HUAWEI

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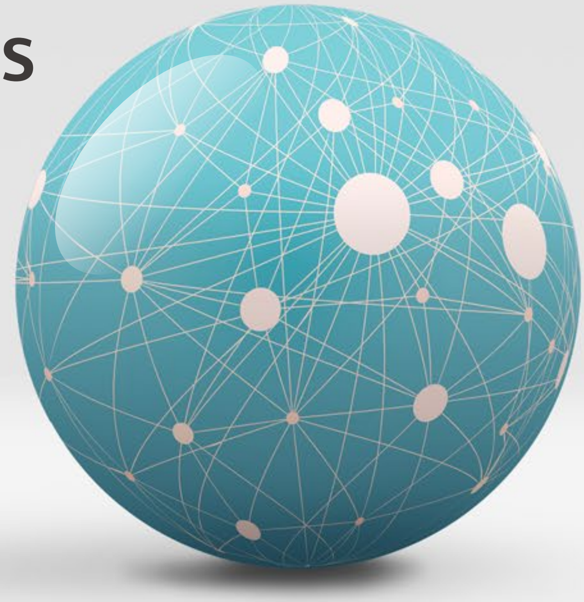
Communications Network 2030



Building a Fully Connected,
Intelligent World

Contents

Industry Trends

Going intelligent has become the general direction that the world is heading in over the coming decade. China, the EU, and the US have all published their new visions for this area.

In its Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and the Long-Range Objectives Through the Year 2035, China prioritizes industry intelligence as an important area of development, and sets clear development goals for industries including manufacturing, energy, agriculture, healthcare, and education, as well as for government management.

In its 2030 Digital Compass plan, the EU articulates the following targets: By 2030, 75% of European enterprises will have taken up cloud computing, big data, and Artificial Intelligence (AI) services, and more than 90% of European small- and medium-sized enterprises (SMEs) will reach at least a basic level of "digital intensity". To achieve these targets, the EU announced an increase in investment into energy and digital infrastructure.

In its Vision 2030 report, the US National Science Board (NSB) recommends increasing investment in AI while continuing investment in corresponding digital infrastructures such as data, software, computing, and networks over the next decade. These recommendations aim to help maintain the US's competitiveness in the intelligent era.

The intelligent development of industries requires enterprises to upgrade their networks. In its Industrial Internet Innovation and Development Action Plan (2021–2023), China's Ministry of Industry and Information Technology (MIIT) puts forward the following measures: (1) Accelerate the network-based development of industrial equipment, drive the upgrade of enterprise Intranet, and promote the integration of information technology (IT) networks and operational technology (OT) networks to build

industrial Internet campus networks. (2) Explore the deployment of new technologies such as cloud-network synergy, deterministic networking, and Segment Routing over IPv6 (SRv6). In its Digitizing European Industry platform plan, the EU considers nanophotonics, AI, 5G, and Internet of Things (IoT) to be key enablers of future industrial networks, and plans to increase investment in these technologies in order to stay ahead in the future.

In recent years, generative AI (GenAI) has garnered much attention around the world, and today is regarded as one of the key enablers of industry intelligence. Serving as "pipes" that connect the massive computing infrastructure on which GenAI relies, networks play a pivotal role in the efficient utilization of computing power. To drive the high-quality development of computing infrastructure, the MIIT and other government departments propose the following targets in Action Plan for High-Quality Development of Computing Infrastructure: (1) Improve the coverage of optical transport networks (OTNs) in key application places. (2) Increase the adoption of innovative technologies such as SRv6. (3) Implement low-latency connections between data centers at hub nodes.

As industries increasingly adopt intelligent technologies, leading telecom carriers around the world are taking action and beginning to explore how they can fully unleash the potential of connectivity in this process. For example:

- China Mobile has unveiled a "5G + AICDE" development strategy, where AICDE stands for AI, IoT, cloud computing, big data, and edge computing.

- China Telecom has set out the goal of building an integrated cloud-network architecture by 2030.

- China Unicom published its CUBE-Net 3.0 strategy, which articulates a new development direction that combines connectivity, computing, and intelligence. It also released Internet 2030 White Paper to consolidate industry consensus as well as promoting next-generation Internet technology and industry evolution.

- In its outlook for 2030, Deutsche Telekom aims to become the leading digital enabler in the business to business (B2B) market, providing comprehensive network, IoT, cloud, and digital services.

A survey conducted by GSM Association (GSMA) shows that carriers worldwide can fully unleash the potential of their connectivity portfolios by focusing on B2B, cloud, and IoT services that target the industry, finance, health, energy, and agriculture sectors. Carrier networks are also undergoing intelligent transformation, with all leading carriers proposing their "AI+" strategies. For example, China Mobile comprehensively promotes the "AI+" action and aims to reach L4 autonomous networks (ANs) by 2025.

By 2030, many amazing things that we can only dream of today will be a reality. For example, highly sensitive biosensors and intelligent hardware connected through broadband networks will enable us to monitor the indicators of our physical health in real time. And we will be able to analyze massive amounts of historical health data securely stored on terminals and clouds through AI. This will allow us to proactively manage our own health and reduce our dependence on doctors, thereby improving our health and quality of life.

New technologies, such as home broadband that supports speeds of over 10 Gbit/s and holographic communications, will enable more intuitive human-machine interactions. An air-ground cubic network will connect all means of transportation, facilitating easy, smart, and low-carbon travel. Sensing technology, 10-gigabit wired and wireless broadband, inclusive AI, and applications that target numerous industries will be available everywhere, allowing us to build urban digital infrastructure that improves the quality of city life.

With Harmonized Communication and Sensing (HCS), automation, and intelligence technologies, we will be able to efficiently protect our environment. New types of labor, such as collaborative robots, automated mobile robots (AMRs), and digital labor, can be adopted in tandem with the industrial Internet to increase accuracy and decrease costs throughout the whole process from demand to production and delivery, while also improving the resilience of the manufacturing industry.

Energy IoT can be integrated into smart grids to form a green energy Internet and fully digitalize all activities, including generation, grid, load, and storage. Zero-carbon data centers and zero-carbon communications sites may soon become a reality. We can also guarantee digital security and trustworthiness by combining blockchain, digital watermarking, AI-driven anti-counterfeiting, privacy-enhancing computing, and endogenous network security.

In 2030, communications networks will evolve from connecting billions of people to connecting hundreds of billions of things, and face many challenges along the way.

First, the scale of communications networks will continue expanding. This means network management will become even more complex. Over the next decade, how can we innovate in software technology to enable self-configuring, self-healing, and self-optimizing networks and prevent operation & maintenance (O&M) costs from rising in step with the continuous expansion of network scale? This poses a daunting challenge.

Second, IoT scenarios such as unattended operations in industrial and agricultural settings, end-to-end (E2E) self-driving vehicles, low-altitude manned flight, and low-altitude drone take-outs and freight movement will require carriers to further improve the coverage, quality assurance,

security, and trustworthiness of their networks. Over the next decade, how can we innovate in protocols and algorithms to enable networks to carry multiple types of services while meeting the requirements for high quality and flexibility? This will be a very challenging task.

Third, although Moore's law has held true for decades, the semiconductor industry is now struggling to maintain that pace of improvement, and new technologies like quantum computing are not yet mature. Meanwhile, demand for computing power, storage capacity, and network energy efficiency continues to grow, and these factors are increasingly becoming bottlenecks. Over the next decade, how can we innovate in fundamental technologies to build a green, low-carbon network and increase network capacity by dozens of times without increasing energy consumption? This is another extremely challenging task that lies ahead of us.

Communications networks are one of the major forces driving the world forward. The development of communications networks kicked off during the first Industrial Revolution and, unlike traditional industries, it still shows no signs of slowing down after nearly two centuries. In fact, the pace of development of communications technologies has been particularly rapid in recent decades. Both the evolution from 2G to 5G and the shift from the asymmetric digital subscriber lines (ADSL) to gigabit optical home broadband took just 30 years. Over the next decade, we will witness the emergence of new use cases and scenarios for communications technologies and fully embrace an intelligent world.

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Future Network Scenarios

Communications networks have come a long way since Samuel Morse invented the electric telegraph in 1837. They have evolved from connecting individuals and homes to connecting organizations and from wired to wireless. In today's environment of diverse and rapidly changing services, it takes continuous innovation for communications networks to keep up with the needs of customers. To meet the rich and diverse business needs that will arise in the intelligent world of the next 10 years, communications networks will need to go beyond connecting individuals. They will also need to connect multiple perception, display, computing resources, and AI agents related to each individual. In the near future, networks will have to connect home users as well as home appliances, vehicles, and content resources, while organizations will expect networks to do more than just create connections between employees — they must also connect an organization's machines, edge computing nodes, and cloud resources.

