ICDT Integrated 6G Network 2.0

未来移动通信论坛
FuTURE MOBILE COMMUNICATION FORUM

摘 要

多重因素驱动 6G 发展。一是解决 5G 网络投资高、功耗高、运维难等挑战的需求。二是“元宇宙”等未来新应用和新场景带来信息处理新需求。三是移动通信技术、计算机技术、人工智能与大数据技术融合（ICDT）发展带来的创新机遇。

ICDT 融合的 6G 将是一个端到端的信息处理与服务系统，是通信网络、感知网络和算力网络融合的智能网络。本文尝试提出信息处理效率概念作为 6G 直观的能力度量，围绕通信能力、计算能力、感知能力、AI 能力和安全能力定义了 6G 能力矩阵及性能指标等级，并探讨信息处理效率理论框架和最大化信息处理效率的技术途径。

ICDT 融合的 6G 网络是感知、通信、计算、智能一体化架构，资源共享、能力开放，应用协同。本文通过定义网络大脑、感知控制、计算控制、通信控制、用户控制与业务控制等关键功能实体，构建了一体化网络控制框架，并分析了分布式计算、分布式感知、分布式智能、内生安全和意图管理等关键技术。

ICDT 融合的 6G 空口是通信感知一体化空口、基于 AI 的空口，具备学习能力、通信能力、感知能力和多频段融合组网能力。其中，基于无线感知的无线通信，以及基于无线通信的无线感知是两个重点技术方向，具有高频谱效率、高硬件效率和高信息处理效率三大优势。

ICDT 融合的 6G 终端是功能升级的智能体，一是从智能个人终端向更友好的终端体验发展，二是从刚性形态向柔性形态发展，三是从个人终端向无人机、无人车、机器人及其他智能化设备的垂直应用终端发展，四是从封闭架构向开放模块化终端发展，为 6G 的丰富应用提供了重要支撑。

ICDT 融合的 6G 技术必然来带 ICDT 融合产业形态，形成以集成电路、基础软硬件为上游，以信息处理基础设施、能力平台和终端为中游，升级的 2C、2B 和 2G 应用为下游的产业新格局。为了 6G 更好的发展，本文建议加快 6G 创新链与产业链融合发展，培养 6G 高端人才体系，形成创新与产业集群效应，解决 6G 发展面临的理论、器件和芯片等瓶颈问题。

Executive Summary

Multi-fold factors drive 6G development. The first is to solve the challenges of high investment, high power consumption and difficult operation and maintenance (O&M) of 5G network. The second one is that the new applications and new scenarios such as "metaverse" bring new requirements for information processing. The third one is the innovation opportunities brought by the integration development of Information, Communication, big Data and AI Technology (ICDT).

ICDT integrated 6G will be an end-to-end information processing and service system, and an intelligent network integrating communication network, sensing network and computing network. This paper attempts to put forward the concept of information processing efficiency as a 6G intuitive capability measure, defines the 6G capability matrix and key performance index priority in terms of communication capability, computing capability, sensing capability, AI capability and security capability, and discusses the theoretical framework of information processing efficiency and the technical way to maximize information processing efficiency.

The ICDT integrated 6G network is an integrated architecture of sensing, communication, computing and intelligence, with resource sharing, capability exposure and service collaboration. By defining the key functional entities such as network brain, sensing control function, computing control function, communication control function, user control function and service control function, this paper constructs an integrated network control framework, and analyzes the key technologies such as distributed computing, distributed sensing, distributed intelligence, Intrinsic security and intention-driven O&M.

The ICDT integrated 6G air interface is an integrated one of sensing and communication, and an AI-based one, with learning ability, communication ability, sensing ability and multi-band networking ability. Especially, wireless communication based on wireless sensing and wireless sensing based on wireless communication are two key technical directions, which have three advantages: high spectrum efficiency, high hardware efficiency and high information processing efficiency.

The ICDT integrated 6G terminals are the autonomous things with upgraded capabilities. First, it develops from an intelligent personal terminal to a more friendly

terminal with excellent experience. Second, it develops from a rigid form to a flexible form for convenient use. Third, it develops from personal terminals to vertical terminals, such as UAVs, unmanned vehicles, robots and other intelligent devices. Fourth, it develops from a closed architecture to an open modular terminal. These new kinds of terminals provide important support for the rich application of 6G.

The ICDT integrated 6G technology inevitably bring an new ICDT integrated industrial form, forming a new industrial pattern with integrated circuits and basic software and hardware as the upstream, information processing infrastructure, capability platform and terminals as the midstream, and upgraded 2C, 2B and 2G applications as the downstream. For the better development of 6G, this paper proposes to accelerate the integrated development of 6G innovation chain and industrial chain, cultivate 6G high-end talent system, form the effect of innovation and industrial cluster, and solve the bottleneck problems such as theory, devices and chips faced by 6G development.

Contents

1. Introduction

Information technology is constantly changing. The 6G technology integrating information technology, communication technology, artificial intelligence and big data technology, and digital twin is developing constantly. On the 6G convention in November 2020, the ICDT-integrated 6G Network white paper 1.0 is officially released, regarding 6G as an end-to-end information processing and service system. Its core function is expanded from information delivery to information collection, information computing, and information application, providing more powerful native capabilities in multiple dimensions, including communication, computing, sensing, intelligence, and security. The white paper details ICDT-integrated network architecture and protocol stacks, sensing-communication-computing integration, space-air-ground integration, native intelligent architecture, intent network, deterministic network, twin body area network, Intrinsic security architecture, open network architecture, AI-enabled air interface, multi-function air interface, terahertz, visible light, ultra-large-scale antennas, IRS, holographic radio, new wave pattern, new coding, and other new air interface-enabled technologies. In the white paper, cross-border integration technologies such as intelligent generalized terminals, quantum information, biological information, and material energy applications are also described.

The 6G technology development is accelerating in the globe during the past year. In January 2021, the European Union has officially launched the 6G flagship research project Hexa-X. In February, the Nokia Bell Labs in the United States has released the 6G Communication Whitepaper. Japan has announced to invest 50 billion yen into 6G technology research in March and has released the Beyond 5G promotion strategy-6G roadmap in April. Germany has initiated the first research project related to 6G technology and has published the 6G fund in July. NGMN has released 6G Drivers and Vision V1.0 white paper and then initiated the research and regulation of 6G cases. In May, European Union Horizon 2020 REINDEER has started the 6G new antenna technology research, and the National Science Foundation in the United States has initiated the RINGS program for NextG networks. In June, South Korea has announced to invest 220 billion won to develop and standardize 6G core technologies before 2025, and the Radio Communications Research Institute of Russia has submitted a draft for 6G research roadmap to the Ministry of Communications of Russia, and China IMT-2030(6G) Promotion Group has released the white paper of 6G Overall Vision and Potential Key Technologies. In September, this group has released other reports such as the Outlook on 6G Network Architecture Vision and Key Technology, Communication- Sensing Integration Technical Report, and Ultra-Large-Scale Antenna Technology Report. In June, China Mobile has established the future research lab dedicated to 6G basic research. In August, the University of Bristol in the UK and King's College London has jointly established the 6G Futures center. In September, Huawei has announced the Intelligent World 2030 Report. The global 6G development is showing its characteristics of cross-border integration and multi-layer breakthroughs.

This white paper is the second version of ICDT-integrated 6G Networks. On the basis of version 1.0 [1], this version focuses on network capabilities, architectures, air interfaces, terminals, and industry, in framework of integrated sensing, communication, and computing, and introduces new progress of 6G, analyzes new problems of 6G, and proposes new solutions of 6G.

2.I CDT-integrated 6G Capabilities

2.1 6G Drivers and Cases

2.1.1 6G Drivers

Multiple factors drive the development of 6G. The first factor is the new needs brought by new applications and new scenarios in the future. The commercialization of 5G inspires people to imagine and expect the next-generation mobile networks. New services, new applications, and cases based on the revolution of the productivity and production relationship are constantly emerging, and performance requirements such as the required network data rate, latency, reliability, and positioning accuracy may exceed the limit of 5G. The second factor is the in-depth integration of information, communication, and big data technology (ICDT), driving multi-dimensional expansion for 6G functions and promoting the overall improvement of network service capability and operational efficiency. Resources such as computing and storage will be expanded from the center to the edge, and the network will be capable of native computing and resource sensing and control. The edge AI and distributed AI development is accelerating, making people consider the AI deployment and AI application support in network design. Data has become the element for life and production, and data security and compliance, data analysis and application, data security circulation, and other application of technologies need to be considered in network design. The third factor is the problems and challenges faced by 5G networks. The design of 6G mobile network architecture should inherit the mature technologies and concepts of 5G mobile networks, and the lessons of system design, commercial deployment, operation experiences, and so on should be learned. Challenges of huge investment, high power consumption, and difficult O&M need to be resolved in 6G.

New services such as the 6G intelligent service, immersive services, and digital twin services are constantly developing, promoting typical new service forms such as "metaverse". This has proposed higher requirements of information processing, driving the communication network toward an upgrade of the communication network to the sensing network, computing network, and intelligent network, and an upgrade of mobile terminals to autonomous things.

2.1.2 Unmanned Service: Autonomous thing Interaction

Autonomous things (ATs) refer to entities capable of environmental sensing, interaction, and response, such as robots, unmanned vehicles, unmanned aerial vehicles (UAVs), and other intelligent mobile devices. Information interaction of autonomous things has become the technical support for new services of 6G, especially unmanned services.

Information interaction of autonomous things refers to the behavior of data and information exchange between autonomous things and systems or other autonomous things. In mission-critical scenarios such as unmanned driving technology and unmanned production, the network and autonomous things must support lower interaction latency, larger interaction bandwidth, and higher interaction reliability. Currently, there are two explicit ways to improve information interaction performance. One way is to merge the information collection (sensing) and information delivery (communication), to reduce unnecessary sensing and communication behaviors, as well as the interaction bandwidth and processing latency. The other way is to enhance the wireless communication capability and wireless sensing capability. For the latter, on one hand, the 6G air interface is developing toward higher frequency bands such as the millimeter wave, terahertz, and visible light, to enhance wireless communication capability and overlap with more wireless sensing frequency bands. On the other hand, wireless communication and wireless sensing have more and more similarities in system design, signal processing, data processing, and so on. This technology trend of technologies has promoted communication-sensing integration technology, providing a revolutionary thinking pattern for information interaction of autonomous things.

The above analysis shows that the information interaction of autonomous things can be classified into two categories, between autonomous things and systems, and between autonomous things. The information interaction between autonomous things and systems is implemented through the network, and the information interaction between agents can be implemented directly or through the network. If the base station (BS) is also considered as a type of autonomous thing, the information interaction of autonomous things can be generalized to the information interaction between autonomous things.

There are four layers for the information interaction of ATs: data interaction, model interaction, reasoning interaction, and decision-making interaction. Data interaction refers to the exchange of sensed data between ATs and systems or other ATs. The data includes the original data or training set data, and it is also called cooperative sensing. Data interaction, through data integration, can increase the sensing dimensions, depth, and accuracy. Model interaction refers to the exchange of training models or sharing model training tasks between ATs and systems or other ATs. It is also known as cooperative training. Reasoning interaction refers to the sharing of reasoning tasks or exchange of reasoning results between ATs and systems or other ATs. It is also known as cooperative reasoning. Decision-making interaction refers to the process of reaching a common decision for ATs and systems or other ATs. It is also known as cooperative decision-making. The decision-making results are notified to the autonomous thing's execution unit, to promote task execution or respond to unexpected, emergent events of tasks.

Unmanned services have three distinctive characteristics: 1. ATs are the service carriers with different capabilities of sensing, communication, computing and learning; 2. There are clear task objectives and life cycles; 3. End-to-end information processing with coupled sensing, communication, and computing is needed.

According to users' instruction or intent (required by the task objective and life cycle), the service management entity conducts task modeling and sub-task breakdown for unmanned services and assigns them to all participating ATs. The management entity can also modify or delete ongoing sub-tasks according to users' intent. A sub-task refers to the operation actions with time-space coupling relationships. All operable actions form an operable space, executed by several information processing procedures. The information procedure of sub-tasks can be divided into sensing, communication, and computing, as shown in Figure 1. Sensing is the information collection of all element attributes and statuses of services, and computing includes all service-related data analysis, model training, reasoning, and decision-making. Communication is used for the interaction of sensing content, computing content, and system information. Every autonomous thing will calculate the phased local service status to determine the operation action. The life cycle of unmanned services starts from the initial status and goes through multiple iterations of information processing loops until the target status is reached.

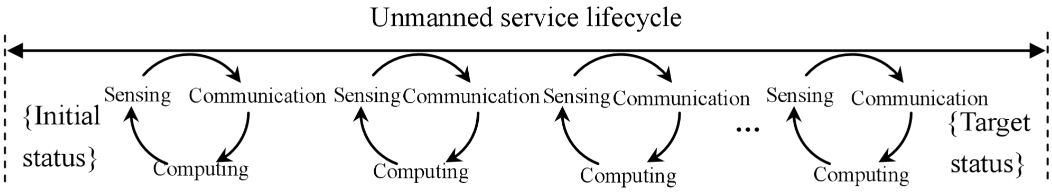

Figure 1 Lifecycle Information Processing Procedure for Unmanned Services

2.1.3 Digital Twin Service: Virtual-Real Interaction

The digital twin is the virtual expression for a physical system, integrating data, models, and analysis tools in the life cycle of the system, to mirror, understand, predict, and tune the physical system status. The digital twin system is composed of the user domain, digital twins, measurement and control entity, physical domain, and cross-domain function entity. The information interaction between the virtual system and the physical system is the basis for digital twin operations, and the information includes the data collected from physical systems and control messages from the virtual system. The virtual system and physical system are strictly synchronized and tend to become consistent, and the physical system is optimized. To this end, the digital twin is also capable of model learning to promote self-evolution.

