure communication networks have been/are being built in many countries [9][10]. Quantum teleportation based ‘quantum internet’ project has been initiated in EU quantum flagship [11]. Satellite based wide-area quantum communication experiments have been reported [12]. Different kinds of quantum computer prototypes, including superconductive circuits, trapped ions and semiconductor have been demonstrated. Quantum-based clock, gravimeter, magnetometer and gyroscope have been extensively investigated.

The underlying pattern in information demand envisioned by 6G era is calling for a revolutionary promotion in information processing capability in order to speed up the growth of a new society characterized by pervasive digitization, ubiquitous connection and high-level intelligence. Being in synergy with existing information systems in the classical domain, QITs are anticipated to achieve unparalleled capability of information processing, which is entailed by the era of 6G and beyond, to endow people with safer and smoother lives and to enable society with ever-increasing productivity.

7.2 Biology information technology

Molecular communication is a short distance communication technique in which molecules are used as information carriers to communicate between transmitters and receivers. A molecular communication architecture mainly contains a transmitter, molecular communication interfaces, a molecular propagation system and a receiver. The transmitter generates molecules and encodes the information into molecules, and then emits the information molecules to the propagation environment. The molecular communication interface is used as a molecules container to encapsulate the emitted information molecules and hide the biochemical and physical properties of the information molecules in the transmission process. Molecular propagation systems passively or actively transmit information molecules (or vesicles that encapsulate information molecules) from the transmitter to the appropriate receiver through the communications environment. The receiver selectively receives the unsealed information molecule and reacts with the received information molecule. This biochemical reaction represents the decoding of information.

The brain-computer Interface (BCI) is a method and system that provides a direct channel for communication between the brain and external devices through bidirectional information stream. BCI technology has been described as the "information highway" for the communication between a human brain and the external world. It is recognized as a new generation of human-computer interaction and the core technology of man-machine hybrid intelligence, which relates to information science, cognitive science, materials science, life science, etc. It has an increasingly important impact on intelligence fusion, bioengineering and neuroscience. BCI technology is promising to restore sensory and motor functions as well as cure neurological diseases, while also giving humans the "superhuman ability" to control intelligent terminals with their thoughts.

The synesthesia internet can get all the senses of bodies. The 6G network will extend the transmission content from traditional pictures, text, voice and video to color, sound, smell, taste, touch and even emotion that can be sensed by human body. In the era of 6G networks, it can notify the terminal to smell the delicious dishes so as to have a real share when the others are posting them online. We will get the same feeling when interacting with real or virtual people and objects according to synesthesia internet. In practical applications and daily life, the synesthesia internet will further upgrade the shopping and game experience, and even get a remote trial experience without actual consumption. The network experience store will become a reality.

The nanorobots can be used as drug carriers to deliver drugs in diseased areas through automatic or manual control. Some nanorobots can even perform in vivo surgery. In addition, they can perform some cell functions, such as carrying oxygen and sugar instead of red blood cells. The medical service of nanorobots will be a key application scenario of future WBAN. Whereas, to further expand the functions of nanorobots, the network needs to support the precise positioning of them and implement the synchronous cooperative communication between them. In the future, the WBAN under 6G will be used to further solve the communication rate, communications reliability and network unified control of a large number of nanobots.

Currently, the digital organ is composed of the sectional information of thousands of organs, which is obtained through anatomy in advance. Then, a digital organ is reconstructed through computer image processing. Finally, the precise simulation of the organ information is obtained by the accurate description of each function of the tissue with a three-dimensional model. However, it lacks of personalization, accuracy and instantaneity. Digital virtual human organs have become an important research field in medicine and anatomy. The future digital organ will provide a completely real-time and dynamic digital model, reflecting the organ changes in real time and accurately describing each person's organ by combining with WBAN under 6G. It puts forward higher requirements for the number and accuracy of sensors, and instantaneity and reliability of the network. With the greater computing power and micronetworks of future communication and data processing center, the granularity of digital organs may be further refined. For instance, the further refinement of the thickness of heart slices is helpful to achieve more precise reconstruction.

Intelligent monitoring and collaboration can be conducted between devices in WBAN. Deep thought interaction can proceed between humans and virtual assistants. Even intellectual exchange can be carried out between humans, so as to comprehensively improve learning skills and efficiency in humans.