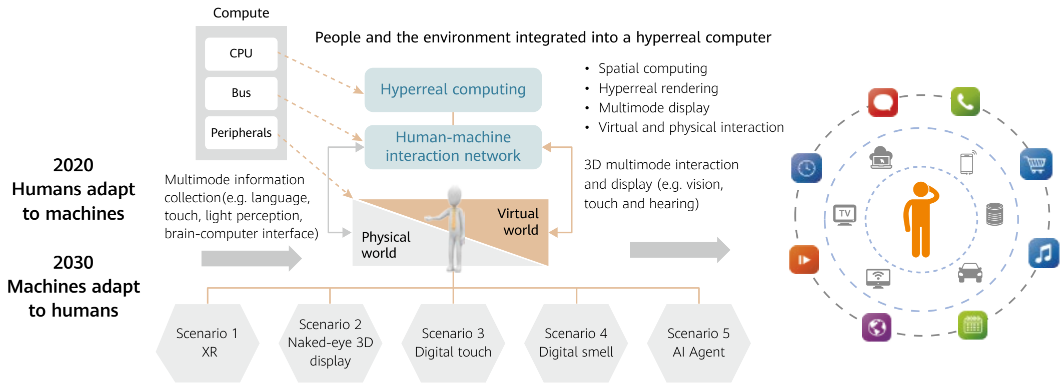
The scope of network connections is expanding, business needs are changing, and the industry has reached a consensus that, over the next 10 years, networks will evolve from 5G to 5G-A/6G, from 5th Generation Fixed Network (F5G) to F5G-A/F6G, and from IPv6 Enhanced to Net5.5G/Net6G, and Autonomous Networks (AN) will evolve from L2 to L4+. In addition, new use cases will continue to emerge.

2.1 Next-Generation Human-Machine Interaction Network: A Human-centric Hyperreal Experience

In a world of cold machines, it is up to human beings to adapt to the machines. With the wide use of the automobile, we learned to work with pedals and a gearstick. In the PC era, we learned to use the mouse and keyboard. In the smartphone era, we learned to use touchscreens.

However, with sufficiently advanced levels of intelligence, it is possible to turn this paradigm on its head and have machines adapt to the needs of their human users. Intelligent machines (e.g., smart screens, smart home appliances, intelligent vehicles, and smart exoskeletons) will be able to understand natural language, gestures, and eye movement, and even read human brain waves, enabling more intuitive integration between the virtual and physical worlds and bringing a hyperreal sensory experience to human-machine interaction. (Figure 1 Hyperreal human-machine interaction experience)

Figure 1 Hyperreal human-machine interaction experience



Over the course of the coming decade, communications networks must evolve to support brand-new human-machine interaction experiences such as XR, naked-eye 3D display, digital touch, digital smell, and AI agent.

2.1.1 XR: An Intuitive Interaction Experience Through a Perfect Synthesis of the Virtual and Physical Worlds

Virtual Reality (VR) is about rendering packaged digital visual and audio content. Augmented Reality (AR) refers to the overlaying of information or artificially generated content onto the existing environment. Mixed Reality (MR) is an advanced form of AR that integrates virtual elements into physical scenarios. eXtended Reality (XR), which covers VR, AR, and MR, is a catchall term that refers to all real and virtual combined environments and human-machine interactions generated by computer technology and wearables. Characterized by three-dimensional environments, intuitive interactions, spatial computing, and other features that set it apart from existing Internet devices, XR is considered the next major platform for personal interactions.

In 2020, due to the impact of social distancing caused by COVID-19, demand for VR games, virtual meetings, and AR-assisted temperature taking increased exponentially. The number of active VR users on the US video game digital distribution service Steam doubled. Some manufacturers have unveiled new AR headsets that are more portable. With the wide adoption of 5G, wireless fidelity 6 (Wi-Fi 6), and fiber broadband, all of which can deliver gigabit speeds, XR services are set to boom over the next decade. Huawei predicts that the number of VR/AR users is expected to reach 1 billion by 2030.

In its Virtual Reality/Augmented Reality White Paper, the China Academy of Information and Communications Technology (CAICT) divides the technical architecture of XR into five parts: near-eye display, perception and interaction, network transmission, rendering processing, and content creation. The white paper also predicts the development stages of XR. The CAICT's conclusions have, to some extent, been endorsed by the ICT industry. (Table 1 Network requirements of XR services)

Table 1 Network requirements of XR services

Technical System	Technical Index	Partial Immersion 2021	Deep Immersion 2022–2025	Full Immersion (XR) 2026–2030
Near-eye display	Monocular resolution	2K	4K	8K
	Field of view (FOV)	120°	140°	200°
	Pixel per degree (PPD)	20	30	60
	Varifocal display	No	Yes	Yes
Content creation	360^{0} panoramic resolution: Weak interaction	8K	12K	24K
	Gaming: Strong interaction	4K	8K	16K
Network transmission (Average value)	Weak interaction (Mbit/s)	90	290	1,090
	Round-trip latency: Weak interaction	20	20	20
	Round-trip latency: Strong interaction	5	5	5
	Transmission medium	Wired/Wireless	Wireless	
Rendering processing	Rendering computing	4K/90 FPS	8K/120 FPS	16K/240 FPS
		/	Fixation point rendering	
Perception and interaction	Eye interaction	/	Eye tracking	
	Voice interaction	Immersive sound	Personalized immersive sound	
	Tactile interaction	Tactile feedback		Refined tactile feedback
	Mobile interaction	Virtual mobility (Movement redirection)		High-performance virtual mobility

Currently, XR is entering the deep immersive experience phase. At the beginning of 2024, Apple Vision Pro was officially launched. Its glasses' viewfinders have 23 megapixels between them, providing greater than 4K resolution in each eye and achieving excellent definition, color accuracy, and visual experiences. We predict that XR will reach the stage of full immersion by 2030, by which time it will be supported by 8K monocular resolution, 200° FOV, and a gigabit-level bitrate.

The improvement of the XR display poses higher requirements on content. If content rendering is implemented on the cloud, the device-cloud motion-to-photon (MTP) interaction requires a network transmission round-trip time (RTT) of 20 ms for carrying XR services. For weak-interaction streaming services with few motions, the requirement for lower than 20 ms RTT latency can be met. For strong-interaction gaming services with frequent motions, the RTT latency must be controlled within 5 ms.

Therefore, to support the development of XR services over the next 10 years, networks must have bandwidth of higher than 1 Gbit/s and latency of lower than either 5 ms or 20 ms, depending on the scenario.

2.1.2 Naked-Eye 3D Display: A Brand-new Visual Experience Through Lifelike Image Reproduction

The implementation of naked-eye 3D display involves three major phases: the digitalization of 3D objects, network transmission, and optical or computational reconstruction and display.

There are two types of naked-eye 3D display technology: light field display (through lenslets) and the use of spatial light modulators (SLMs).

Light field display leverages the binocular parallax to create 3D visual effects. It uses parallax barriers, lenticular lenses, and directional backlight, all of which impose fairly inflexible requirements in terms of viewing angles. Their adoption would require real-time capturing of user location and dynamic adjustment.

An alternative approach would be to use SLMs. An interferometric method is used to store all amplitude and phase information of light waves scattered on the surface of a 3D object in a recording medium. When the hologram is irradiated with the same visible light, the original object light wave can be reproduced thanks to diffraction, providing users with a lifelike visual experience. (Table 2 Network requirements of naked-eye 3D display)

Table 2 Network requirements of naked-eye 3D display

Technical System	Technical Index	Lenslet (2021-2025)	SLM (2025-2030)
Maturity prediction		Large-scale deployment and high maturity	Sporadic application
Display	Size	70-inch screen	10-inch to 70-inch screens
	Resolution	16K	16K
Network transmission	Bandwidth	Around 1 Gbit/s	10 Gbit/s - 1 Tbit/s (4K,60 frames, and 10 Gbit/s are required forobjects with a size of 10 x10 cm.)
	Round-trip network latency	Weak interaction: 20 ms Strong interaction: 5 ms	Weak interaction: 5 ms Strong interaction: 1 ms
	Transmission medium	Wired/Wireless	
Interaction design	Voice interaction	Location tracking and spatial sound	
	Gesture interaction	Gesture recognition	
	Mobile interaction	Location tracking and spatial computing	
Availability		Audio: 99.9% Video: 99.999%	

References: IEEE 1981.1 Tactile Internet and Digital Holography and 3D Display

In recent years, naked-eye 3D display featuring light field display has developed rapidly, in step with the development of user location awareness and computing technologies. Some manufacturers have commercialized their innovative products. We predict that a large number of use cases will emerge in the entertainment and commercial sectors by 2025. This type of 3D display requires higher than 1 Gbit/s bandwidth and real-time interaction. In strong interaction scenarios, the network latency must be less than 5 ms, and commercial applications will require network availability of 99.999% (this means annual downtime must be less than 5 minutes and 15 seconds).