A new application scenario is the digital twin of human beings. A digital twin human is completely mirrored from a human being from the real physical world, including the exterior, actions, organs, language, thinking, emotions, and so on. There are three levels for future service scenarios of the human digital twin: The first level is the sign twin, to implement all-around remote measurement and accurate prediction of the human body signs. The second level is the communication-sensing twin, to transmit the emotion of the human body and the feelings of the five sense organs. The third level is the control transplant, to realize the thought control, mind transplant, brain-computer communication, and even brain-brain interaction. Analysis of personal behavioral habits, physiological characteristics, and thinking patterns can help improve interaction experience.

The digital twin system is a typical system integrating sensing, communication, and computing. First, the sensing technology is required to collect the attributes and status information of a certain dimension and at a certain level, which are then transmitted with low-latency and high-reliability to the virtual system for computing (modeling, analysis, and prediction) and decision-making. The decision command is then sent to the physical system in a low-latency high-reliability manner again, driving the physical system (including the human body) to change the status, optimizing the performance or completing the objective task.

The 6G network supports not only the information interaction between the virtual system and the physical system but also the information interaction between virtual elements (components) and the information interaction between multiple virtual systems, to implement the digital twin aggregates.

2.1.4 Immersive Services: Multi-Mode Human-Machine Interaction

Immersive services refer to services of ultra-realistic experience in the forms such as AR/VR/XR (vision), holograph (vision), and multi-mode interconnections (multiple senses). Multi-mode human-machine interaction (HMI) is the key for immersive services, including the intent expression through human beings' language, gesture, expressions, brain waves, and so on, and realistic multi-organ experience of vision, hearing, touch, taste, and smell.

The 6G capability with integration of sensing, communication and computing supports XR cloud rendering and 3D reconstruction. The 3D reconstruction helps build ultra-realistic digital models for users so that users can immerse themselves in the 3D virtual environment through cloud rendering and low-latency interaction.

Computing power is the basis for constructing image content, blockchain network, and AI for building ultra-realistic user experience. Computing power makes the creation and experience of virtual content possible, and the rendering of more realistic modeling, rendering, and display requires more computing power. Computing-power-supported AI technologies can help users with creations, to generate more abundant and realistic content. The computing-power-based Proof Of Work is currently the most consensus mechanism for blockchains, ensuring the equity and exchange of virtual assets.

The strong basic capabilities of 6G will support the recognition, consensus, and respect of digital image, digital identity, digital assets, digital equity, and digital emotion and value, to gradually form the "metaverse" ecosystem.

2.1.5 Network Autonomous Services: Intent Interaction

The intent-driven network （IDN） can eliminate the difference in service providers and the operating systems, and transform the fragmented management into an autonomous management of the network. The system is capable of automatic operation, spontaneous adjustment, and autonomous correction via the parameters of the intent. Intent is a declarative language for the expected results, indicating the users' service requirements for the network. Intent interaction aims to eliminate the gap for users to manage the network conveniently. It devotes to on-demand services, which is an important aspect for 6G and the basis of network autonomous services.

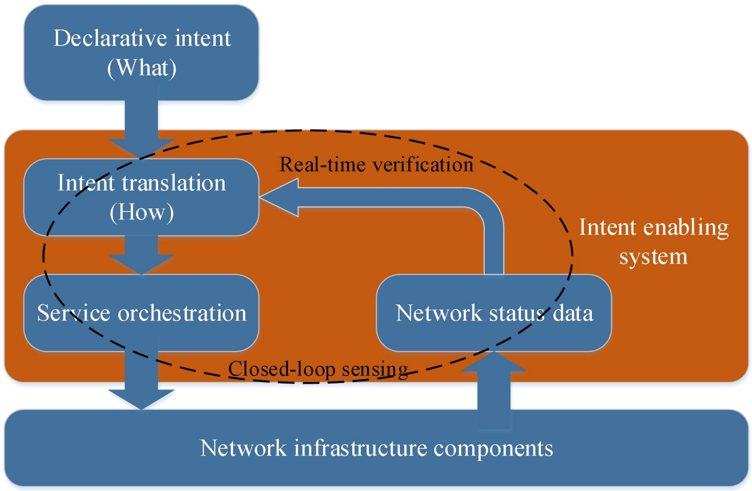

Figure 2 Intent Interaction Loop

Intent interaction can transmit data and intents between the users and network, as well as network status. The information of intent interaction mainly includes the intent, physical network element (NE) topology, available resources, service providers and operating system versions, and so on. Therefore, the flow direction of intent interaction includes the top-to-bottom intent issuing process and the bottom-to-top status sensing process. Figure 2 shows the intent interaction loop. The intent enabling system obtains the intent and completes the intent translation and service orchestration, and then generates the configuration files to the network infrastructure components. The network infrastructure components and intent enabling system proactively exchange the network status data. The information interaction among the users, intent enabling system, and network infrastructure components can implement the closed-loop sensing and real-time verification of network autonomous services.

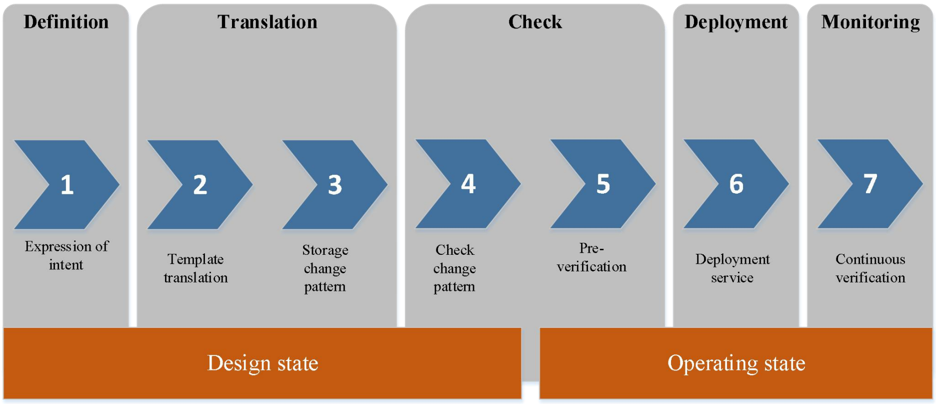

Figure 3 Network Autonomous Service Process

The network autonomous service is faced with greater service complexity and OPEX in 6G networks. Figure 3 shows the operation procedure for enabling the highly efficient, agile O&M from the lifecycle perspective. First, the user defines the expression of abstract and macroscopical intent. Then the intent can be translated into logic policy. For regular services, a template can be used for the translation; for new services, intent-policy mapping can be generated in an adaptive manner stored in the database. The validity of the new service needs to be further proved, and the translation result of regular service needs to be pre-verified based on the network status. It is necessary deploy the executedpolicy to the network infrastructure, whcih satisfies the intent. In the end, the system will monitor the network status, and continuously verify the policy execution. The network autonomous services help realize 6G network automation and intelligent O&M, which will fundamentally bring service agility, ensure users' extreme experience, and reduce OPEX.

2.2 6G Information Processing Requirements and Trends

Information perception, information delivery, information computing, and information application are the four functional procedures that are independently decoupled from each other. This chimney-type information processing cannot fully utilize the prior information of different processing loops, causing unnecessary sensing, communication, and computing behaviors and prolonging the information processing latency. The ICDT-integrated service trend promotes the coupling of information processing functions and the overlap of adjacent information processing loops, and it supports the important function requirements of the information processing procedure to be integrated into 6G information processing and service architecture design. The traditional information processing and service architecture is faced with revolution, and communication-sensing integration, computing-network integration, service-network integration are becoming the trend for information processing, as shown in Figure 4.

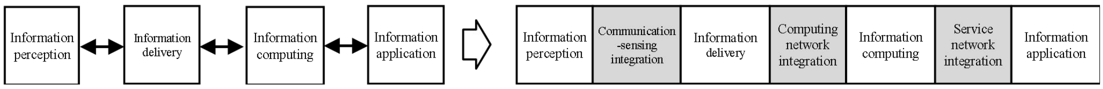

Figure 4 ICDT-integrated Information Processing Architecture

Communication-sensing integration: the overlapping and integration of sensing and communication. On one hand, the wireless sensing shares the frequency spectrum, hardware, and information with the wireless communication, and the joint signal processing and data processing can be carried out; on the other hand, the tasks are adjusted and compromised in the sensing and communication processing phase of the life cycle for the unmanned service, immersive service, and virtual-real twin service, to optimize the information processing efficiency.

Computing-network integration: Communication and computing are overlapped and integrated to construct flat, ubiquitous computing power networks. The network and computing power are integrated regarding protocols, forms, and brains. Computing power and the network are integrated on the protocol layer, breaking through the traditional method of destination-addressing routing and creating a computing power network collaborative route that integrates the computing power status sensing and scheduling; Computing power and the network are integrated on the form layer, realizing computing power in the network and network in the computing power; Computing power and the network form a unified orchestration scheduling center on the brain layer. Computing power is a network resource, as well as a function and a service.

Service-network integration: In the controlled function entity on the network, the service management entity settings dynamically schedule network resources and reconstruct network functions based on the service status, or dynamically schedule service requirements based on the network and autonomous thing status.

Therefore, the traditional information service architecture composed of the services, users, networks, and terminals will evolve into the information service architecture integrating sensing, communication, and computing, as shown in Figure 5. In this architecture, the attributes and statuses of services, users, networks, and terminals (autonomous things) are mutually open and shared. The attributes and statuses of users pass through the network, terminals, and application platforms.

Higher capabilities are undoubtedly needed for the network and terminals, to provide more abundant content, more immersive experiences, and more natural interaction for users.

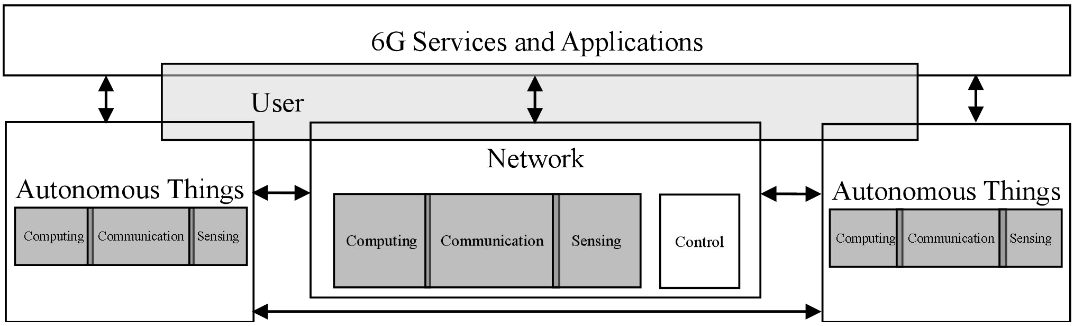

Figure 5. ICDT Network Architecture for Information Interaction

2.3 6G Capability Measurement Criteria

6G is an intelligent network integrating the communication network, sensing network, and computing network, and therefore the capability measurement should be conducted for the comprehensive capabilities from the perspectives of services and applications. In this thesis, we attempt to propose the concept of information processing efficiency for the intuitive capability measurement for 6G. It is an important theoretical topic to build the information processing efficiency theoretical framework and study the technical path for maximizing information processing efficiency and the impact on 6G system design.

First, 6G is an information processing system. The information processing efficiency can be roughly defined as the maximum information processing volume under specified information processing resource conditions. In the meantime, 6G is also an information service system, and the valid information processing volume for 6G services and in the application lifecycle needs to be further defined. Valid information processing volume is the necessary information to promote the transformation of services and applications from the initial status toward the target status. Necessary information, which can be obtained through the information increment during the information processing, can be roughly divided into the information sensing volume, information delivery volume, and information computing volume, and each processing procedure will generate information increment. Information sensing provides the original increment, information computing provides the final effective increment, and information delivery realizes the spatial replication of the original increment and the final increment. Thus, the operation to determine (optimize) the 6G information processing efficiency can be converted and decomposed into minimizing the service information increment. Determining the minimum information increment aims to avoid unnecessary information processing, thus maximizing the information processing efficiency.

In the information processing efficiency theoretical framework, the key is the modeling and decomposition of information processing tasks and the modeling and quantification of information processing resources. Information processing tasks include sensing sub-tasks, communication sub-tasks, and computing sub-tasks. Information processing resources include sensing resources, communication resources, and computing power resources. Under the assumption that multi-dimensional resources can be quantified and scheduled, the information processing task can be divided into different sub-task solutions, and there are different requirements for resources in different dimensions. Therefore, the information processing efficiency optimization ultimately becomes the problem of how to match the information processing task and the information processing resource. Constraint indicators such as the information processing latency and information processing reliability can be further defined. Information processing latency includes sensing latency, communication latency, and computing latency, and information processing reliability is the reliability of the information increment with sensing reliability, communication reliability, and computing reliability considered. Constraint indicators are the insurance of service quality and service experiences and the constraints of joint scheduling of multi-dimensional resources. To simplify the problem-solving process, two second-best solutions are adopted. One is to find the optimized processing task decomposition method according to the network resource status, and the other one is to find the optimized resource scheduling solution according to the information processing task indicators. The final optimization result is, of course, the iterative optimization of the mutual resource scheduling solution and the processing task decomposition solution.

2.4 6G Capability Matrix

The multi-dimensional function and performance definition of 6G form the 6G capability matrix. Functions represent what 6G can do, and performance represents how well 6G can do. Different functions correspond to different priorities of performance indicators. In the following analysis, 5 points are considered to indicate the highest priority, and performance indicators with a score lower than 3 points are not listed in the matrix.

2.4.1 Communication Capability

6G communication is divided into two parts, including terrestrial communication and satellite communication, and their performance indicator dimensions are basically the same as those of 4G and 5G, including the peak value and experience rate, latency, reliability, capacity (number of connections), coverage, and so on. Of course, frequency spectrum efficiency and energy efficiency should also be focused on. Compared with 5G, the same indicators need to be further improved, especially the certainty, which is the key indicator of 6G capabilities. Under the satellite-ground integration architecture, satellite communication is the supplement of terrestrial communication, and the key performance indicators of satellite communication include the experience rate and global coverage rate.