7.3 New materials and new energy

7.3.1 New material application technologies

Currently, new materials widely used in the ICT field include nano-composite materials, meta-materials and photoelectric/ thermoelectric materials. And the following subdivision directions focus on:

- New composite materials for heat dissipation: Based on the high thermal conductivity of nanomaterials such as graphene (more efficient thermal radiation coating materials), with the help of the processability of polymer materials, the communication heat dissipation scheme is optimized to solve the problems of high power consumption and high heat dissipation costs of communications equipment.
- New antenna: Reflective intelligence surface design based on metamaterials; antenna design based on materials such as liquid metals.
- New devices: Based on excellent optoelectronic properties, new materials have a wide range of applications in Millimeter Wave/Terahertz/Optical communications devices. How to overcome the speed barrier of silicon

microelectronics and how to achieve small-scale optical gains need to be solved with new materials. For example, the ultra-high carrier mobility of graphene, the conduction band and the valence band have a symmetrical conical shape around the K and K'points at the edge of the Brillouin zone, and the band structure in contact with each other at the "Dirac point", so It can be applied to ultrafast optical/high frequency devices.

7.3.1 New energy application technologies

Energy consumption, energy supply and mobile equipment endurance are always the critical challenges in mobile communications development. 5G NR technologies, especially large-scale antenna technology, increase in the power consumption of base stations and terminals, all bring cost pressure. At the same time, VR and other large video terminals, unmanned vehicular / UAV / robot / intelligent dust and other mobile ATs, sensors put forward higher requirements on battery capacity and endurance. 6G design requires breakthroughs in new energy and new battery technologies to solve the problems of battery life and energy consumption. The following research directions can be focused on:

- New battery: Silicon anode battery, graphene based battery, ultra long-life battery and battery with ultra-low self-discharge rate, long-distance wireless charging and other technologies to solve the problems of energy supply and endurance for UAVs, unmanned vehicles, robots and heterogeneous intelligent IoT equipment.
- New energy: New energy self-harvesting and storage technology, energy sharing through smart grid, to solve the problems of power supply for personal terminals, remote base stations and small base stations.
- The simultaneous wireless information and energy transfer.

8. Global 6G Development Initiative

To promote a healthy and sustainable global 6G development, we propose to:

- Promote globally consistent 6G new spectrum planning
- Building a globally consistent technology validation environment

- Builde global open 6G technology and ecosystem
- Advocate the legal use of big data and the protection of digital rights and interests
- Pay attention to the fairness and ethics of network artificial intelligence

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Abbreviations

AI	Artificial Intelligence
ATs	Autonomous Things
BBU	Baseband Unit
BCI	Brain-Computer Interface
CBSs	Control Base Stations
CP	Control Plane
CUPS	Control Plane and User Plane Splitting
DBSs	Data Base Stations
DetNet	Deterministic Networking
DMA	Dynamic Metasurface Antennas
DUDe	Downlink and Uplink Decoupling
DT	Digital Twin
E2E	End-to-End
FTN	Faster-than-Nyquist
GFDM	Generalized frequency division multiplexing
HMI	Human-Machine Interfaces
HTC	Holographic Type Communication
IRS	Intelligent Reflecting Surface
LIS	Large Intelligent Surface
ML	Machine Learning
MMI	Machine-Machine Interface
nRTFs	non-Real Time Functions
OFDM	Orthogonal Frequency Division Multiplexing
O&M	Operation and Maintenance
QIT	Quantum Information Technology
PaaS	Platform as a Service
PAPR	Peak to Average Power Ratio
PMS	Programmable Metasurface

QKD	Quantum Key Distribution
RAN	Radio Access Network
RIC	RAN Intelligence Controller
RIS	Reconfigurable Intelligent Surface
RRM	Radio Resource Management
RRU	Remote Radio Unit
SBA	Service Based Architecture
SEFDM	Spectrally Efficient Frequency Division Multiplexing
SDE	Software Defined Security
UP	User Plane
VNFs	Virtual Network Functions
WBAN	Wireless Body Area Network
XR	Extended Reality
TSN	Time Sensitive Network

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