Over the past several years, breakthroughs have also been made in holographic technology, which is based on optical reconstruction. Product prototypes have been developed with a thickness of 10 cm and a projection size of around 100 cm^2. We predict that these small-scale holographic products will become commercially available at exhibitions, for teaching purposes, and as personal portable devices over the next 10 years. They will require bandwidth of around 10 Gbit/s, latency of no more than 5 ms or as low as 1 ms, and network availability of more than 99.999%, the same as that required in commercial settings. True-to-life holographic products will require higher bandwidth (over 1 Tbit/s), but we do not expect them to be ready for large-scale commercial deployment by 2030.

Therefore, the naked-eye 3D display products coming to market over the next decade will need to be supported by networks capable of delivering 1–10 Gbit/s bandwidth per user, latency of 1–5 ms, and 99.999% availability.

2.1.3 Digital Touch: Tactile Internet Made Possible Through Multi-dimensional Sensory Interaction

In IEEE's tactile Internet architecture, digital tactile technology is divided into three layers: user layer, network layer, and avatar layer. The user layer enters information such as location, speed, force, and impedance. After being digitalized over the network, the information is converted into instruction data and provided to the avatar layer. The avatar layer then collects tactile, auditory, and proprioception data and provides the data to the user layer through the Internet to inform users' real-time decision making.

Digital tactile technology has two interaction modes. The first is machine control. Use cases include remote driving and remote control. The second is hyperfine interaction, and use cases include electronic skin and remote surgery. (Table 3 Network requirements of digital touch)

Table 3 Network requirements of digital touch

Interaction Mode	Direction of Traffic	Traffic Type	Reliability	Latency (ms)	Bandwidth
Machine control	User-Avatar	Touch	99.999%	1-10	2Mbps
	Avatar-User	Video	99.999%	10-20	1-100Mbps
		Audio	99.9%	10-20	512Kbps
		Tactile feedback	99.999%	1-10	20Mbps (100 DOFs)
Hyerfine interaction	Avatar-User	Tactile feedback	99.999%	1-10	1~10Gbps (Electronic skin)

Active coqnitive capability: The network layer also needs to support services such as dynamic performancemonitoring,task awareness, and 3D mapping.

Reference: IEEE 1981.1 Tactile Internet

Machine control has numerous use cases in industrial settings, and has high requirements for network availability (above 99.999%). Some industries even require availability to reach 99.99999%. The required bandwidth is generally less than 100 Mbit/s, and the maximum permissible latency varies from 1 to 10 ms, depending on the specific circumstances.

Electronic skin powered by flexible electronics in hyperfine interactions has the most development potential. Electronic skin integrates a large number of high-precision sensors such as pressure and temperature sensors. According to a study by the University of Surrey in the UK, each square inch of electronic skin will require bandwidth of 20 to 50 Mbit/s, meaning that an average hand would require bandwidth of 1 Gbit/s. The wearers of electronic skin won't all be humans; intelligent machines present another class of potential users. The user layer may perform analysis, computing, and decision making based on the massive amounts of data collected by the electronic skin on the avatar layer to control the avatar layer. The user layer can also be directly connected to humans through brain-computer interfaces or myoelectric neural interfaces to deliver an immersive remote interaction experience. We predict that network bandwidth of 1 to 10 Gbit/s will be required in hyperfine interaction scenarios.

Therefore, to support digital touch, networks will need to deliver 1–10 Gbit/s bandwidth per user, availability greater than 99.999%, and latency below 10 ms, or as low as 1 ms in certain use cases.

2.1.4 Digital Smell: Internet That Enables Us to Smell Through Deep Sensory Interaction

Among our five senses, two of them – touch and taste – require direct contact, while three – sight, hearing, and smell – do not. Of the latter three, smell involves the deepest interaction.

Digital smell includes three technical phases: odor perception, network transmission, and smell reproduction.

There have been some use cases for odor perception, such as using composite materials to form a barcode, which can generate chemical reactions according to the odor and create color changes. The relationship between the barcode and odor can then be identified through Deep Convolutional Neural Network (DCNN) algorithms. Use cases can be found in specific scenarios like detection of dangerous goods and detection of food freshness.
There are already some commercial odor reproduction products available in the industry, such as smelling generators for VR games, which use five odor cartridges and selectively release odors from the cartridges. They emit scents such as the ocean, gunpowder, wood, and soil, deepening the immersion of the gaming experience. However, some research reports suggest that the future of smell in VR won't rely on these odor cartridges, but will instead work through brain-computer interfaces to enable people to sense odors more directly and accurately.

The combination of odor perception (using electronic noses) and odor reproduction can help create an Internet that enables us to not only hear and see, but also smell. It is not yet clear what kind of network bandwidth and latency this function will require, but the computing requirements are already relatively well understood.

In a nutshell, the next-generation human-machine interaction network will support brand-new experiences including XR, naked-eye 3D display, digital touch, and digital smell. Making these technologies work will require networks capable of delivering bandwidth of 10 Gbit/s and 99.999% availability, with latency as low as 1 ms for some use cases.

2.1.5 AI Agent: Independent Personal Assistant for Near-Human Interaction

Advancements in AI are driving AI application development toward agents. Once given a task, an AI agent will break it down into sub-tasks and create a prompt for each sub-task based on external feedback and autonomous thinking to complete the sub-tasks, and ultimately, fulfil the task it was assigned and the user intent.

The introduction of AI agents will directly result in four changes in the physical world:

- Change in objects: AI agents constitute a new type of connected object on our networks — independent silicon-based entities. The range of interactions occurring in the physical world is broadening from human-to-human alone to include interactions such as human-to-digital human, human-to-robot, human-to-household robot, and robot-to-robot interactions.

- Change in experience: Conventional network design prioritizes coverage and capacity for downlink services. However, AI agents are more sensitive to network latency and uplink speed, and in the future, network design will have to take this into account.

- Change in content: Interaction modalities are expanding from 2D audio and video to more sophisticated modalities such as environment information and 3D calling. For example, AI can generate a virtual 3D calling setup in real time in which two people in different locations meet each other as if in person, in an immersive shared environment in which participants even experience the same temperature.

Change in scope: Today's network services are predominantly human-centered, with service capabilities determined based on the scope of human activities. Future network service design will factor in the activities and activity scope of human-like AI agents to provide 24/7 services covering every conceivable domain.

During interactions between AI agents and people, user experience will hinge on RTT. RTT is the sum of the time the AI spends processing and network transmission latency. Huawei estimates that a typical AI agent will require that RTT be no more than 400 ms to deliver a human-level face-to-face communication experience. GPT-4o, despite being an LLM and not an agent, is still an instructive example. Launched by OpenAI in 2024, GPT-4o requires that RTT be kept below 700 ms in order to deliver near-human interactions.

Huawei predicts that by 2030, human-to-AI agent interactions will entail transmission of three images together with voice streams per second on average. This requires a guaranteed network speed of at least 10 Mbit/s to 20 Mbit/s for excellent experience and at least 32 Mbit/s to 64 Mbit/s for superior experience. (Table 4 Network latency and bandwidth requirements of AI agents)

Table 4 Network latency and bandwidth requirements of AI agents

	Image Size	Network Latency	Guaranteed Bandwidth
Excellent Experience	200 KB (small)	200 ms	10 Mbit/s
	400 KB (large)		20 Mbit/s
Superior Experience	200 KB (small)	70 ms	32 Mbit/s
	400 KB (large)		64 Mbit/s

In the future, the average person may own several AI agents, just like most of us own several computers today. Huawei predicts that globally by 2030, there will be 6 billion active wireless AI agent users, including those using digital twins in the virtual world and embodied AI in the physical world, such as industrial robots, service robots, companion robots, autonomous drones, and autonomous vehicles. These AI agents will run as independent entities and become independent participants in society.

2.2 Networks That Deliver a Consistent Experience for Homes, Offices, and Vehicles: The Third Space with the Same Broadband Experience

With the large-scale commercial use of Huawei's Advanced Driving System (ADS) and Tesla's Full Self-Driving (FSD) system and the widespread use of Baidu's Apollo Go robotaxi in Wuhan, it is foreseeable that end-to-end autonomous driving will become a new norm by 2030. Vehicles will automatically pick up passengers from parking lots, drive along the road, and park at the destination, and the brain, eyes, hands, and feet of drivers will be freed. When we envision the future of self-driving cars, the most appealing feature for many is that we will be able to enjoy the immersive entertainment, social, and work experience we get at home while on the go. Multi-screen collaboration has been used both at home and in cars, and 3D display and holograms will be used in the future. 8K and 16K smart screens will be gradually adopted at home and MR will be widely used in cars.