Function/Performance	Experience Rate	Latency	Reliability	Certainty	Capacity	Coverage
Terrestrial communication	5	5	4	5	5	4
Satellite communication	5	4	4	3	4	5

Table 1.1 6G Communication Capability Matrix

2.4.2 Computing Capability

Computing capability, in the narrow sense, refers to the computing performance of individual computing centers, servers, or computing chips. The comprehensive computing performance in the target domain under the computing network integration framework should be considered for the 6G computing capability. 6G computing has the characteristics of diversified cores, distributed ubiquitous, and computing power cluster advantages through network connections. 6G computing will support computing architectures such as general computing, dedicated computing, high-performance computing (e.g. matrix computing), and brain-like computing, application requirements such as AI computing, privacy computing, trusted computing, emotion computing, and data computing, and multi-domain multi-level distributed cooperative computing including cloud computing, edge computing, and terminal computing.

6G computing capability is generally divided into computing and storage. Computing is divided into subfunctions of general computing, dedicated computing, cloud computing, and edge computing. The primary performance indicators of computing and storage are the peak computing rate (such as the floating-point operations per second) and reliability. Latency, certainty, and capacity performance are focused on in different scenarios.

Function/Performance		Peak Computing Rate	Reliability	Latency	Certainty	Capacity
Computing	General computing	5	5	4	4	5
	Dedicated computing	5	5	5	4	4
	Cloud computing	5	5	4	4	5
	Edge computing	5	5	5	5	4
Storage		5	5	5	4	5

Table 1.2 6G Computing Capability Matrix

2.4.3 Sensing Capability

6G sensing capability is the comprehensive representation of the network sensing and terminal sensing. Due to the limitation of the terminal sensing capability, only the network sensing capability matrix is analyzed. In the function dimension, sensing includes target positioning, target detection, target imaging, and target recognition. Target positioning includes three subfunctions of distance measurement, angle measurement, and speed measurement. In specific applications, target positioning can also be divided into horizontal positioning, triangle positioning, absolute positioning, relative positioning, and so on. Target imaging is usually used to support upper-layer applications such as target recognition and target classification. In the performance dimension, the key indicators, similar to the communication system performance indicators, include sensing accuracy, reliability, latency, certainty, capacity, and so on. Other indicators such as energy efficiency, coverage distance, and availability can also be focused on. Sensing accuracy is the most critical indicator of the sensing function. Specifically, it can be divided into the accuracy of distance measurement/speed measurement/angle measurement, non-blur distance/speed, resolution of distance/speed/angle, and so on. The detection accuracy usually refers to the detection probability, including the virtual detection probability and missed detection probability. Imaging accuracy is usually represented by the imaging resolution. For information processing tasks with high real-time requirements, sensing latency must be considered. Usually, the response latency and signal processing latency in the sensing device are examined.

Function/Performance	Accuracy	Reliability	Latency	Certainty	Capacity
Target positioning (distance measurement, speed measurement, and angle measurement)	5	5	4	4	5
Target detection	5	5	4	4	5
Target imaging	5	5	4	4	4

Table 1.3 6G Sensing Capability Matrix

2.4.4 AI Capability

6G is an architecture-level intelligent network integrating human-machine-thing intelligent interconnection, autonomous thing high-efficiency interconnection, and "sensing-decision-execution" integration. Multi-layer in-depth integration with AI helps realize network autonomy, self-adjustment, and self-evolution.

6G AI capability is represented by internal intelligent sensing, intelligent management, intelligent decision-making, and intelligent orchestration, and so on, and external extraction and packaging network capability, to provide underlying capability guarantee for AI applications. An important feature of 6G AI is distributed multi-level multi-domain AI, enabling high-efficiency real-time cooperation between scattered devices with low computing power and autonomous things, to form network-enhanced AI. Terminal AI can sense and analyze user behaviors, to improve terminal resource efficiency and save energy; the access network AI senses and analyzes the terminal and air interface status, to improve the air interface transmission efficiency and save energy; the core network AI sensing service requirements and optimizes network deployment and management, to build the network brain.

6G AI capability will expand from supporting emotion interaction, brain-machine interaction, autonomous thing-human interaction to supporting autonomous thing interaction and interconnection. This greatly expands 6G AI applications. Table 1.4 shows the 6G AI capability matrix

Requirement/Capability	Intelligent Sensing	Intelligent Decision-making	Intelligent Management	Intelligent Orchestration
Terminal Intelligence	5	5	4	4
Access network intelligence	4	5	5	4
Core network intelligence	4	5	4	5

Table 1.4 6G AI Capability Matrix

2.4.5 Security Capabilities

ICDT integration and space-air-ground-sea integration development have more demand for the basic trust mechanism, intelligent collaboration, certification and traceability, and emergency disposal. The system security threats are not fully considered for the traditional decentralized, add-on, and patched security defense modes, which cannot effectively achieve the expected security goals in aspects such as completeness, availability, and privacy protection. With the reference to the concept of human biology, we adopt an inward thinking pattern. The integration design of communication and security to build an Intrinsic security system featuring self immunity is the revolutionary trend for 6G security. In 6G, the advantages of ICDT deep integration will be fully utilized. The sensing, computing, AI, big data, and digital twin native capabilities of the network are used to implement real-time monitoring, analysis, tracing, correlation, practice, and prevention against attacks, to transform passive defense into active defense.

In the perspective of scenarios and requirements, the 6G Intrinsic security has three types of requirements to be satisfied: service security, secure service, and secure security. Service security refers to the Intrinsic security requirements that the security of each 6G network layer needs to be protected, including the security of each capability component and each industrial scenario, including software and hardware device, resources, transmission, operations, big data, and AI; Secure service refers to the application-layer-oriented Intrinsic security, and the native can provide security services such as security capability and security management. For example: when an old service goes offline, the service needs to achieve secure retraction adaptation, and when a new service goes online, the security capability needs to be automatically orchestrated; secure security indicates that the Intrinsic security can ensure its own security. In general, the security and system exposure surface are related in the same direction. Therefore, the 6G Intrinsic security should follow the principle of simplification, to integrate into the network as deep as possible and simplify and optimize devices to the maximum extent, including software, hardware, and interfaces.

From the perspective of capability, the 6G Intrinsic security need to have capabilities in at least four aspects: integration, collaboration, intelligence, and measurability. Integration indicates that security should be considered, designed, and constructed with related functions of the network since the protocol design. Cooperation indicates that the security capability on the end, network, management, and other levels can implement all-network, integrated cooperation. Intelligence includes intelligent decision-making and intelligent self-adaptation. Intelligent decision-making indicates that 6G security, especially 6G security service and secure O&M, should be able to support complete intelligent automatic decision-making and delivery, such as the flexible and intelligent orchestration of security strategies and security capabilities, in-depth identity including the physical layer or biological identity, and so on. Intelligent self-adaptation indicates that in the 6G era, the security capability needs to automatically analyze the impact and adapt and upgrade capability for the entire network in accordance with the network changes, external attack changes, and internal and external information changes after construction. This requires the 6G security-related functional modules to be able to have memory and self-learning ability. Measurability indicates that 6G security can be planned, calculated, and controlled, similar to that the network planning optimization can be implemented for the network coverage, and the investment and effect can be measured.

Function/Performance	Integration	Collaboration	Intelligence	Measurability
Service security	5	5	5	5
Secure service	5	4	4	4
Secure security	5	5	5	4

Table 1.5 6G Security Capability Matrix

2. ICDT-integrated Network Architecture

3.1Sensing-Communication-Computing Integrated Network Architecture

The 6G network architecture will be a sensing-communication-computing integrated architecture. Specifically, it contains three layers: resource layer, capability layer, and application layer, as shown in Figure 6. In the architecture, the resource, capability, and service are integrated into one, to implement resource sharing, capability openness, and service collaboration. That is, the resource is service, and capability is service.

The 6G resource layer includes the sensing resource, communication resource, computing resource, dataset resource, and so on. The sensing resource includes the wireless sensing frequency spectrum resource and software and hardware resource. Specifically, the resource includes radars, cameras, dedicated sensors, and so on, as well as computing and storage resource and related software resource. The communication resource includes the software and hardware resources such as routers, network gateways, and base stations, as well as wireless frequency spectrum resources. The computing resource includes various types of heterogeneous general or dedicated computing units, memories, servers, and so on. The dataset resource refers to the original dataset, training set, test set, and so on that are related to all users, services, networks, and environment in and out of the network, including personal big data, medical big data, industrial big data, transportation big data, education big data, and so no. The resource layer, with the microservice cloud platform, manages and calls resources to form different atomic functions, to provide services to the capability layer.

The 6G capability layer includes the sensing capability, communication capability, computing capability, and AI capability. The sensing capability refers to the capability of the network and terminal to obtain the attributes and status information of all 6G system elements. In addition to obtaining the multi-domain status through data interfaces, 6G will use wireless sensing to implement target positioning (distance measurement, speed measurement, and angle measurement), tracing, detection, and imaging, to further provide location-based services, distance-measurement-based services, imaging-based services, target monitoring and recognition services, and so on. The communication capability includes accessing, forwarding, addressing, routing, and synchronization. to provide deterministic transmission services, transmission services with lower latency and higher reliability, and 100 G to 1 Tbps enhanced broadband services. The computing capability includes general computing, dedicated computing, matrix computing, heterogeneous computing, distributed computing, and so on, providing AI computing, data computing, and communication computing. The AI capability mainly refers to data training and reasoning, providing services such as biology recognition, natural language processing, computer vision, and robot decision-making. These basic service capabilities can further support human-machine interaction, autonomous thing interaction, and virtual-real interaction, to implement comprehensive applications at a higher level.

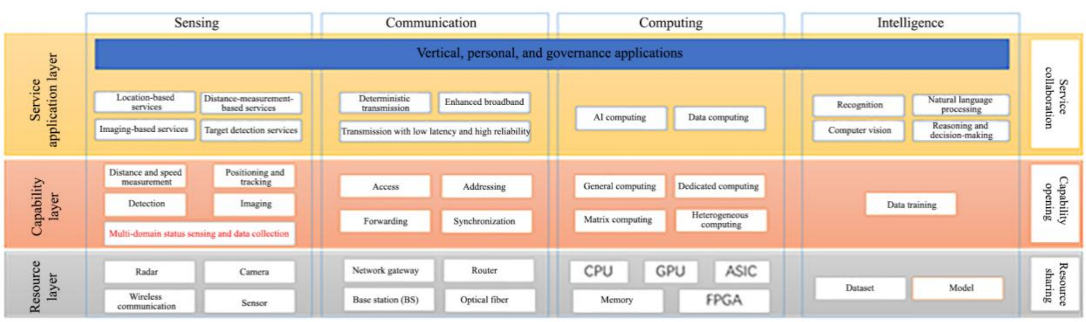

Figure 6 6G Network Architecture with Integrated Sensing, Communication and Computing

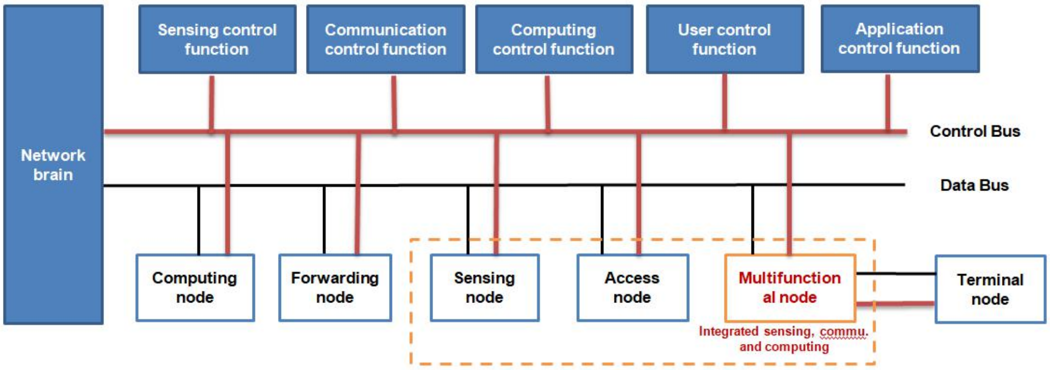

Figure 7 6G Intelligent Control framework with Integrated Sensing, Communication and Computing

To effectively manage the network resource, capability, and application, the key management entity and topology of the 6G network need to be defined, as shown in Figure 7. It mainly includes the network brain (network intelligence and control center), sensing control function, communication control function, computing control function, user control function, service control function, and other function entities, as well as computing nodes, communication nodes (access and forwarding), sensing nodes, and terminal nodes, and other resource entities. These entities interact with each other through the control bus and data bus. The network brain forms a global management strategy for resource and capability based on global sensing, to realize the service orchestration based on communication and computing power status or the joint orchestration of communication and computing power based on service requirements. In particular, the sensing function senses all element attributes and statuses of the entire system and shares them with the network brain and other functional entities in real time. The key is to schedule sensing resources based on the network brain's resource and function management strategy, in order to form sensing capability and ensure the requirements for network operations and service operations. The brain of the network empowers the collaborative "centralized + distributed" control for hierarchical integrated networking where the intelligence is ubiquitous. It enables flexible resource scheduling between the centralized network and edge networks, and centralized + autonomous collaboration at the application and control layers. By integrating collaborative clouds, edges, terminals, and industries in distributed and centralized patterns, it, on the one hand, extends more network functions to the edges of the network for regional autonomy of edge networks, and on the other hand, concentrates the functions that are oriented toward global orchestration & scheduling for the purpose of supporting more complicated cross-domain services.