With 5G-A, F5G-A, and Net5.5G, mobile and fixed broadband basically enters the ultra-gigabit era at the same time, making it possible to deliver the same level of experience to users regardless of whether they are at home, in the office, or on the go. In the future, self-driving cars will become the "third space" beyond homes and offices, and users will enjoy the same broadband service experience in all three scenarios. (Table 5 Network requirements for delivering a consistent experience at home, in the office, and on the go)

Table 5 Network requirements for delivering a consistent experience at home, in the office, and on the go

Scenario Type	Commercial Deployment	Home			Vehicle
		Service	Peak Bandwidth	Round-Trip Latency	Service
Cinema	Within 10 years	16K video (180-inch screen)	1.6 Gbit/s	50 ms	1.6 Gbit/s, 20 ms (16K XR)
Gaming	Within 10 years	360° 24K 3D VR/AR	4.4 Gbit/s	5 ms	4.4 Gbit/s, 5 ms (24K XR)
Holographic teaching	Within 10 years	10-inch hologram	12.6 Gbit/s	20 ms	12.6 Gbit/s, 20 ms
Holographic meeting	Within 10 to 20 years	True-to-life hologram (70-inch)	1.9 Tbit/s	1–5 ms	12.6 Gbit/s, 1–5 ms (Miniature hologram, 10-inch)
Autonomous driving	Within 10 years	Home robots	10 cm positioning	99.999% availability	5–20 cm positioning Availability: 99.999% to 99.9999%
Cloud PC	Within 2 to 3 years	Ultra-fast GPU cloud PC (shallow compression encoding, 4K 60 FPS)	≥ 500 Mbit/s	≤ 15 ms	—
Storage	Within 1 to 2 years	Ultra-fast converged storage (localization-like experience)	≥ 5 Gbit/s	≤ 5 ms (edge cloud deployment)	—
Home security	Within 2 to 3 years	3D optical sensing (1024*768 30 FPS)	About 1 Gbit/s	≤ 20 ms	—

Over the next decade, common home and office services will include smart screens, multi-screen collaboration, 3D, holographic teaching, and XR. With the continuous development of embodied intelligence and humanoid robot technologies, robots will be smarter and more human-like, as well as perform more physical tasks. As the "eyes" of robots, visual sensing is an important part of multimodal interaction and environment sensing. To implement full environment sensing, machine vision requires high spatial resolution, a high frame rate, and a wide light sensing range, which sharply increase the amount of image information. Additionally, to meet the real-time requirements of human-like interaction, network bandwidth needs to be 100 times higher, and the network needs to meet the ultra-low latency requirement. Considering that the penetration rate of true-to-life holographic conferencing will be low in 2030, the mainstream broadband requirements of home and office services will still be 1–10 Gbit/s bandwidth and lower than 5 ms latency. In the future, home and office networks will not only provide seamless broadband coverage, but also support brand-new scenarios such as working from home, premise security, and robotics. Based on HCS capabilities, home networks will be able to sense user locations, indoor space, and environment security, and create a more user-friendly living and work environment for people. By 2030, the average monthly home network traffic will reach 1.3TB.

According to insights into the enterprise service market, more than 90% of urban residents work and live on different campuses, and more than 80% of GDP and more than 90% of innovations are generated on campuses. People are increasingly dependent on cloud and AI technologies during production activities in fields such as government, finance, manufacturing, energy, and transportation. According to statistics from authoritative organizations, the number of terminals per person has increased from 1 in 2022 to 3–5 in 2025. In addition, numerous IoT and dumb terminals are connecting to networks in wireless mode, driving the number of wireless terminals to increase 10-fold by 2030. Video conferencing has become a pivotal tool for remote communication and hybrid office in enterprises, and the high definition (HD) video conferencing market is emerging as a key driver of growth, as it is projected to expand at an annual rate of 10%. In enterprise scenarios, it is crucial to provide Wi-Fi 7 and 10 Gbps infrastructure to deliver better cloud computing and AI services for enterprises.

Services like 3D, holographic teaching, and XR will also be available in our self-driving cars. Over the next decade, their key requirements for network bandwidth will be 1 to 10 Gbit/s, and latency requirements will be less than 5 ms. As autonomous driving will require vehicle-road collaboration, it will require network availability greater than 99.999% and positioning precision of 10 cm. Moreover, with the continuous improvement of scenarios such as automatic parking and passenger pick-up, clear requirements are imposed on the network coverage and rate at vehicles' start and stop locations such as parking lots.

In addition to immersive entertainment, future homes will also have a wide range of services, including cloud PC, home security, cloud storage, and NAS. Cloud PC is an important cloud service under the cloud-network synergy trend. It uses cloud rendering technology to transfer computing and rendering from terminals to the cloud. In this way, users can use lightweight terminals to enjoy computer services. In addition to existing smart cameras for home security, other sensing technologies are upgrading and converging. New security solutions, such as 3D optical sensing for healthcare, are gradually emerging. Home storage is developing towards high speed, convergence, and application integration. Ultra-fast cloud storage provides localized experiences of basic services such as data storage and backup, and supports ultra-fast speed for operations such as online file editing and video-on-demand playback. In addition, it can integrate various online applications such as document collaboration and smart album.

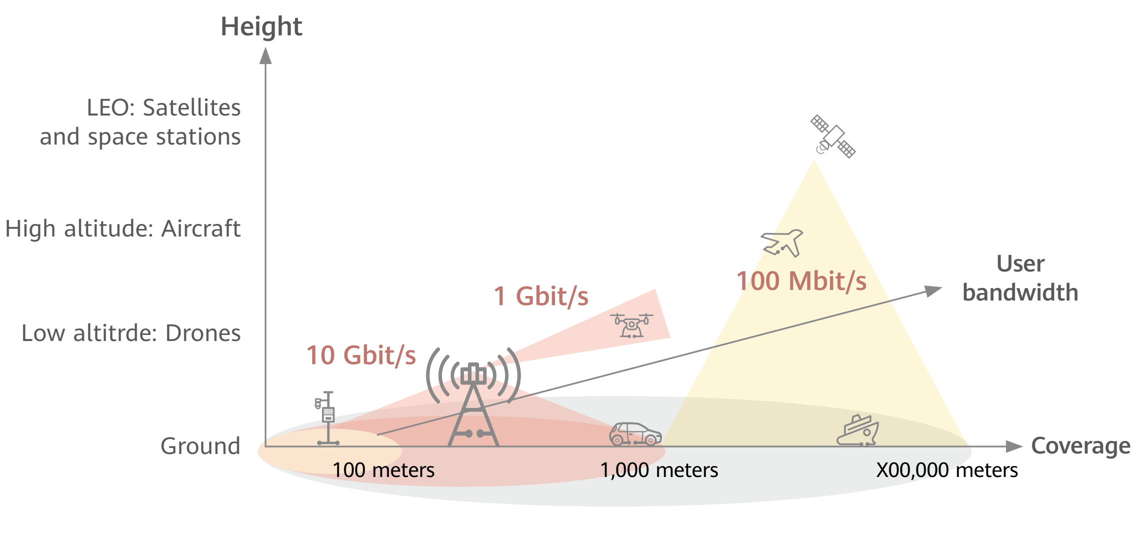
Huawei predicts that by 2030, the penetration rate of personal cloud disks in home cloud storage will reach 35%, that of home cloud computer services will reach 17%, and that of home healthcare using privacy-protection 3D radar optical sensing will reach 8% globally. Moreover, the penetration rate of home guard and security cameras will reach 24% in China and 15% globally. With the intergenerational development of global fixed optical fiber networks, F5G-A will become the mainstream by 2030, the number of global fiber broadband users will reach 1.6 billion, the penetration rate of gigabit or higher home broadband will reach 60%, the penetration rate of F5G-A 10 Gbps home broadband will reach 25%, the penetration rate of FTTR for Home fibers will reach 31%, and the penetration rate of FTTR for SME broadband will reach 41%.

If networks are to meet the needs of these new technologies and provide a consistent experience across our three spaces (home, office, and self-driving cars), we will need to build new network capabilities that deliver the high bandwidth, high availability, and low latency required.

2.3 Space-Air-Ground Cubic Network: Borderless Broadband for Seamless Global Coverage

In the foreseeable future, broadband coverage will extend beyond the ground, encompassing the air and even space. These networks will connect devices at various heights, such as drones and manned aircraft flying at altitudes of less than 1 kilometer, aircraft at altitudes of up to 10 kilometers, and spacecraft in low-earth orbit (LEO), hundreds of kilometers above the earth's surface. A space-air-ground cubic network will consist of small cells with a coverage radius of 100 meters, macro sites with a coverage radius of 1–10 kilometers, and LEO satellite networks with a coverage radius of 300–1000 kilometers, which will provide users with consistent and seamless broadband experiences of 10 Gbit/s, 1 Gbit/s, and 100 Mbit/s, respectively. Broadband will be omnipresent in daily life; the diversification of leisure activities and the growing demand for unmanned operations in intelligent industry and agriculture underscore the necessity of providing broadband everywhere, from land to sea and sky. (Figure 2 All-domain cubic broadband network)

Figure 2 All-domain cubic broadband network



2.3.1 Terrestrial Networks

Wireless networks have already proven their importance in boosting the digital economy and creating huge socio-economic value. To facilitate the diversified experiences of emerging services, terrestrial networks are constantly evolving toward faster speeds and deeper coverage of indoor spaces.

To support XR, naked-eye 3D display, and other services that require ultra-high network speeds, 5G-A increases the network bandwidth 10-fold. Specifically, the downlink bandwidth is increased from 1 Gbit/s to 10 Gbit/s and the uplink bandwidth from 100 Mbit/s to 1 Gbit/s.

Ultra-broadband spectrum is the basis of this 10 Gbit/s capability. Therefore, equipment is being developed to support multiple frequency bands and broadband. In addition to the nearly 100 MHz of FDD spectrum and 100–200 MHz of TDD spectrum currently allocated for 5G, higher-bandwidth upper 6 GHz (U6G) and mmWave are also introduced to provide 200–400 MHz and up to 800 MHz of spectrum, respectively. Operators in different regions can choose when to deploy sub-6 GHz, U6G, and mmWave based on their service requirements and network construction pace, adding spectrum as the need or opportunity arises. Because sites for installing wireless base stations are often expensive and difficult to acquire, the most economical and efficient way to build a high-speed terrestrial network is to add new frequency bands to existing macro and micro sites. This means that a single piece of equipment may need to support multiple frequency bands, and new technologies will need to be introduced to overcome the limited coverage of U6G and mmWave, in order to maximize the utilization of existing base station site resources.

Wireless networks must provide deep coverage to serve indoor users, as indoor use accounts for 80% of total wireless network use. Digital indoor solutions can provide large enough capacity for indoor scenarios, such as airports, stadiums, and shopping malls, by using technologies such as Distributed Massive Multiple-Input Multiple-Output (Massive MIMO). In addition, technologies such as FDD Massive MIMO, supplemental downlink (SDL), and super uplink (SUL) can be introduced to the sub-6 GHz frequency band to improve the outdoor-to-indoor (O2I) penetration of outdoor macro sites, thereby meeting the experience requirements of most indoor scenarios.

2.3.2 Non-terrestrial Networks (NTNs)

71% of the earth's surface is covered by water. The open ocean is beyond the reach of terrestrial broadband networks, as are uninhabitable or sparsely populated places on land, such as remote mountains and deserts. However, as economic globalization promotes the extraction of natural resources, these places are increasingly visited by people and equipped with IoT devices, underscoring the demand for broadband coverage there. Terrestrial networks cannot meet this demand, but satellites can. LEO satellites are located 300–2000 kilometers above the earth — high enough to provide ultra-wide coverage over unpopulated or sparsely populated places. Therefore, satellite broadband and narrowband communications are gaining popularity. In the past decade, rocket recycling technologies have matured, substantially lowering the cost of putting a satellite into orbit. Some enterprises have already deployed constellations of LEO satellites that provide 100 Mbit/s broadband for home users in areas beyond the coverage of cellular networks. Many other enterprises are planning similar deployments in the near future.

However, due to spectrum constraints and communications disruptions, the peak capacity of an LEO satellite in a satellite network is about 10–20 Gbit/s and the single-user-perceived speed of broadband access is 100–200 Mbit/s. Suppose a global satellite network comprises 10,000 satellites distributed on multiple orbital planes from very low earth orbits (VLEOs) to LEOs, and each satellite maintains links with satellites around it in all directions using over 100 Gbit/s lasercom. Considering at least half of the areas passed over by the satellites are areas where demand for broadband is minimal (e.g., oceans and deserts), the actual effective capacity of the satellite network will be around 100 Tbit/s, and the capacity density will be less than 2.5 Mbit/s/km2 (just a few percent of the capacity density of a common terrestrial 4G network in urban areas).

The 3rd Generation Partnership Project (3GPP) is defining a global mobile communications protocol standard for NTNs. In Release 17, it introduced the first 5G-based transparent payload technical standard. In Release 18, it improved the coverage and performance of IoT-NTN, and completed research on features such as air interface transmission link enhancement. For the upcoming Release 19, 3GPP is studying a network structure of regenerative satellite payload and inter-satellite link technology in order to further improve the performance and efficiency of satellite networks. Release 20 is expected to introduce a new standard for smart handheld NTN broadband terminals.

In contrast to terrestrial networks, satellite networks feature dynamic inter-satellite connections and topologies that vary with time, which brings new challenges to the development of satellite networking technologies. The Internet Engineering Task Force (IETF) is actively developing standards for dynamic networks. It has set up a working group on Time-Variant Routing (TVR) to explore and standardize the application scenarios, functional requirements, and management models of time-variant dynamic networks, including satellite networks, which are an important application scenario of TVR.

LEO satellite broadband terminals are becoming smaller. The latest commercially available portable broadband satellite CPE weighs just 1.1 kg, and is small enough to be carried in a backpack. Powered by batteries, the product can meet the typical mobility requirements of individuals, such as use in connected cars, camping trips, and exploration. It is foreseeable that satellite communications will be used as a supplement on the fringes of terrestrial 5G-A networks to meet the narrowband and broadband service requirements of people and things and achieve borderless global coverage.

2.4 Industrial Internet: A New Type of Network for Intelligent Manufacturing as Well as Human-Robot and Robot-Robot Collaboration

The industrial Internet is a new type of infrastructure that deeply integrates ICT into the industrial economy and fully connects people, machines, things, and systems. For industries, this means the birth of a brand-new manufacturing and service system that covers entire industry value chains and paves the way for digitalization, network-based operations, and the intelligent transformation of all industries. The traditional industrial Internet system consists of four key components: industrial control, industrial software, industrial network, and information security. The industrial network is the foundation of the entire system.

Traditional industrial networks are built based on the International Society of Automation 95 (ISA-95) pyramid model. This architecture was introduced more than 20 years ago and is a manufacturing system centered on human management. However, the development of intelligent manufacturing requires a new architecture that will facilitate human-robot and robot-robot collaboration.

The new architecture will be built upon three equal elements – humans, robots, and an intelligent platform (cloud/edge computing). Private industrial communication buses will be replaced by universal industrial networks and open data layers that support real-time data transmission. The intelligent platform will aggregate data collected from humans and robots for real-time analysis and decision making and support effective collaboration between humans and robots.

To support the stable development of the industrial Internet, the network must meet the following requirements:

- Deterministic network latency: Industrial applications like automatic control and motion control pose strict requirements on the latency, jitter, and reliability for network data transmission.

- Network reliability: Control services on industrial sites are typically performed within milliseconds. This requires protection switchover to be completed within sub-seconds.

- Intelligent O&M management: Effective O&M management for industrial networks hinges on achieving zero workload through streamlined processes that minimize the burden to industrial production.

Huawei predicts that the total number of global connections will reach 200 billion by 2030, including about 100 billion wireless (cellular) connections (including passive cellular connections) and about 100 billion wired, Wi-Fi, and short-range connections. In industrial settings, the multitude of connected devices will include not only pressure, photoelectric, and temperature and humidity sensors, but also numerous intelligent cameras, drones, and industrial robots. With the advent of the AI era, Huawei predicts that 20 million industrial robots will enter the cutting-edge smart manufacturing field by 2030. Consequently, industrial networks, currently characterized by a fragmented landscape of different narrowband technologies, will adopt universal broadband technologies.

Universal industrial networks will erase the technical boundaries between consumption, office work, and production. These networks will support multiple types of services using deterministic broadband networks and slicing technologies, such as 5G, Time Sensitive Networking (TSN), IPv6 Enhanced, Wi-Fi 7, and industrial optical networks, allowing enterprises to connect any workforce and migrate all consumption, office work, and production elements to the cloud.

Universal industrial networks will enable on-demand data sharing and seamless collaboration between office and production systems within a company, between different companies in the same industry, and even between the related services of different vertical industries. They will support broadband-based interconnectivity and multi-cloud data sharing of any workload.

Universal industrial networks will also be smarter than ever, facilitating the movement of data in boundary-free and mobile scenarios across industries and across clouds. They will support intent-driven automated network management and AI-based proactive security and privacy protection, ensuring service security and trustworthiness at any workplace.

An enterprise usually has multiple types of services, so a universal industrial network must ensure

the availability, security, and trustworthiness of services. For example, smart healthcare involves services such as remote diagnosis, monitoring & nursing, and remote surgery; a smart grid involves video-based inspection, grid control, and wireless monitoring; and smart manufacturing involves factory environment monitoring, information collection, and operation control. (Table 6 Network requirements of intelligent enterprises)

Table 6 Network requirements of intelligent enterprises

Industry	Service Type	Network Requirements of Services															
		Number of Connections per Enterprise	Service Availability (Requirements per User or per Service)										Security		Trustworthiness		
			Bandwidth per User (Mbit/s)					Latency (ms)									
			B1	B2	B3	B4	B5	T1	T2	T3	T4	T5	S1	S2	M1	M2	M3
			1~10	10~20	20~50	50~100	>100	50~100	20~50	10~20	5~10	<5	Logical Isolation	Physical Isolation	Visible	Manageable	Operable
Smart health	16K remote diagnosis	10					1G										
	Monitoring & nursing	2K															
	Holographic remote surgery	5					10G										
Smart grid	Video-based inspection	-															
	Grid control	-															
	Wireless monitoring	-															
Smart manufacturing	Factory environment monitoring	100															
	Information collection	10K															
	Operation control	1K															

Reference: CAICT, Research Report on Industry SLA Requirements for 5G E2E Network Slicing

Based on the typical bandwidth and latency requirements of each service and forecasts on the number of devices used by enterprises in 2030, we predict that a medium- to large-sized enterprise will require network bandwidth of 100 Gbit/s and the maximum bandwidth per user will reach 10 Gbit/s. Acceptable latency will vary greatly from one use case to another, from as low as 1 ms to as high as 20 ms. In addition, it will be necessary to ensure the security and trustworthiness of industrial networks.