In the ISAC architecture, two new types of nodes are defined: multi-functional network nodes and multi-functional terminal nodes. The former ones integrate some or all features of network nodes, forwarding nodes, computing nodes, and storage nodes in traditional networks, with multi-level distributed characteristics. The latter ones are mobile terminals with local communication, sensing, computing, and intelligence features, i.e., autonomous things.

3.2 Key Technologies

3.2.1 Distributed Computing

Computing network is one of the essential attributes of 6G. Upon unified management and collaborative scheduling of resources in multiple dimensions such as communication and computing, the technology can optimize connections and computing power throughout the network, including centralized, distributed, and combined technology routes. Among them, distributed computing is vital for two reasons: one is driven by computing power needs for distributed sensing, distributed AI, and deployment of network functions on edges; and two is driven by needs for sharing of decentralized computing power resources and efficiency increase.

Distributed computing is based on network distributed control protocols. By implementing the distribution of computing power information and the routing based on computing power addressing, it decomposes and assigns the computing tasks to proper computing nodes. Therefore, distributed computing has the following key elements: modeling and decomposition of computing tasks, modeling and sensing of computing power resources, and allocation and synchronization of computing tasks. Distributed computing is challenged by heterogeneous data, heterogeneous computing resources, and different AI models & algorithms.

3.2.2 Distributed Sensing

With emerging new technologies, new scenarios, and new services of 6G, driven by the deep integration trend of the ICDT, the 6G network architecture will evolve towards intelligence and servitization, imposing more and more stringent requirements for high energy efficiency, flexibility, and timeliness of networks. Systems consisting of independent sensors are difficult to tackle the increasingly complex differentiated needs in reality. Sensing problems that are to be improved or difficult to solve in current communication networks result in various sensing needs of the 6G network. Distributed sensing would be the key technology to solve these problems. The distributed system is a system composed of a set of computer nodes that communicate via networks and work collaboratively to implement common tasks, for the purposes of utilizing more machines and processing more data. Distributed sensing is a multi-sensor data processing method established by taking distributed computers as a reference.

In the distributed sensing system, sensors process their own information independently, share observation results with each other, and send decision-making results to the data center for fusion. The data interconnection in this way is simple and highly reliable, with lower requirements for computing and communication resources. While providing massive data, the use of distributed sensing technologies could avoid serious performance degradation due to electronic countermeasures against a single sensor system.

3.2.3 Distributed Intelligence

"Intelligence" means that AI/ML acts as the core technology for sensing, analysis, and optimal decision-making of the network itself. Distributed intelligence is an important feature of the intelligent native 6G network architecture [1]. For the past decades, the only standard method to share data and digital content is always the centralized system. As systems become more complex and require point-to-point sharing instead of hierarchical sharing, the storage and computing power of a single computer is far behind the real needs, so the distributed intelligence system architecture turns to be an urgent need. In such a context, system resources are inherently distributed throughout the network, eliminating the bottlenecks of centralized systems. As intelligence joins, each node becomes a complete autonomous thing that is capable of coordinating and cooperating with other nodes to achieve local and global goals.

Distributed intelligence focuses on studying how do logically or physically distributed intelligent systems coordinate their own intelligent behaviors for concurrent problem-solving. Such distributed problem-solving studies aim to build a collaborative system consisting of multiple subsystems, which work collaboratively to solve specific problems. In the distributed problem-solving (DPS) system, problems to be solved could be decomposed into sub-tasks and problem-solving execution subsystems designed for each sub-task. Based on the interaction strategy, a system could be designed and integrated into a unified whole with a top-down method so that the problem-solving system could fulfill the given requirements on the top.

In the next 20 years, AI will become the mainstream of science and technology and be widely deployed in different walks of life. Meanwhile, mobile devices will grow exponentially, driving the computing resources to transfer from clouds to edges [2]. Distributed computing resources will make the centralized AI platforms based on centralized clouds shift to distributed AI platforms. Such distributed AI platforms enable the transmission of some parameters or running results, instead of all raw data, between intelligent nodes or devices involved in the collaboration. Moreover, distributed AI platforms could support the exchange and collaboration of models between edge devices, as well as the joint reasoning across networks [3]. Distributed AI breaks through the operational bottleneck of centralized intelligence, which not only avoids wastes and low efficiency of data transmission but also greatly promotes AI popularity in the whole society. Therefore, large-scale distributed training, collective intelligence-based reasoning collaboration, and privacy protection of data call for the native support and distributed deployment of AI platforms for the 6G network. This will make AI applications possible everywhere and help to build new industry-wide intelligent communication ecosystems.

Currently, a potential distributed AI approach, distributed federated learning, has become a hot spot in the industry. To accelerate the model training, distributed learning was proposed in the industrial circle. As a distributed machine learning (ML), the current research hotspot, namely, federated learning, trains central models discretely through local training using decentralized data on nodes at mobile terminals. This could gain high-quality training effects and reduce costs for data transmission, achieving the purpose of protecting data privacy. Figure 8 shows the federated learning architecture in which nodes use local datasets for model training and transmit updated parameters to servers; then servers update aggregated parameters and return them to different nodes [4].

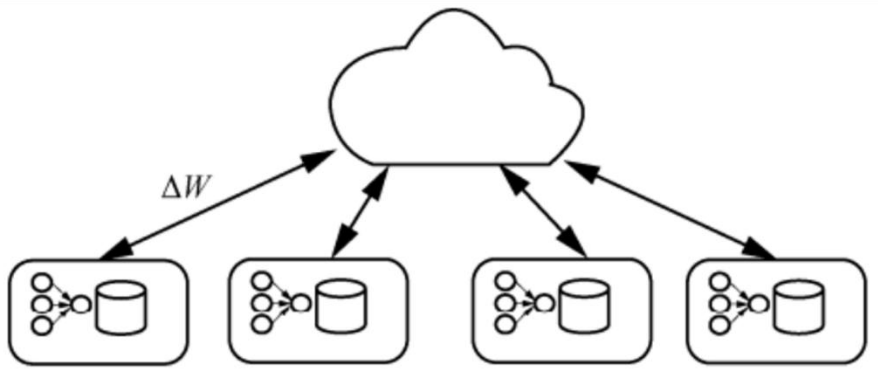

Figure 8 Distributed Federated Learning Architecture

Distributed federated learning will be the key technology to implement the multi-user intelligent distributed collaboration in the 6G network. In the 6G era, how to design distributed learning architectures and optimize parameter communication modes will become critical considerations affecting the productivity of AI applications in the 6G network.

3.2.4 6G Intrinsic security

To create Intrinsic security immunity capabilities systems for 6G, the first step is to design and build unified, 6G-specific, and consensus-based trusted identity and trust evaluation systems. It is critical and fundamental to build deep-level consensus-based trusted identities that are irresistible, unforgettable, and tamper-proof. The identities for people and devices are of the same type and subject to real-time dynamic association management. Based on trusted identities, several factors including behaviors will be extracted to further build an identity trust evaluation system. The 6G consensus-based identity and trust systems will be deployed in such a combined "centralized + distributed" manner that better supports the ubiquitous access and service running of space-air-ground-sea integrated networks, and efficient security processing, such as forensics and traceback.

Furthermore, on the basis of the 6G consensus-based trusted identity and trust evaluation systems, an integrated, collaborative, intelligent, and computable security immunity capabilities system will be built for 6G through the design of all network levels, NEs, and edge levels. At all network levels, the network-wide security management system with 6G network-wide security will be the core to build the logical plane for 6G network-wide security. Technologies such as ML will enable massive security data analysis, intelligent decision-making, intelligent orchestration, intelligent memory, and self-adaption for network-wide security management. On the NE side, space-air-ground-sea integrated 6G NEs require certain security sensing & identification, security defense, intelligent security analysis & memory learning, intelligent security collaboration, and some other capabilities, to improve the threat discovery capability and local processing efficiency of the 6G security. Generally, edges are the best places to discover threats in advance, control security risks, and minimize security-induced losses; therefore, strict security strategies shall be deployed on the 6G network edge side. Under a unified access authentication framework, on the basis of the consensus-based trusted identity and trust evaluation systems, service- and scenario-specific security access mechanisms will be designed, and the trust evaluation performed continuously, to keep an appropriate balance between security and efficiency.

The communication-security integration design spurs the 6G native trusted vision. Communication-security integration means that attempts are made to ensure that, theoretically, the communication-security jointly designed systems fulfill the security needs, so as to eliminate the bottleneck that 2G-5G add-on security mechanisms have no native trusted security attributes. The key is to establish a theoretical model that demonstrates or verifies a system can fulfill security needs in given attack cases, for example, demonstrating that the probability of system failure is less than a given value or that the system fulfills the security attributes.

Some security models have been applied in specific communication scenarios, however, academic researches are still needed for system-level security models. In the ISAC scenario, taking the confidentiality and integrity security needs as an example, the concealment and anti-interference of radar signals can be measured on the basis of interception probability, side lobe level, and interruption probability. The confidentiality of communication information is measured by the Shannon encryption capacity. The communication-sensing signal waveform may be designed reasonably so that the system concealment and anti-interference fulfill the given security needs with the maximum encryption capacity, to achieve the combined design effects of communication, sensing, and security. In the communication authentication scenario, the security of an identity authentication mechanism may be proven by security models such as eCK or confirmed by formal verification theories. To design an authentication mechanism, the first thing is to identify the security threats to the authentication mechanism of the communication system and the security requirements to be fulfilled. The authentication mechanism is designed to minimize the communication overhead and computing latency without compromising the security requirements. The communication-security integration can extend to the design of native communication protocols because those for 2G-5G do not take the security into full consideration and are vulnerable to malicious attacks. Communication-security integration protocols include communication functions, security threats, and security requirements into communication protocols so as to formally verify the security attribute set {φ1, φ2, …, φn} while fulfilling the communication functions, i.e., both the communication goals and security goals can be satisfied.

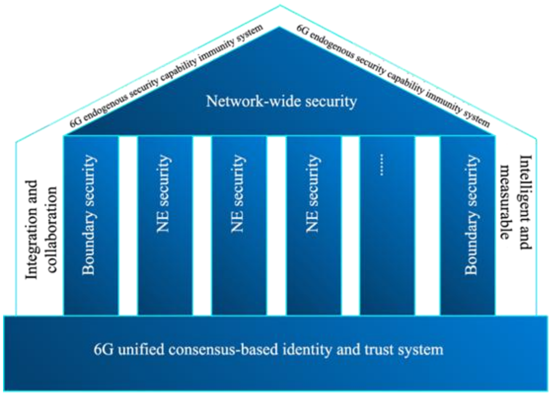

Figure 9 Framework of 6G Intrinsic security System

3.2.5 Intent Agile Management

The intent agile management technology is an important foundation for network and service orchestration to achieve autonomous network management. By integrating three main steps including intent engine, service orchestration, and implementation verification, IDN implements agile network management that "links intents upstream and sensing downstream" oriented to user/network intents, as shown in Figure 10. The intent agile management technology offers a top-down user intent refining capability and a bottom-up infrastructure abstraction capability. The user-centered intent agile management technology gives an abstract approach that, under the collaboration of service level protocols and minimum network capability exposure, affects the design, supply, deployment, and assurance of network services. With declarative intents, users interact with the network of their requirements, without detailing the configuration-level information. IDN can receive user/network intents and extract the information required for different network nodes through service orchestration and real-time optimization. Finally, IDN enables the configurations of network functions for agile management of the 6G network.

Intent becomes the key to a network management framework when it is associated with service supply or delivery goals. The intent engine builds intent models which map context information from user/network intents to the network services. Intent can be matched with the Service-Level Agreement (SLA) contracted with service providers, which offers appropriate resources and network functions for users. Service orchestration abstracts resource status with a set of network coordinators and makes specific configurations for different user/network intents in the forms of network slices, virtual network graphs, or service function chains. Due to the dynamic network status, the real-time verification, based on theories such as ML and digital twin, can drive policy to upgrade dynamically by virtue of the closed-loop feedback mechanism. The verification can ensure the dynamic lifecycle of user/network intents, enable real-time fault detection, and implement autonomous network optimization.

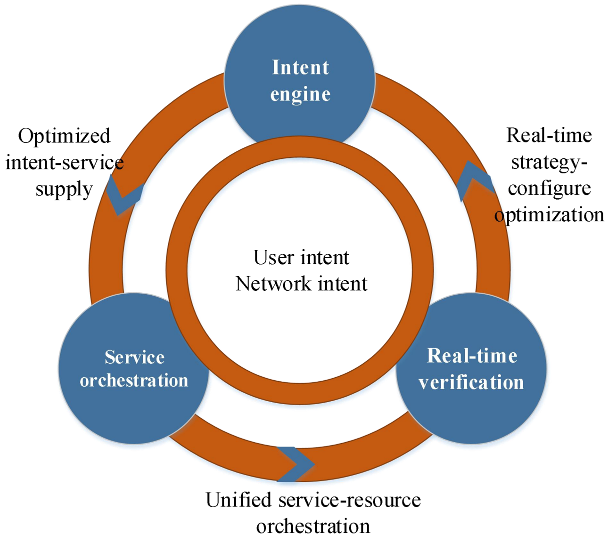

Figure 10 Intent Agile Management

4.ICDT-integrated 6G Air Interface

4.1 Integrated Air Interface of Sensing and Communication

The overall framework of the ISAC technology is as shown in Figure 11, with three layers: resource layer, capability layer, and application layer. The resource layer includes communication-sensing integration frequency spectrum, communication and sensing software and hardware resources, computing resources, etc. The capability layer involves functions including data processing, communication, sensing, and collaboration. Specifically, the communication function covers access and forwarding; and the sensing function relates to target positioning (distance, speed & angle measurement), target tracking, target detection, target imaging, etc. The application layer is based on the functions of the capability layer, offering communication services such as deterministic transmission, low-latency high-reliability transmission, and large bandwidth transmission; sensing services such as positioning, distance measurement, and imaging services; and applications of these services in unmanned services in the mode of autonomous thing information interaction.