2.5 Computing Power Network: Orienting Towards Machine Cognition and Connecting Intelligent Computing Centers, Massive Amounts of User Data, and Computing Power Services at Multiple Levels

The social value of communications networks is reflected in the services they support. In the past, networks helped establish communications channels between people by providing communications services. Today, with smart devices and the cloud connected to networks, more diverse content services are provided through communications networks.

The networks we use today are designed for human cognition. For example, the frame rate for motion video (typically 30 frames per second [FPS]) is chosen based on the human ability to perceive motion, and the audio data collected is compressed with mechanisms that take advantage of the masking effects of the human cognitive system. For human perception, such encoded audio and video can be considered high quality. However, for use cases that require beyond-human perception, the level of quality may be far from enough. For example, robotic monitoring systems will need to detect anomalies by listening to sounds beyond the human audible frequency range. In addition, the average human response speed upon seeing an event is about 100 ms. Therefore, many applications have been designed based on this latency. However, for certain applications that are beyond human usage, such as emergency stop systems, shorter response time is required.

The Innovative Optical and Wireless Network Global Forum Vision 2030 and Technical Directions states that compared with today's networks that are designed for human cognition, future networks designed for intelligent machines such as XR, machine vision, and self-driving vehicles will have enhanced performance in four dimensions:

- Cognitive capacity: Systems will be able to capture objects in the physical world more finely, precisely, and in a multi-sensory manner. For instance, in manufacturing monitoring systems, motion capture at 120 FPS will detect anomalies that would otherwise be undetectable.
- Response speed: Systems will be able to respond to the status change of a controlled object within 10 ms.
- Scalability in computing: Systems will be able to accommodate varying and uncertain workload while achieving high resource utilization, through methods such as dynamic linear scaling of computing resources.
- Energy efficiency: Energy efficiency can be greatly improved if enterprises eliminate on-premise computing resources and adopt a cloud-based model. Moreover, energy efficiency will be further improved with an event-driven approach where a system is deployed on a serverless computing platform.

Intelligent machines will create more accurate data. For example, network clocks and geolocation stamps can be used for precise modeling of the physical world in a digital twin system. This will lead to a shift in data processing and computing, from today's Internet platform-centric model to a data-centric model, decoupling data, computing, and communications.

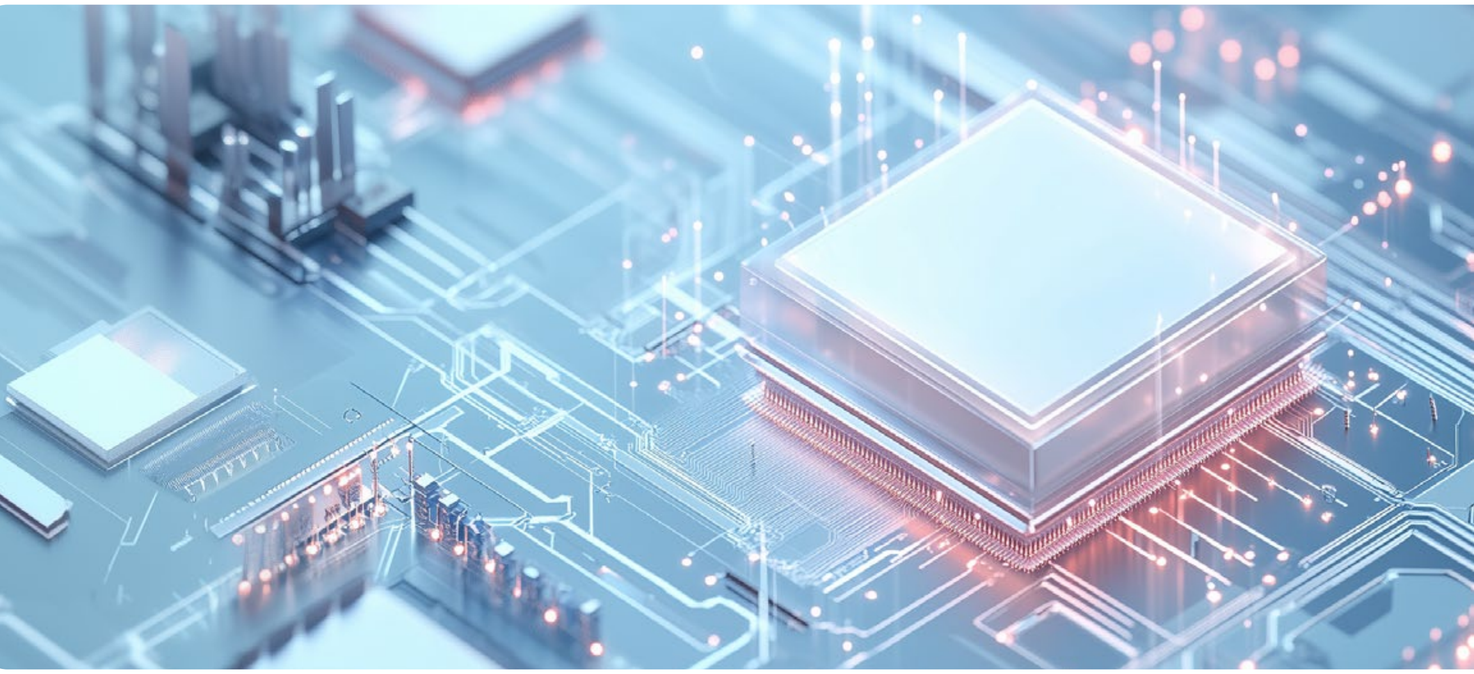
The network infrastructure designed for machine cognition should satisfy the following requirements:

- Accommodating the collection and transmission of massive amounts of data, having an ultra-low latency, and supporting a very large number of subscribers.
- Managing publishers' data generation and injection based on the overall condition of the system and the importance of the data.
- Supporting the storage and sharing of data among communications and computing nodes in the network.

- Supporting precision time and geolocation stamping.
- Providing strong protections for data security, privacy, and integrity.
- Providing a data brokerage between IP and non-IP nodes, with the data brokerage being accessible through multiple networks.

As AI foundation models continue to advance, data centers will witness the number of model parameters increasing to trillions, tens of trillions, or even hundreds of trillions. Such huge numbers will overwhelm a single intelligent computing center. A common intelligent computing center can now host an array of 10,000 to 50,000 Graphical Processing Units (GPUs)/Neural Processing Units (NPUs), while a cutting-edge one usually accommodates up to 60,000 such GPUs/NPUs. As the scale of GPUs/NPUs exceeds 80,000, a single intelligent computing center will face a variety of challenges, ranging from unstable power supply and inefficient heat dissipation to inadequate network bandwidth. These technical bottlenecks make it difficult for a single intelligent computing center to accommodate 100,000+ GPUs/NPUs. As such, distributed computing power collaboration across data centers has emerged as a pressing necessity to keep pace with AI's growing demands for computing power. Data center networks will continue to evolve toward hyper-converged data center networks, replacing multiple network technologies such as Ethernet, IB, and FC with hyper-converged Ethernet. This will enable large-scale, high-throughput, and high-reliability data center networks.

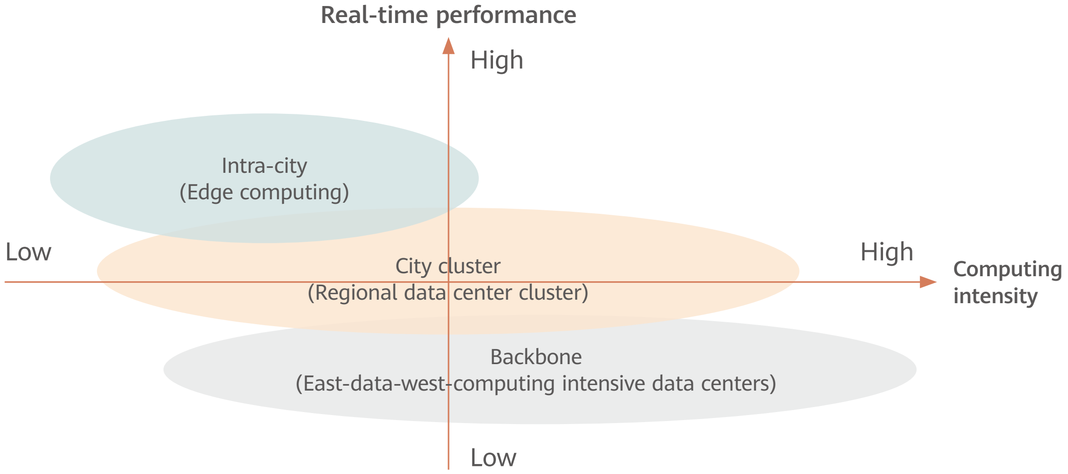
In terms of terminals, the computing industry can no longer rely on Moore's law for rapid development given the miniaturization of chips is approaching its physical limits. For example, manufacturing Central Processing Units (CPUs) with more than 128 cores in smart terminals presents economic bottlenecks. Furthermore, the local computing power of devices cannot support the running of ultra-large models due to volume and power consumption constraints. In addition, due to bandwidth costs and latency, cloud data centers may not be able to satisfy the massive amount of time-sensitive service processing required by intelligent systems. That said, the new type of network oriented to machine cognition must allow foundation models to be deployed at the edge for data analytics, processing, inference, and more, without needing to transmit all data to the central cloud.

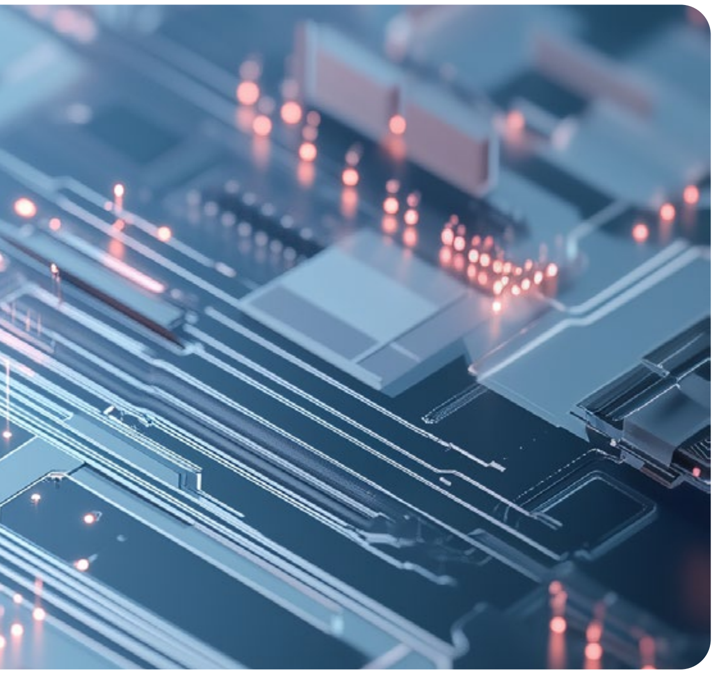


In the future, the cloud, edge, and devices will be connected, and computing workloads will be apportioned to one of three levels (distributed edge nodes in a city, regional data center clusters that cover multiple cities, or backbone centralized data centers) in real time based on their latency thresholds. In use cases that can tolerate latency of about 20 ms, data may be sent to a centralized data center. In use cases with lower latency tolerance (from 5 ms to as low as 1 ms), computing will be performed in a regional data center cluster or at the edge. (Figure 3 Three levels of computing resources for machine data services)

Computing efficiency and reliability are correlated with network bandwidth, latency, security, and isolation. Therefore, computing and networks should be coordinated. Major carriers have articulated a new business vision for computing and network convergence services based on a new concept of "computing power network". They aim to connect diverse computing power in the cloud, on the edge, and across devices to implement on-demand scheduling and sharing for efficient computing power services at multiple levels. The computing power network represents a significant shift in network design, from focusing on human

Figure 3 Three levels of computing resources for machine data services





cognition to focusing on machine cognition.

The Chinese government released the Guiding Opinions on Accelerating the Construction of Collaborative Innovation System of National Integrated Big Data Centers, which states: "With the acceleration of digital transformation and upgrade in various industries, the total volume of data being created by society as a whole is growing explosively, and the requirements for data resource storage, computing, and applications are greatly increasing. Consequently, there is an urgent need to promote an appropriate data center layout, balance between supply and demand, green and centralized development, and interconnectivity. We should build a new computing power network system that integrates data centers, cloud computing, and big data, in order to promote flows and application of data elements and achieve green and quality development of data centers." In addition, the document proposed that "as data centers should be developed on a large scale in a centralized and green manner, network transmission channels between national hubs and nodes should be further streamlined to accelerate the program of 'Eastern Data and Western Computing' and improve cross-region computing power scheduling."

To support proactive development of computing power network standards, the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) has launched the Y.2500 series of computing power network standards, with Y.2501 (Computing Power Network – framework and architecture) as the first standard. This series of standards will be compatible with a raft of computing power network standards developed by the China Communications Standards Association (CCSA). Many carriers have incorporated the computing power network into their 6G and future network research. The computing power network will be a key scenario for communications network evolution over the next 10 years.

Huawei predicts that by 2030, optical connections in a city will be extended to all city scenarios, such as homes, buildings, enterprises, and 5G base stations, to enable 1 ms access to cloud and computing, and every 10,000 people will have four all-optical OTN anchors, among which 100G anchors will account for 25%, and the OTN coverage rate of transmission networks will reach 100% in government agencies, financial institutions, key universities and scientific research institutions, large hospitals, and large industrial enterprises, as well as development zones and industrial parks at the county level or above.

2.6 AN: Unattended Self-evolving Network

Throughout the history of the communications industry, the continuous innovation in crucial technologies has helped to improve the network capabilities of carriers, which in turn stimulates the innovation in a diverse range of services while advancing various industries. Additionally, networks have proposed an objective of achieving Highly Autonomous Networks featuring agile service provisioning, precise user experience assurance, and efficient cross-domain O&M. The significant breakthroughs in GenAI and rapid development of crucial technologies such as the telecom foundation model have created unprecedented opportunities of new traffic, connections, and services in the telecom industry, significantly accelerating the transformation toward network intelligence. In the future, carriers will leverage AI agents and digital assistants to deliver a zero-trouble, zero-wait, and zero-touch service experience to customers and implement self-configuration, self-assuring, and self-optimizing O&M for networks. This will help them promote service innovation to increase revenue while empowering various industries to develop new quality productive forces. Huawei expects that AN Level 4 will be reached by leading carriers by 2025 and by most carriers by 2030.

From the technical perspective, AN Level 4 is characterized by machines functioning as the major O&M entity which is assisted by humans during decision-making in key tasks/scenarios. In the future, machines will be widely used to understand human intents through AI, generate suggestions on network planning and optimization, and use decision-making AI models to complete intelligent decision-making, so as to achieve machine-oriented AN.

TM Forum also characterizes AN Level 4 from the perspective of service value, offering a valuable reference for the industry to systematically evolve towards AN Level 4. (Table 7 AN Level characteristics)

Table 7 AN Level characteristics

Perspective	Dimension	Level Characteristic	
		L3/Machines assisting humans	L4/Humans assisting machines
Customer	Zero-wait	Automated service provisioning	Automated service delivery
	Zero-trouble	Experience awareness and visualization	Experience evaluation and assurance
	Zero-touch	Visualization	Interaction
Network	Self-configuration	Automated configuration delivery	Pre-event simulation Post-event verification
	Self-healing	Precise fault diagnosis	Potential risk prediction and prevention
	Self-optimizing	Single-objective exclusive optimization	Multi-objective collaborative optimization

The telecom foundation model is a key enabling technology for AN Level 4. It employs AI agents and digital assistants to redefine network capabilities in an E2E manner, empowering carriers to achieve the transformation toward network intelligence. AI agents can leverage the intent understanding and logical reasoning capabilities through the telecom foundation model to break down complex problems and find optimal solutions. System capabilities can then be employed to implement scenario-specific autonomy, delivering a new network O&M experience. AI digital assistants can be customized using the natural language understanding capability of the telecom foundation model to complete complex human-machine interaction through different roles, simplifying learning and improving learning efficiency for employees. Additionally, AI digital assistants can offer vast amounts of knowledge and data to employees on demand to enhance O&M efficiency.