The wireless ISAC design intends to implement the sensing and communication functions on the same device within the same frequency spectrum. Therefore, specific ISAC systems may be designed to enable the orthogonal frequency spectrum resource multiplexing (to minimize interference), common Tx-Rx antenna (additional sensing signal receiving antenna may be required), and RF circuits, as well as the joint signal processing at the base band (to eliminate interference). When communication data is related to service flows of sensed data, further joint data processing may be required. In the unmanned service process, joint signal processing or joint data processing may be flexibly configured according to the coupling requirements of the information processing flow based on the common frequency spectrum and common device.

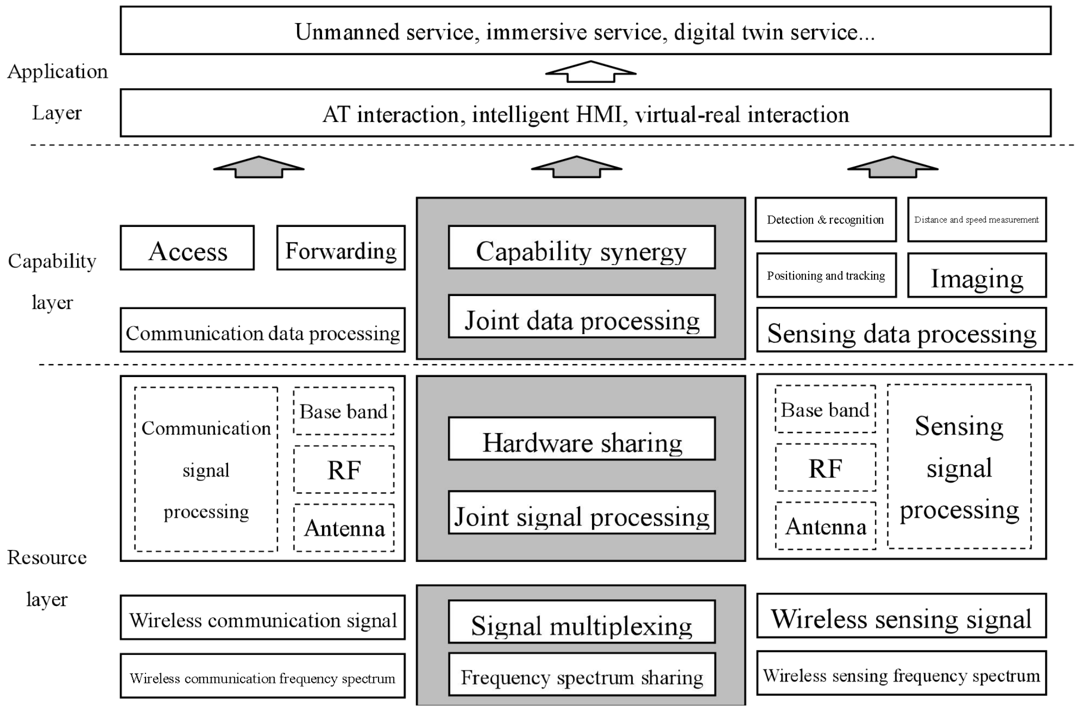

Figure 11 ISAC Technology Framework

When the communication-sensing integration technology is applied to the interaction of autonomous thing information, some or all agents will be configured with integrated devices. In this manner, there are four wireless signal modes for information interaction, namely, wireless communication, wireless sensing, wireless sensing-based wire communication, and wireless communication-based wireless sensing. The first three are the main modes, as shown in Figure 12. Wireless communication and wireless sensing are conventional approaches. The wireless sensing-based wire communication is to convert the wireless sensing's capability of collecting target information into a communication approach. This is like QR code scanning based on optical imaging (image recognition), visible light imaging communication, radio frequency identification (RFID), and backscattering. However, QC codes are static; visible light imaging communication has dynamic transmissions, but the transmission rate is quite low, and the transmission can only work in the visible light frequency band. RFID and backscattering technologies are low-rate short-range passive communication technologies, generally used for object labeling and logistics tracking, not applicable to autonomous thing interaction in dynamic environments.

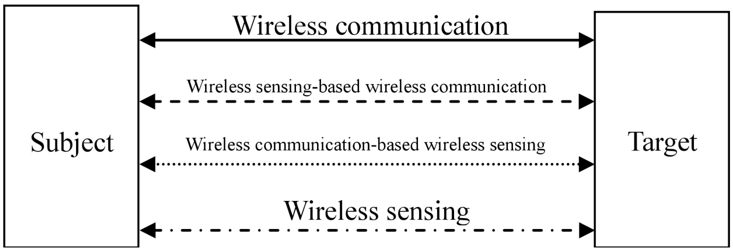

Figure 12 Information Interaction Modes Based on Wireless Signals

Wireless sensing and wireless sensing-based wireless communication share the same Tx-Rx processing flow, except that: in wireless sensing, the sensing subjects detect target status, but targets do not; while in the wireless-sensing-based wireless communication, targets encode the information to be transmitted, and sensing subjects detect the response echo signals. The echo detection for both cases can be combined.

The wireless sensing-based wireless communication has multiple information coding methods, for example, gesture coding like "sign language", or IRS coding. The IRS' birth offers a new approach for wireless sensing-based wireless communication [9]. In the IRS technology, autonomous things on one side of the information interaction are configured with metasurface units (basic units of structured electromagnetic materials, with specific responses to electromagnetic waves) that can be regulated or tuned in a mechanic, electronic, optical sensing, or another way, to change the arrangement of autonomous things according to the information codes to be transmitted. The autonomous things on the other side of the information interaction transmit the specifically modulated electromagnetic waves and receive echoes from the counterpart. As echoes carry electromagnetic wave characteristics corresponding to the code information of the counterpart, echo detection may be employed to acquire the counterpart's code information. The wireless sensing-based wireless communication system consists of two parts: sensing signal transceiver and echo modulator, as shown in Figure 13. In the sensing subject transceiver, the sensing signal generator produces sensing signals, which may be radar signals in a radar system (such as chirp signals) or wireless signals modulated based on a pseudorandom sequence in a communication system (such as OFDM signals). Sensing signal Tx links are mainly RF links and transmitting antennas, which may share the communication signal Tx link. Transmitting antennas may be large-scale digital array antennas. Echo signal Rx links are mainly RF links and receiving antennas, which may share the communication signal Rx link. Receiving antennas may share the transmitting antenna or may be set with a separate one as long as the interference between them is avoided through detachment and/or elimination measures. Echo signal detectors detect the received signals using the local sensing signals and send the detection results to the target information decoder for decoding with the communication baseband processing module shared. The decoding algorithm corresponds to the coding scheme of the sensing target encoder. The decoded information data may be jointly processed with the communication data and then reported to the application layer. In the sensing target encoder, the information encoder is for channel coding of the relevant information sequences, for example, RS codes or convolution codes in GF(256). The echo modulator regulates the electromagnetic units in the encoded metasurface based on the code inputs so that the incident wave echoes have electromagnetic characteristics corresponding to the code information.

Sensing subjects and sensing targets stipulate the communication parameters in a preset way in two stages. In the first stage, with the preset parameters, the communication is based on wireless sensing, to obtain the subsequent communication parameters, including the estimated sequence generation parameters and length of channel states, periods and lengths of estimated subframes and information code subframes of channel states, information coding modes, etc. In the second stage, wireless sensing-based communication is made according to the communication parameters obtained in the first stage. The channel state estimation sequence may be a pseudo-random sequence with fixed or variable length. Those with ASCII or GB2312-80B code are used for channel estimation at the semantic layer.

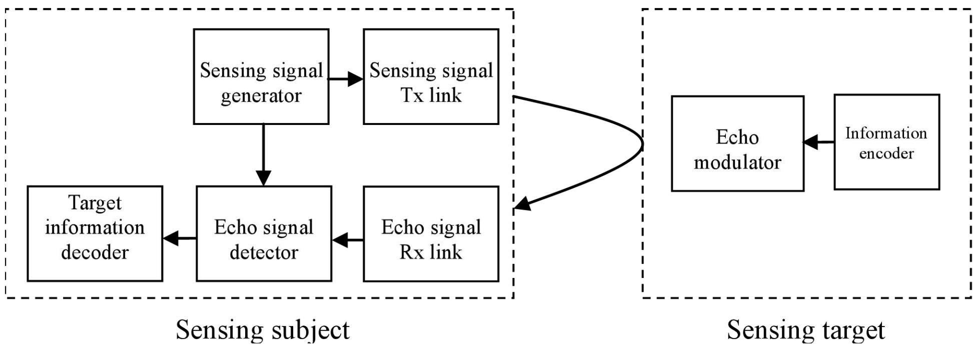

Figure 13 Structure of Wireless Sensing-based Communication System

4.2 AI Air Interface

The AI-Native Air Interface (AI-AI) is defined as Air interface designed by end to end AI/ML technology which adapts to different radio environments, hardware, data, and applications, as illustrated in Figure 14. Compared to previous air interfaces, it is not only designed to reliably transmit bits, but also to serve an application with the data it needs in an optimal way.

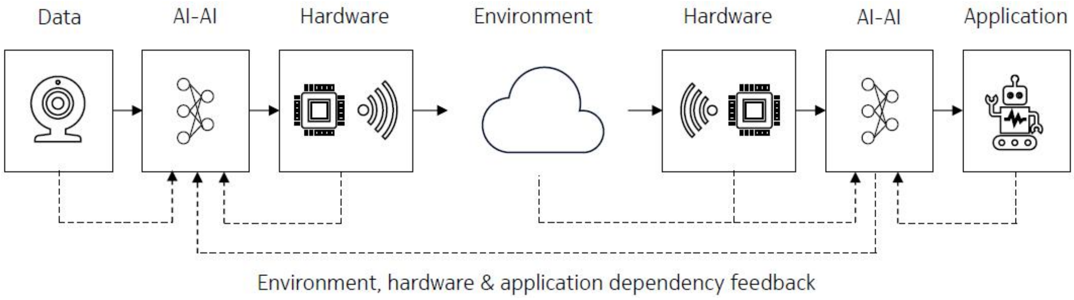

图 14. AI-Native Air Interface (AI-AI) concept

The goal of the AI-AI is to serve an application with the data it needs in the most efficient way by taking into account the constraints of the available hardware and the radio environment. The AI-AI hence no longer decouples source and channel coding as well as communication of data from the intended use by an application, and embraces hardware constraints and undesired effects of the communications channel rather than fighting them.

The typical 6G AI native Air interface (AI-AI) could be characterized and has benefits as follows:

- First, in contrast to a single classical waveform choice such as OFDM in 5G, the AI-AI could enable learning of bespoke waveforms for different frequencies, which not only make more efficient use of the spectrum but are also optimally adapted to practical limitations of the transceiver hardware and channel, such as non-linear power amplifiers, hybrid analog-digital processing, low quantization resolution, very short channel coherence time and bandwidth, phase and impulsive noise. Also new modulation schemes, pilot sequences, and codes can be learned or optimized with ML to squeeze even more performance out of the spectrum.
- Second, fully learned transceivers have the benefit that they do not need to undergo the very costly and time-consuming traditional process of algorithm design and hardware implementation anymore. They can be trained directly for the targeted

hardware platform (or even on it, depending on the capabilities). This versatility becomes essential for increasingly rich diversity of expected 6G use-cases and the emergence of small-scale sub-networks, where 6G can cater for each individual use case and deployment scenario in the best way possible.

- Third, the more we follow the AI-AI principle of learning-based design and specification, the less needs to be standardized. The current 5G specification boasts a very rich sets of options and parameters for different frequency bands and scenarios, which pose a difficult challenge from an implementation point of view. It is undesirable to scale this approach to even more complex and diversified settings in 6G. If, on the other hand, only a sufficiently flexible framework for air interface learning was standardized, the system could auto-adjust to any kind of scenario. With a bit of wishful thinking, one could hope that 6G could be the last communication system to be standardized

- Fourth, the AI-AI allows integration of the data and the application consuming it into a single end-to-end learning process. Using the terminology from Shannon and Weaver's seminal book, the AI-AI no longer only solves the problem of reliably transmitting bits (Level A), but simultaneously addresses the problems of semantics (Level B) and effectiveness (Level C) of communication. While the latter aspects may not be applicable to the generic internet communication scenario, they become relevant for communication systems that are tailored to specific purposes and under the control of a single entity, such as industrial communication systems for sensing, surveillance and robot control.

- Lastly, the idea of end-to-end learning naturally extends to the MAC layer, where it would be desirable to emerge optimized signaling schemes and channel access policies that fluently transition from contention to schedule-based depending on the use case and environment. Protocol learning could also address the problem of optimally multiplexing resources for communication and sensing (or other applications that radio waves can be used for). Ultimately, PHY and MAC layers could be jointly learned together

Compared to traditional each generation of cellular communication systems which is marked by a defining disruptive technology of its time, such as orthogonal frequency division multiplexing (OFDM) for 4G or massive multiple-input multiple-output (MIMO) for 5G. In the 6G era, Machine learning (ML) and AI will play a defining role in the development of 6G networks end-to-end across the design, deployment and operational phases. Thus, the classical approaches used to implement the scientific breakthroughs by Shannon and Wiener (as well as many others) in the last decades must be revisited and new theories developed to achieve the technological breakthroughs needed for a possible 6G system.

4.3 Key Technologies

4.3.1 Learned Transmission with Neural Receiver

Normally three important phases are foreseen in the development and transition to 6G AI-AI as schematically shown in Figure 15.

- ML replaces single processing blocks: In the first phase, which is already happening in the industry today, ML will be used to enhance or replace some of the processing blocks, mostly in the receiver. Examples are physical random access channel detection, channel estimation, or symbol demapping.
- ML replaces multiple processing blocks: In the second phase, more functionality is given to ML models, which take on the joint role of multiple processing blocks. This could be, for example, joint channel estimation, equalization and demapping. In this phase of the transition, the ML models will grow larger, hardware acceleration becomes increasingly important, and vendors need to commit to an “ML-only/ML-first” approach, because it is not viable to implement ML and non-ML backup solutions in parallel in the same processing platform due to increased power consumption and cost. This means that ML is also trusted more, although the inner workings of large models are less interpretable, but the potential gains are also higher.
- ML designs parts of the air interface: In the third phase, we will give even more freedom to ML/AI and let it design parts of the physical and MAC layers itself. This represents another paradigm change in the way communication systems are designed, because not all aspects of the PHY and MAC layers might be fixed in advance. This approach requires new forms of signaling and procedures to enable distributed end-to end training. Rather than specifying modulation schemes and waveforms, for example, one would need to specify procedures that can be used to optimize these aspects of the air interface at deployment time. This is clearly

something that nobody has ever done before and that requires a massive change in the way communication systems are standardized.

The first two phases do not require any new signaling or procedures as they only impact the implementation of transceiver algorithms. They can therefore be carried out on future 5G systems to gather practical experience while the research on 6G is progressing.

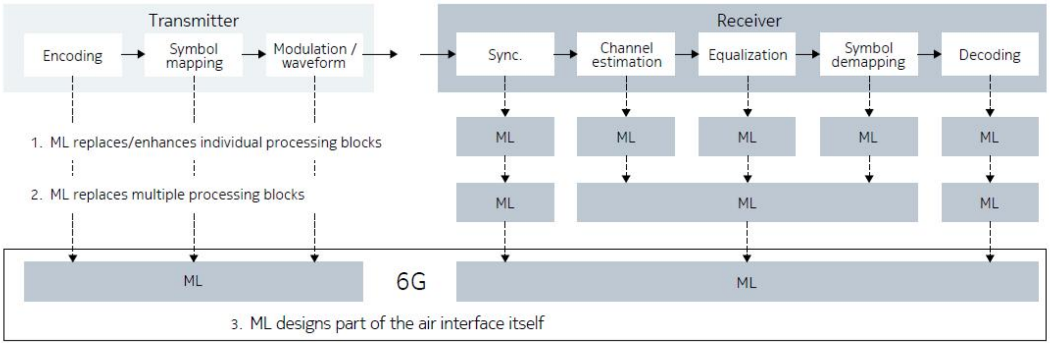

Figure 15. Three steps toward the AI-AI

A case study is presented going through the three phases toward the AI-AI outlined above and demonstrates the respective BER performance gains as shown in figure 16.

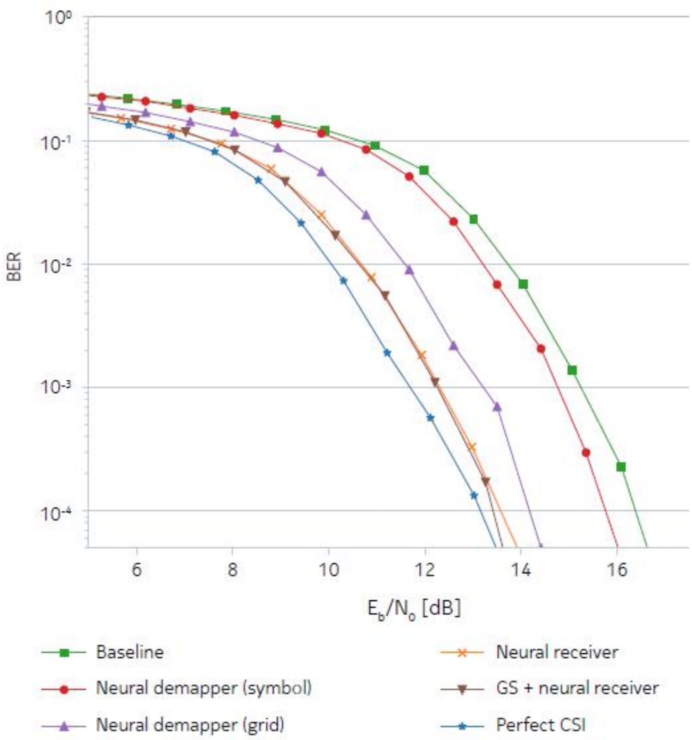

Figure 16 BER performance of all compared schemes in the case study

In the case study, a doubly selective single-input single output (SISO) channel at a carrier frequency of 3.5 GHz with the TDL-A power delay profile and a delay spread of 100 ns is considered. The receiver is assumed to move at a speed of 50 km/h and the channel evolves in time according to Jakes' model. We consider cyclic prefix-based OFDM with 72 subcarriers spaced 30 kHz apart and assume transmission time intervals (TTIs) of 14 consecutive OFDM symbols, which contain codewords of length 1024 bits at a code rate of 2/3, generated by a 5G-compliant code.

The non-ML baseline assumes 64-quadrature amplitude modulation (QAM), pilots transmitted on every other sub-carrier on the third and twelfth OFDM symbols, least-squares channel estimation, equalization based on the nearest pilot, exact demapping to log-likelihood ratios (LLRs) assuming a Gaussian post-equalized channel, as well as a standard belief propagation (BP) decoder. One can see that there is approximately a 3 dB gap between the baseline and a receiver, assuming perfect channel state information (CSI). We now describe some ways to close this gap using ML-enhanced receiver processing before delving into the benefits of optimizing parts of the transmitter too.

Due to channel aging and imperfect channel estimation, the quality of the post-equalized symbols that are fed into the demapper changes over the grid of resource elements (REs) within a TTI. A first possibility to cope with this problem is to learn a bespoke neural demapper for each RE (Phase 1). The BER performance of such a scheme is shown by the red line with dot markers in Figure 3. As expected, it provides some 0.5 dB gain over the baseline by computing better LLRs, but cannot compensate for channel aging, which results in a rotation and scaling of the equalized constellation.

In order to address these shortcomings, one can use a larger neural demapper which does not operate symbol-by-symbol but rather produces LLRs for the full TTI. It was shown in [1] and [2] that a fully convolutional ResNet architecture with dilated separable convolutions achieves remarkable performance for this task (see Figure 17). By having access to the full TTI of post-equalized symbols, the learned demapper can compensate for some of the errors made by the channel estimator and equalizer to provide a 2 dB improvement over the baseline (see purple line with triangular markers in Figure 16).

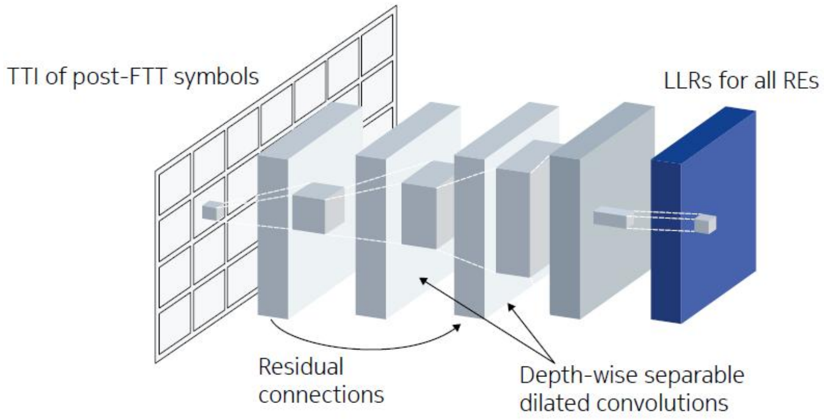

Figure 17 The neural receiver produces LLRs for an entire TTI of post- FFT symbols.

Interestingly, it turns out that one can assign the joint task of channel estimation, qualization, and demapping to a neural network with a similar architecture (Phase 2). It is fed with a TTI of post-FFT received signals from which it directly computes LLRs for all symbols. In addition to the gains of the learned demapper, this neural receiver is now able to carry-out data-aided channel estimation and detection, resulting in an additional 0.5 dB gain. By increasing the model complexity and the size of the input (more sub-carriers and OFDM symbols), the performance can be brought arbitrarily close to the perfect CSI performance [1].

Lastly, we would like to investigate the benefits of a learned constellation (i.e., geometric shaping (GS)) at the transmitter side (Phase 3), which is jointly optimized together with the neural receiver. Figure 5 shows this constellation, which is used on every RE instead of the mix of pilots and 64-QAM symbols sent by the baseline. As can be seen from Figure 16, this system achieves the same BER as the neural receiver with 64-QAM, but has the additional benefit that no pilots are transmitted. End-to-end learning could hence remove the need and control overhead for demodulation reference signals.

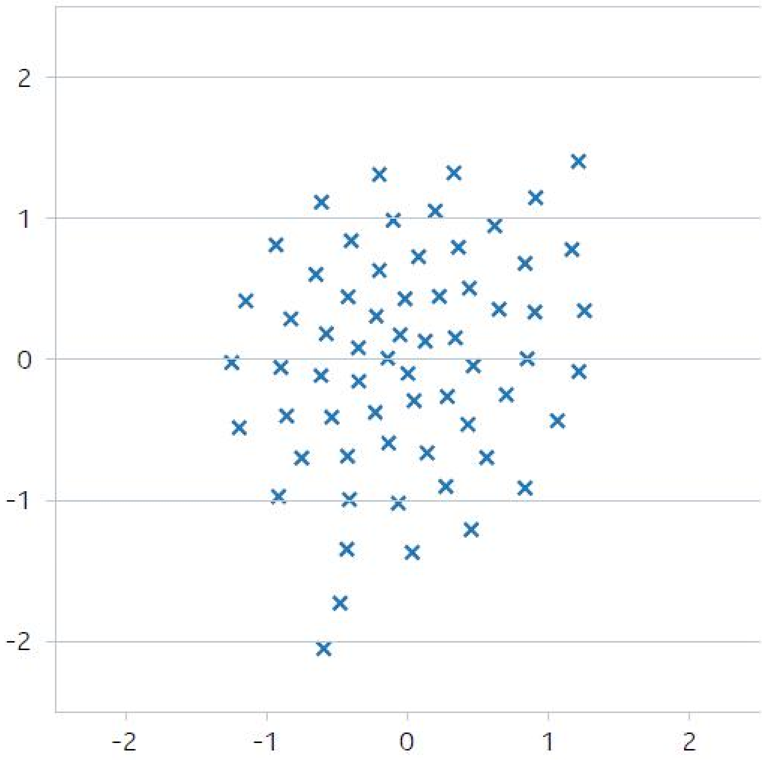

Figure 18. Learned constellation allowing pilotless transmissions together with a neural receiver. It has zero mean, unit power, and a single axis of symmetry. The optimal bit-labeling is also learned but not shown for readability

This case study has only scratched the surface of what will be possible in the future. Interesting directions for future research include end-to-end learning for new waveforms, constrained hardware, very short messages, as well as joint source-channel coding for a specific application (which is also learned). Meta, transfer and federated learning are key enablers to make such schemes practical.

4.3.2 Wireless Sensing-based Wireless Communication

It is a technological category that uses sensing technology to assist, feed reversely, or replace communication technology in communication-sensing integration. On the one hand, with the introduction of technologies such as HF communication, large-scale antenna communication, and IRS, the parameter configuration of communication systems needs to perceive more dimensional information, adding weights to sensing-aided capabilities. On the other hand, the sensing capability improvements may directly implement communication functions and explore new approaches to wireless communication.

In sensing-aided communication, sensed data may be prioritized in ultra-large-scale antenna applications, as shown in Figure 19. Beams are adjusted based on accurate position or imaging information to enhance the beam alignment capability so that the user throughput is increased and the latency caused by blockages is reduced. In the sensing-aided beam management process, the information about the beam adjustment between terminals can be obtained through sensing collaboration and then included in the beam reporting list to select the optimal beam on the network side in advance. In addition, the echo sensing information may be used to quickly determine whether the estimation terminal is blocked on the network side. In such a case, beams can be switched automatically before the recovery process is initiated at the terminal. This reduces the overheads of reporting reference signals and measurements in the beam management, shortens the handover latency, and improves the beam recovery success rate, etc.

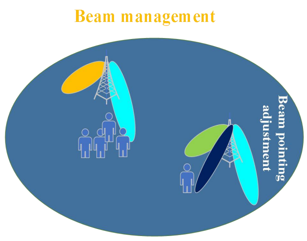

Figure 19 Sensing-based Ultra-large-scale Antenna Beam Management

Intelligent reflecting surface (IRS, or reconfigurable intelligence surface, RIS) is also a typical technical case of sensing-aided communication. By sensing and iteratively updating positioning information or CSI, and dynamically adjusting electromagnetic parameters such as phase, amplitude, frequency, and polarization, it shapes and controls electromagnetic responses of environments, achieving the purposes of anti-interference adjustment, blockage avoidance, and improvements of communication throughput and latency. In the sensing process, IRS also plays an intelligent relay role to improve the reception quality of sensing signals.

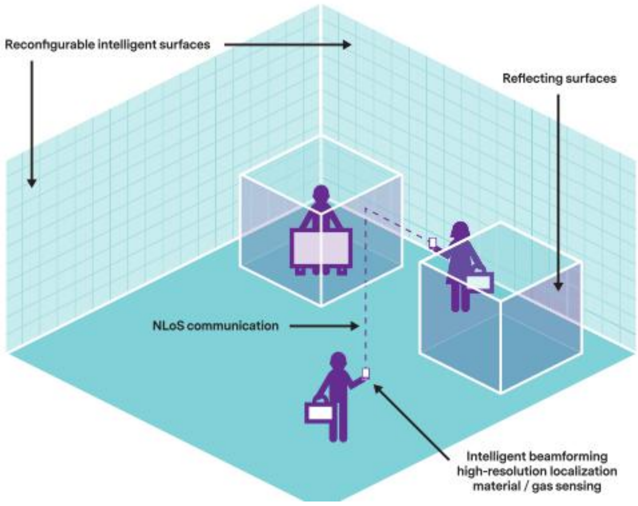

Figure 20 IRS Operation Schematic Diagram

Wireless sensing also enables wireless physical-layer secure communication. The physical-layer secure communication scheme based on the Shannon encryption capacity relies on all knowledge with attack channels at the Tx terminal, however, this assumption is difficult to meet in practice, restricting the application of the physical-layer secure communication. With the help of Radio environment maps (REMs), the 6G millimeter wave MIMO ISAC can sense the physical positions of potential attackers near the sensing-communication direction using the sensing capabilities, and based on the signal states of adversaries predicted by AI, modulate the optimal security codes according to the real-time channel states of both sides in the legal communication. This enables the physical-level secure transmission with complete Shannon confidentiality, so it can be applied in 6G high-security industrial applications, autonomous driving, and some other scenarios.

4.3.3 Wireless Communication-based Wireless Sensing

The wireless communication-based wireless sensing technology can make full use of communication transmitting devices and communication-related signals to simplify some sensing functions, such as zero transmission design and cooperative sensing.

Zero transmission design, or non-contact sensing technology, is a technology in which the receiving terminal automatically learns signal change models and characteristics from wireless communication data to sense the surrounding environments or target behavior activities causing signal changes. The Fresnel Zone Model may be introduced in non-contact sensing to characterize the relationship between transceiver positions and target object states with the wireless receiving signals. This relationship reveals the impacts of environmental parameters on time- and frequency-domain characteristics of wireless signals, and the mechanism and limit of sensing target status. Based on macrocell wireless signals, non-contact sensing enables weather forecasting, and multi-base radars realize long-range target (UAV) detection. In short-range wireless signal coverage scenarios, non-contact sensing may also enable fine-granularity lip-reading recognition, keystroke detection, breathing and abnormal action detection, etc. WI-FI sensing also falls into the same type. This type of technology requires receiving terminal design only, with lower system costs.

Compared with zero transmission design, inserting certain formats of sensing signals in wireless signals may further expand and reinforce sensing functions. 5G NR defines a cooperative wireless positioning technology based on positioning reference signals. Base stations or terminals implement positioning or speed measurement by detecting the propagation latency, incident angle, emergence angle, Doppler frequency offset, and some other information of reference signals. Meanwhile, the multiplexing of communication resources may be considered to implement sensing functions. For example, flexible symbols in time slots may be multiplexed to realize sensing functions of sensing signals. By prioritizing the frame structure configuration signaling, sensing functions do not interfere with or preempt normal communication resources, achieving flexible and dynamic time slot configuration as needed for sensing and communication.

4.3.4 Multi-band Networking

The frequency bands below 6GHz have been allocated out, and the millimeter wave bands at 26GHz and 39GHz are also allocated for 5G. In order to ensure 6G wireless network coverage and reduce deployment costs, it is crucial to maintain continuous development and efficient use of low-spectrum resources. Meanwhile, for richer scenarios, higher capacity, and ultra-high experience rate, higher-band communication technologies must be studied, such as millimeter wave, terahertz, visible light, etc. The deployment of new-generation mobile communication networks will support more diversified application scenarios and service requirements. The multi-band (HF and LF) integrated networking communication will become the irresistible development trend of mobile communication networks.

As higher frequency bands such as millimeter wave, terahertz, and visible light, as well as new service scenarios, appear in the arena of new-generation wireless networks, the multi-band collaborative networking becomes more complicated, for example, the distributed collaborative networking, space-air-ground integrated networks, low-frequency brand/millimeter-wave/visible light/terahertz integrated networking, etc. The multi-band networking technology expects to develop the ideology and principles for overall architecture design for different network scenarios, so as to study differentiated networking architectures and technical schemes in combination with scenarios under such overall ideology and principles.

The space-air-ground integrated multi-band networking is as shown in Figure 21. Under this architecture, the 6G network develops toward higher frequency bands, in which the MF and LF bands, such as those below 10GH may be configured with continuous large bandwidth for basic network coverage. This will support the deployment of seamless ground network coverage and guarantee the improvements of basic service capabilities. Meanwhile, the 6G network supports full-band access, while deploying as needed and dynamically enabling HF bands such as millimeter wave, terahertz, and visible light to fulfill the service requirements of ultra-high rate and ultra-large capacity.

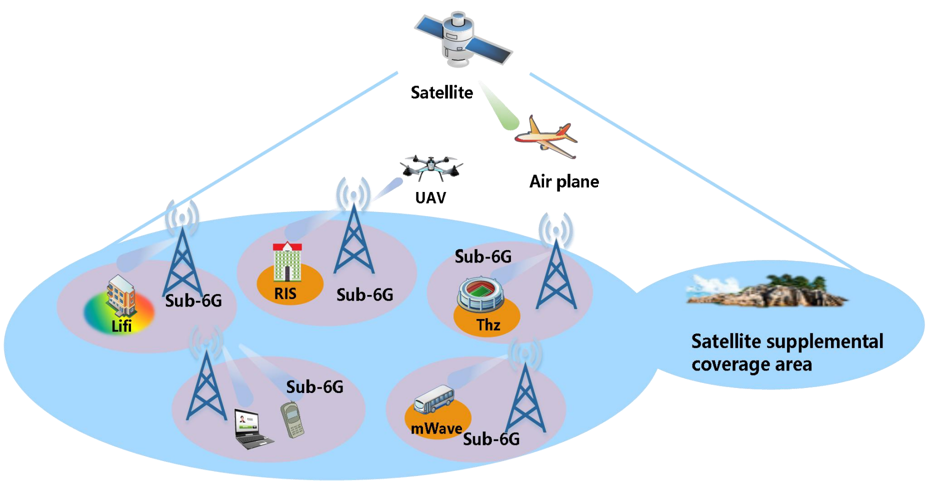

Figure 21 Multi-band Networking Based on Space-air-ground Integration

However, these new networking methods also bring new technical challenges and call for more intelligent and sufficient integrated networking solutions. First, after integrating higher frequency bands such as millimeter wave, terahertz, and visible light, the networking architecture may vary, causing complex network interference and network operation and maintenance difficulties compared with 5G. Second, the multi-band networking may realize the dynamic complementation between different frequency bands besides optimizing the overall service quality of the entire network and improving the network frequency spectrum efficiency, but the intelligent mechanism improvement is required for the purpose of reducing energy consumption and costs. Third, multi-band networking imposes more stringent requirements for terminal capabilities and requires the analysis of terminal capacity needs in different networking scenarios.

5.ICDT-integrated 6G Terminal

ICDT-integrated 6G capabilities will bring a series of new functions for future mobile terminals, leading to a new shift. While expanding from personal terminals to industrial terminals, mobile terminals stretch to unmanned vehicles, UAVs, robots, and other intelligent generalized terminals. Besides, they also explore new capabilities and new morphs such as intelligent interaction, flexibility, implantability, and modularization, with stronger environment adaptability and service application capabilities. Terminals will integrate tactile feedback, sensing and imaging, holographic image, AI, and other functions by 2030. These new functions are redefining terminal devices and their roles in our daily lives. Mobile terminals are evolving to embrace the following capabilities:

- Human-level sensing, such as the wireless bandwidth provided for human-level visual/audio sensing and Hi-Fi person-to-person communication;
- Environmental sensing, such as multispectral imaging and high-precision positioning capabilities;
- Human-network interaction, such as holographic near-eye displays for interaction between human and digital world;
- Energy harvesting, such as wireless charging, simultaneous wireless digital

energy transfer, etc.

These capabilities transform current terminal devices into super-autonomous things, driving the physical world the access the digital world in a brand new way and embracing some functions beyond man's power, such as the unique intelligent recognition and environment sensing of unmanned terminals.

5.1 Friendly Terminals

Hundreds of billions of devices will be network-collected to cater to diversified needs of different scenarios by 2030 and beyond. These tremendous devices include sensors (for environmental monitoring, industrial manufacturing, body area network, etc.), water and power meters, smart homes, wearable devices (watches, XR glasses, etc.), mobile phones, etc. Current terminal pains (power consumption, complexity, coverage, cost, volume, etc.) will be exacerbated in the case of new 6G scenarios and enhanced capabilities, becoming bottlenecks restricting the development of 6G. The 6G ubiquitous scenario needs require minimal terminal access, including ‘0’-power consumption communication. Therefore, it is urgent to study terminal-friendly 6G technologies to alleviate burdens on terminals, "leaving complex tasks to networks and making operations easy for users".

In terms of terminals, the "terminal-friendly" concept is to improve the user experience by reducing the power consumption, costs, and complexity of terminals, supporting the terminal diversity, expanding access scenarios and extent, increasing the uplink efficiency (energy efficiency, spectrum effect), and improving the user experience, or to sacrifice the experience at one point for a better experience at most points.

In terms of networks, the "terminal-friendly" concept is to simplify relevant processes and technical complexity of terminals by improving network capabilities. Technologically "terminal-friendly" concept will develop towards:

- WAN access and ubiquitous access of terminals supported by air-ground integration and multi-band integration technologies
- Flexible terminal access supported by native networking of terminals
- Terminal service capabilities extended through communication-sensing-algorithm integration
- ‘0’ sensing mobility experience on terminals supported by cell free

technology

- ‘0’-power consumption of terminals supported by backscatter and near zero-power consumption receivers
- Grant free transmission and uplink asynchronous transmission supported by new multi-address access
- Terminal user experience improved by integrating AI and communication

5.2 Unmanned Terminal

The development of computing power, AI/ML, and semiconductor technologies lays a solid foundation for better computing performance, higher energy efficiency, smaller chips, and higher transistor density, accelerating the implementation of unmanned terminals. Unmanned terminals are mobile terminals with independent decision-making and execution capabilities, including UAVs, unmanned vehicles, robots, and other intelligent devices. Unmanned terminals are carriers for executing unmanned services. With independent local sensing, computing, communication, and AI capabilities, they can take the place of human beings to execute tasks in diversified unmanned environments, including unmanned driving, unmanned logistics, unmanned manufacturing, unmanned patrol, etc.

By virtue of the advantages of the next-generation ICDT 6G integrated networks, such as ultra-high data rate, ultra-low latency, and ultra-high reliability connection, unmanned terminals will enable the offloading of computing-intensive tasks to edge clouds. Based on distributed computing and learning, they can achieve the task goals through cloud centralization and self-organizing control. As the 6G short-range communication technology and AI/ML algorithm evolve, unmanned terminals, such as UAV groups, vehicle fleet, and robot clusters, can interact with each other locally, and with environments, to improve the service experience and productivity.

5.3 Flexible Terminals

Flexible electronics may be summarized as an emerging electronic technology that attaches electronic components made of organic/inorganic materials on flexible or ductile plastics or metal sheet substrates. It can be applied in flexible electronic displays, OLED, RFID printers, thin-film solar panels, electronic skins, flexible fiber batteries. This will make terminals "invisible" and support new display and battery endurance capabilities, giving users a more diversified and inconspicuous experience.

Key indicators of flexible electronics process include chip feature size and substrate area size, aiming to integrate smaller flexible electronic components with a certain density on larger surface substrates to compare the performance of traditional silicon-based chips. Thin film transistors are made on the substrate, which is cheaper and more flexible. Flexible electronics technology will break through the inherent limitations of classic silicon-based electronics, and bring opportunities for change in terminal device integration, terminal energy consumption, terminal applications, etc. in the post-molar era.

Attaching wearable electronic devices to the skin allows you to monitor a variety of physiological functions, such as heart rate, electrocardiogram, skin temperature, limb movements, and blood pressure. They are widely used in sports, military activities, medical care and daily life. A retractable touch glove based on a fabric sensor array recognizes the shape of a single object, estimates the weight of the object, and draws a touch mode while holding the object. It is equipped with 548 sensors to record hand-object interactions, and then train a deep convolution neural network to extract the grip touch features. These features are useful in the development of robots and prostheses.

Building on carbon nano tube (CNT) thin films at room temperature, a wearable device for broadband flexible terahertz imaging can be developed, which can passively image flat and curved samples. Such technology will drive the application of portable terahertz devices in many fields, including safety inspection and health monitoring. Semiconductor quantum dot-sensitized graphene-quantum-dot photodetector (GQD-PD) can be used in flexible, transparent wearable devices to monitor heart rate in reflection and transparent transmission modes or to track changes in human emissions for health monitoring.

Flexible terminals currently face two major challenges. First, mechanical problem. Flexible electronic components are prone to crack when subjected to alternating stress for a long time. Second, electronic packaging problem. It requires the development of new technologies to ensure the performance of integrated packaging of components on flexible substrates. Third, electromagnetic radiation problem.

5.4 Modular Terminal

The continuous upgrading of terminal capabilities requires new ideas for the design of modular mobile terminal architecture with open extension architecture. The generational change of traditional mobile terminals results in waste of resources. By combining software, module upgrade and demand, a new form of modular terminal is created, which supports multi-band, multi-system wireless access and multi-functional integration, achieving the transformation of terminal from closed to open extension architecture, as well as the sustainable evolution of 6G terminal.

Smartphone modules are seamlessly applied to smart TV to enhance the video viewing experience. Wearable devices use the smart phone's communication module to collect information directly. As smart factory devices connect to 6G networks, a large number of low-cost and low-power-consumption IOT devices will be ubiquitous. And modular terminals will support smart city and home, smart medicine, pollution monitoring and other applications. These devices will act as sensors and executors for a digital-physical fusion system that integrates computing, networking, and physical processes. In addition to smart mobile terminals, ICDT-integrated network architecture will help all types of terminal devices to act as sensor and executor modules.

In the future, wireless network connection will become the basic capability of various devices. In highly immersive and multi-mode human-computer interaction scenarios, the on-demand combination of multi-sensory capability modules can achieve more functions for human collaboration, such as overcoming disability, thus providing more possibilities for human development. Enhanced wireless communication module will also be an important part of modular terminals, serving a wider range of communication needs of different user groups. By splicing the remote D2D module, wireless sensing network module, satellite communication module, etc. on the terminals, users can achieve customized functions such as field self-organizing network communication, large-range sensor data collection, and area communication without ground network coverage without replacing the common terminals. With the development of wireless connection capability of terminals, the connection between terminal modules will break through the shackles of physical connection, and use a variety of media (electromagnetic, acoustic, optical media) and protocols to achieve collaborative work and data sharing. The concept of modular terminal will change from device-centered to human/task-centered, and flexible networking of multiple devices serving people/tasks will be incorporated into modular management to achieve data fusion, sensing fusion and computing power fusion among modules. Modular terminals will help people interact more deeply with machines, physical world and digital world, and make use of ICDT-integrated 6G system more flexibly to make highly reliable and responsive intelligent connection exchange more expressive.

6.ICDT-integrated 6G Industry

6.1 Trend of 6G Industry

The development of ICDT-integrated 6G technology will bring 6G industrial form of ICDT integration. The 6G industry will be integrated with integrated circuits, basic materials, basic software, computers, AI, big data and other industries, as shown in Figure 22. Its upstream industry expands from equipment manufacturing and products to integrated circuits and basic components, midstream aggregates to infrastructure, platforms and terminals, and downstream integrates communications applications, AI applications, Internet applications, computer applications, driving new upgrades in vertical applications, governance applications and personal applications.

The upstream of ICDT industry is dominated by integrated circuits and basic software. The integrated circuit industry consists of three main links, design, manufacturing and closed beta test, which involve the supply of basic raw materials, equipment and EDA tools. The output products mainly include analog devices, separator devices, ASIC special chips, logic devices, memory, optoelectronic devices, sensors and processors. The basic software industry includes the development of software, network/server/terminal operating system and all kinds of tools and software, and together with hardware products, are the core supply of computing devices, communication devices, sensing devices and AI devices in the midstream.

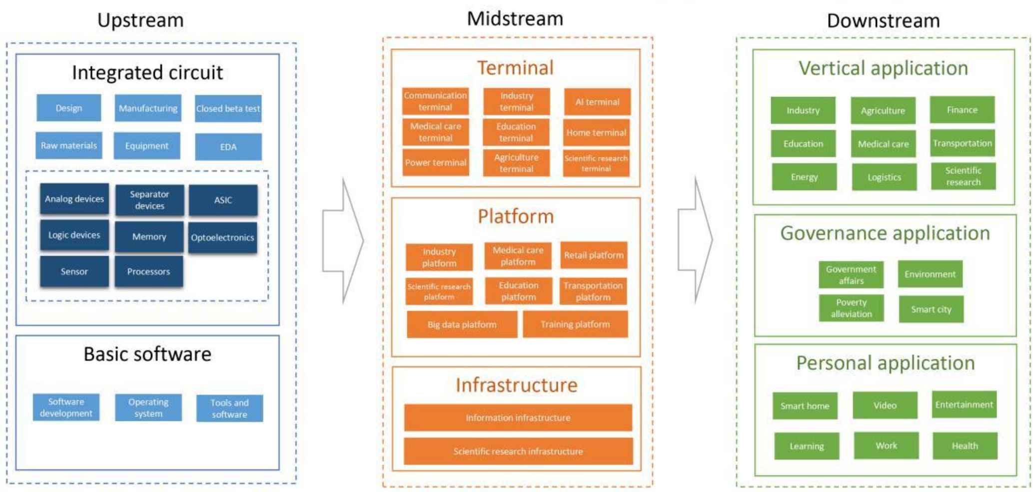

Figure 22. Development Trend of ICDT-integrated 6G Industry

The midstream of the ICDT industry is mainly infrastructure, capacity platforms and terminals. Infrastructure includes communications infrastructure, computing centers and large data centers, as well as related ICDT scientific research infrastructure and public infrastructure such as transportation, industry, and medical care. Platform is the core of ICDT industry, including manufacturing and big data platform, medical care and big data platform, e-commerce and big data platform, transportation and big data platform, education and big data platform, scientific research and big data platform, and AI training platform. Terminal is the link between the midstream and downstream of ICDT, including personal terminal, industry terminal and scientific research terminal, to be specific, terminals for communication, industry, AI, medical care, education, home, power, agriculture, transportation and scientific research.

The downstream of ICDT is mainly in three areas, personal application, vertical application and governance application. Relying on the upgrade of ICDT-integrated infrastructure, platform and terminal, these applications are developing towards unmanned, remote, immersive, intelligent and virtualized direction. The new ecology represented by the "metaverse" will further drive the convergence of ICDT industry, create innovative life and production modes for human beings, and satisfy people's permanent pursuit of happy life.

6.2 Suggestions for 6G Industry Development

The development of ICDT industry is facing many challenges. It is necessary to build an industry self-circulating ecological environment around the industrial policy system, talent and disciplinary education system, scientific research system and infrastructure.

First, the 6G industrial policy system.

Accelerate the construction of 6G industrial policy system. Make efforts in terms of laws and regulations, factor mobility, performance appraisal, etc. Improve the 6G laws and regulations system. Establish the intellectual property system of 6G industry. Build a 6G technology and achievement evaluation, trading, incubation platform and 6G technology demand publishing platform, thereby promoting the connection between 6G technology supply and demand, and realizing technology value inspection and realization with market-oriented liquidity. Adhere to the idea of both bottom line and inclusiveness to constantly revise and improve the laws and regulations supporting the development of 6G industry. Improve the ownership, usufruct, security risk liability, infringement, civil subject of AI system, AI damage liability, personal privacy protection, AI personality right, AI copyright, etc. of big data and biological data.

Establish an innovative industrial factor liquidity mechanism. Establish smooth channels for 6G industrial capital, talents, and technology to divert and guide the industrial breakpoints, blocked points, and hot spots. Optimize and increase the investment of large funds in 6G industry, focusing on the weak links (blocked points) of design and manufacturing of high-end chips and devices related to 6G industry, tools and technology related to 6G technology R&D, and software and equipment technology, improve the investment and financing platform and environment of the primary market and secondary market of 6G industry, and promote the healthy development of application market (hot spots). Establish a talent incentive system, including national 6G talent qualification certification and national green card, so as to break through the barriers to talent employment between the industry, university and research innovation chains, and support double employment and multiple employment. Establish a mechanism to support investment and financing channels between the double chains. Encourage enterprises to invest or acquire the main body of the innovation chain, and in turn, encourage the main body of innovation chain or scientific researchers to invest in enterprises, and support the enterprise-style operation of the main body of innovation chain and provide supporting investment policies.

Strengthen performance appraisal of double-chain fusion. First, enterprises are guided to increase investment in scientific and technological innovation through laws, regulations and policies in the primary and secondary investment and financing markets, and to evaluate the proportion of scientific researchers and research funds, the number of patents, and the participation degree of industry alliances. Second, the appraisal of achievements conversion rate is strengthened in colleges and universities and scientific research institutions to provide incentives for scientific research units and personnel that focus on the weak links of the industry and achieve breakthrough results to match the value of their achievements.

Second, the 6G talent and disciplinary education system.

Cultivate and establish a multi-level 6G talent system. Adhere to local training and international return and introduction to maintain the growth of talent echelon, meet the needs of 6G innovation and industrial development, and expand the scale of high-level talents. Expand the group of AI entrepreneurs by cultivating or introducing AI entrepreneurs, build AI enterprise brands, and enhance both the quantity and quality of AI industrial chain subjects. Expand the group of AI scientists through cultivation and introduction to build a well-known AI team in academia and industry. Establish a mechanism to support 6G talent flow between double chains. For example, 6G entrepreneurs and scientists are encouraged to plan multi-professional roles, and the scientist spirit of entrepreneurs and the entrepreneur spirit of scientists are advocated; the multi-level and multi-link talent training mechanism is improved to encourage 6G courses to enterprises and 6G product prototype demonstration to colleges and universities.

Adjust and optimize disciplinary education system. Reset "new engineering" and "new science". Carry out the multi-level 6G education throughout undergraduates, graduates, vocational education and skill training, and expand the scale of 6G related discipline education in colleges and universities. Expand the scale of 6G related discipline education in colleges and universities. The scale of domestic 6G undergraduate education continues to expand but is still at the beginning stage, so 6G talents are still in short supply. Therefore, university teachers should be further developed and trained, especially international famous professors in 6G discipline, the scale of teachers should be expanded to ensure the stability of 6G discipline teaching, but teachers should be allowed to double or multiply employment to participate in the scientific research activities of 6G innovation carrier. In addition, optimize 6G education resources, further expand the proportion of integrated circuit and AI courses, strengthen the teaching of AI key algorithms and technologies, pay attention to the teaching of "AI+" applied technology, and cultivate AI talents required by academia and industry at multiple levels; Accelerate the implementation of the special action for AI high-level talent training with the integration of industry and education to improve the number and quality of AI postgraduates.

Adhere to the global training and competition of 6G talents. Continue to unblock international exchange channels, encourage students to further study in universities with 6G advantages, actively attract foreign students to return home or strengthen international cooperation through domestic 6G industrial policy dividends, market dividends and industrial opportunities, so as to promote the ecological construction of global 6G technology and industrial globalization and avoid the disconnection of talents.

Third, 6G industry classification system.

Further reconstruct the four-level architecture of the national industrial classification system. On one hand, the classification system should be refined by setting up directories of five or six levels to further subdivide the 6G market, tap the needs of the 6G industry, improve the quality and demand, and avoid more branches but less contents. On the other hand, it is also important to shift from horizontal classification to vertical value chain classification, and refine the upstream classification of 6G industry, particularly the key sub categories affecting the supply chain quality of 6G industry, including the sub categories of major equipment, equipment parts and materials of 6G industry, so as to avoid excessive contents without a solid foundation.

Establish a 6G industrial classification mechanism to fully guarantee the 28 nm intra-industrial circulation capacity. According to the current situation and development prospect of 6G industry, the industry is planned and promoted in three dimensions: breakpoints, blocked points and hot spots. Make full use of the big data advantages, market scale and industrial capacity of new infrastructure and fields such as industry, medical care, finance and telecommunications to ensure industrial growth characteristics and promote to a higher industrial level in stages. Expand the capacity of hot spots of 6G industry with controllable production capacity, promote the dredging of industrial blocked points with the development of hot spots, and repair industrial breakpoints or change the way of development based on the industry’s own tenacity and long-term investment of resources. Guide 6G enterprises to have differentiated strategic positioning and focus on the main business according to the industrial level to avoid excessive homogeneous competition.

Fourth, 6G scientific research system.

Set up 6G research project system at multiple levels. 1. Set up a national innovation carrier in the risk link of the supply chain (breakpoints) and establish an open competition mechanism to select the best candidates; 2. Set up an industrial fund project in the weak link of the industrial chain (blocked points), and build a cluster base to give play to the leading role of the chain; 3. Set up a science and technology special project for application demonstration pilot in the advantageous link of the value chain (hot spots) to strengthen the depth of vertical application.

Create a new project organization and implementation mode. 1. Form new innovation carriers, integrate advantageous and innovative resources to jointly tackle key problems, and rebuild national (key) laboratories, innovation centers and technology demonstration areas. 2. Find new project assessment methods, introduce the "valuation adjustment mechanism" model, and set major reward expectations for project achievements.

Fifth, 6G infrastructures.

Build a 6G industrial innovation and integration cluster base. In terms of 6G new infrastructure, focus on planning the national double-chain integration cluster base, build the 6G industrial base in areas with good 6G education and scientific research structure, strengthen the setting of 6G scientific education and research institutions in areas with promising 6G industry, thereby exerting the cluster effect to improve the efficiency of production and innovation. Build a national/industrial technology demonstration area in the cluster base, which coordinates with regional economy and integrates into one, thus optimizing 6G industrial spatial structure and forming regional cluster effect and competitive advantage.

Build 6G national platform, big data platform and computing center. Build a national scientific test platform, a medical platform to support remote medicine and mobile health services, a transportation platform to support automatic driving service, and engineering and manufacturing platforms. Develop AI application products such as CNC machine tool programming, chip design error detection and quality detection. Create platforms for government affairs, livelihood, environment and agriculture. Set up a national big data platform, model base and training center.

7.Conclusion

The integrated development of mobile communication technology, computing technology, sensing technology and AI technology is forming a new ecology of 6G technology, bringing many new concepts, technologies and schemes at all levels of network, air interface, terminal and application. At the same time, the communication industry will also integrate with the computing industry, sensing industry and AI industry, forming a new industrial pattern and resulting in more abundant terminal forms and downstream applications. It is believed that through the aggregation of 6G innovation chain and industrial chain resource elements, a strong 6G end-to-end information processing and service capability will be constructed.

Acknowledgement

Responsible editors: I Chih-Lin, Pan Chengkang

China Mobile: Pan Chengkang, Wang Ailing, Wang Yajuan, Ma Liang, Jin Jing, Wang Qixing, Sun Junshuai

HONOR: Wu Shuxia

ZTE: Ge Linna, Yu Guanghui, Zhu Qinghua, Meng Xi

Nokia Bell: Wang Zequan

Xiaomi: Chen Dong, He Zhibin, Sun Yuzhe

Unicom: Ma Jingyan, Liu Shan, Yang Yan

vivo: Jiang dajie

BUPT: Cui Qimei

XDU: Liu Junyu, Wen Juan, Bai Weigang, Cheng Nan, Yang Chungang, Ou Yangying, Song Yanbo, Zhang Lulu

Ericsson: Fan Rui

FuTURE FORUM：Zhang Shuya, Li dan

References

[1] White Paper. ICDT Integrated 6G Network 1.0, Future Forum, November 2020.

Abbreviations

AI	Artificial Intelligence
ATs	Autonomous Things
CSI	Channel State Information (CSI)
HMI	Human-Machine Interaction
ICDT	Information, Communication, big Data and AI Technology
ISAC	Integrated Sensing and Communication
ML	Machine Learning
NE	Network Element
O&M	Operation and Maintenance
RE	Resource Element
RFID	Radio Frequency Identification
SLA	Service Level Agreement
UAV	Unmanned Aerial Vehicle