The increasing application of AI agents and digital assistants across the entire network production process — involving planning, construction, maintenance, optimization, and operations — will transform communications networks from the following perspectives by 2030:

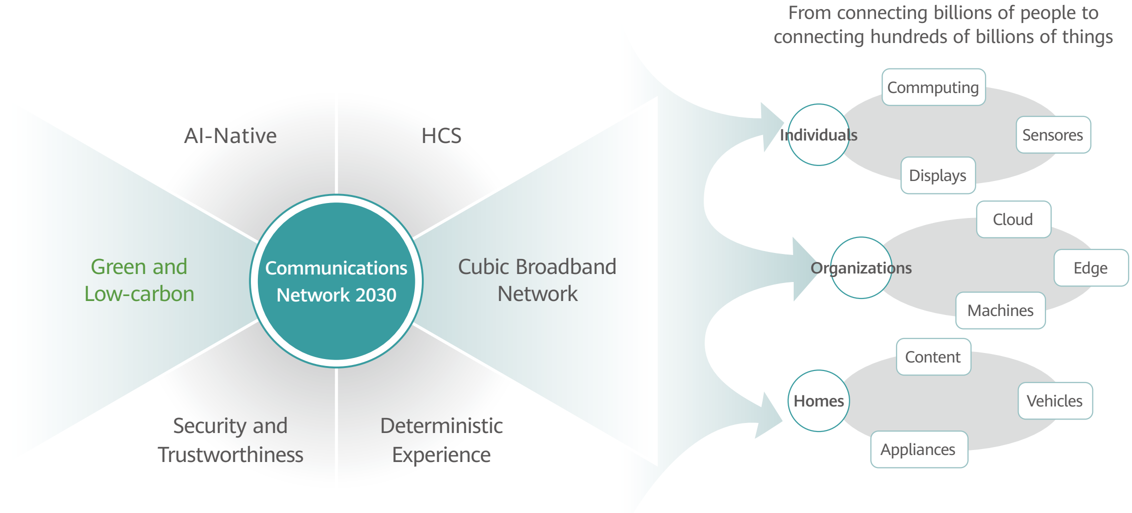
- O&M mode: creating a new interactive O&M mode based on natural language
- System capabilities: improving system capabilities in terms of awareness, analysis, decision, and execution
- Service processes: designing service flows centering on machines to automate E2E processes and reduce the time to market (TTM) of services
- Integration mode: replacing the conventional application programming interface (API) integration mode with the self-service integration mode through large models to reduce the TTM of services

Defining Features of Future Networks

3.1 Development Directions of Future Network Technologies

Future networks won't just connect billions of people; they will connect hundreds of billions of things. We envision those connections as being supported by green and cubic broadband networks that are AI-native, secure, trustworthy, and capable of providing deterministic experiences and HCS. (Figure 4 Vision for the communications network of 2030)

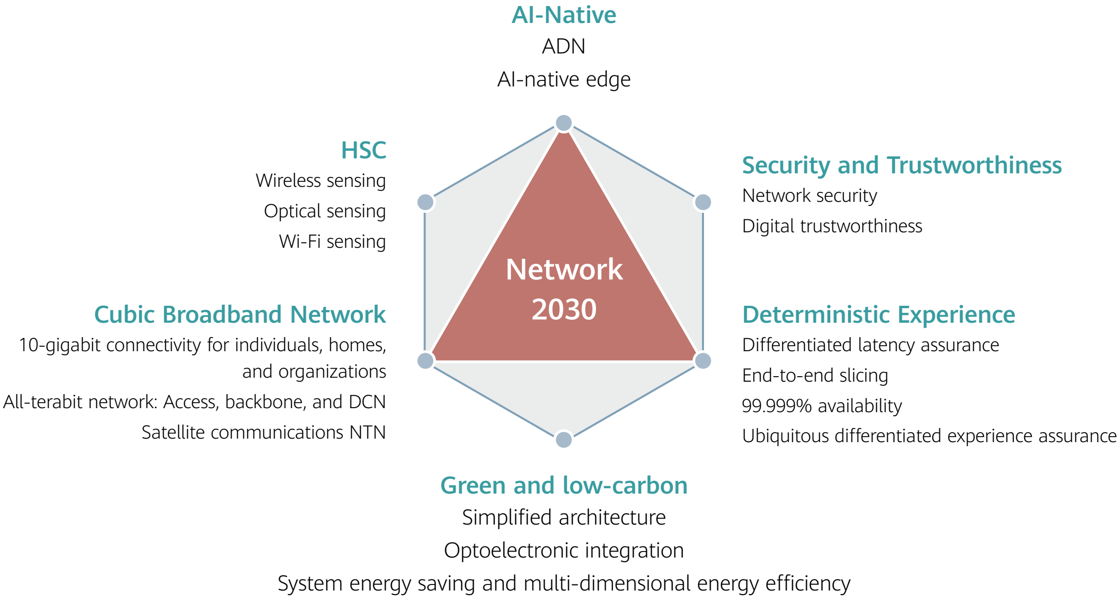
Figure 4 Vision for the communications network of 2030



3.2 Defining Features

The communications networks of 2030 will have six defining features enabled by 17 key technologies, and each key technology will rely on research on multiple technological fronts. (Figure 5 Defining features of the communications network of 2030)

Figure 5 Defining features of the communications networks of 2030



3.2.1 Cubic Broadband Network

The coming few years will see continual improvement in network performance. We will see an evolution from today's ubiquitous gigabit toward ubiquitous 10-gigabit. The global penetration rate of gigabit or higher home broadband networks is expected to reach 60%, and that of 10-gigabit home broadband networks is expected to reach 25%. The average monthly network data usage per household is forecast to increase by 8-fold to 1.3 TB. Network ports will be upgraded from 400G to 800G or even 1.6T, and single-fiber capacity will exceed 100T. In terms of coverage, network construction up until now has focused on connectivity on the ground, but in the future, we will see the construction of networks connecting the ground, air, and space.

1) 10-Gigabit Connectivity for Individuals, Homes, and Organizations

Fiber networks are expected to be widely deployed globally by 2030, transforming today's gigabit connections for individuals, homes, and organizations into 10-gigabit connections.

To deliver 10G home broadband, 50G passive optical network (PON) technology will be applied to more than one million ports by 2027 and 200G PON technology will likely be used by 2030 on optical access networks. The coherent detection technology typically used for wavelength division multiplexing (WDM) will be used in the PON field, which will significantly improve receiver sensitivity and support modulation formats with higher spectral rates, such as quadrature phase shift keying (QPSK) and 16-quadrature amplitude modulation (16-QAM), to achieve higher data rates.

To deliver 10-gigabit broadband for individual users, mobile network research has been focusing on full use of sub-100 GHz spectrum combinations and iterative evolution of Massive MIMO, and has produced the following landmark innovations:

- Extremely large antenna array-Massive MIMO (ELAA-MM): This helps overcome the limited coverage of high frequency bands (such as mmWave and 6 GHz) to achieve ubiquitous 10 Gbit/s downlink experience.
- Multi-band serving cell (MBSC): By binding multiple frequency bands into a virtual large carrier to share control channels, control channel resources are conserved, downlink user experience is improved by about 30%, and cell capacity is increased by about 20%.
- Flexible spectrum access (FSA): Uplink resource bottlenecks are alleviated through flexible uplink and downlink slot configuration, achieving 1 Gbit/s uplink experience.

In 2020, 3GPP Release 16 defined two frequency ranges, Frequency Range 1 (FR1) and Frequency Range 2 (FR2), for 5G new radio (NR), covering all spectrum bands for International Mobile Telecommunications (IMT) between 450 MHz and 52.6 GHz. In 2022, Release 17 defined the 6 GHz spectrum as an IMT licensed band for NR (numbered n104). In 2023, Release 18 specified the range of the band n104 (6425–7125 MHz), and its freezing marks the start of 5G-A. Release 19 will cover the major evolution directions of 5G-A, with the first batch of initiated topics covering new services and technologies such as AI for air interface, integrated sensing and communication (ISAC, channel research), and Ambient IoT, and will start the research on the channel model for the 7–24 GHz spectrum.

Regarding the ongoing evolution of Massive MIMO, Release 17 defined FDD CSI enhancement and TDD SRS capacity expansion standard features, and work has been initiated on some important aspects of multi-antenna technology, such as hybrid beamforming (HBF) for the new U6G band, sub-band full duplex, and FDD 64T/128T Massive MIMO, with an eye to inclusion in Release 19.

To make 10-gigabit campus networks possible, more research is needed on all-optical Ethernet technologies for 10GE and 100GE access and next-generation Wi-Fi technologies that support millimeter-wave and high-density MIMO. Theoretically, Wi-Fi 7 standards should be able to support 10-gigabit user access. With wireless air interface technology approaching Shannon's limit, further evolution of Wi-Fi and mobile technologies will require more spectral resources, which are scarce. This has prompted industry-wide discussions about the feasibility of converging Wi-Fi 8 and 6G.

2) All-Terabit Network: Access, Backbone, and DCN

Taking into account the growing broadband requirements of individuals, homes, and enterprises, as well as in AI training and prediction scenarios, future access network equipment will need to support terabit-level interfaces. Backbone equipment will support 40–100 Tbit/s per slot and data center equipment 400 Tbit/s per slot.

By 2030, there will be broadband networks that can achieve terabit-level transmission speeds in many parts of the networks, from access, backbone, and data center to the Internet. These will mostly serve the world's largest cities – those with populations of 10 million or higher.

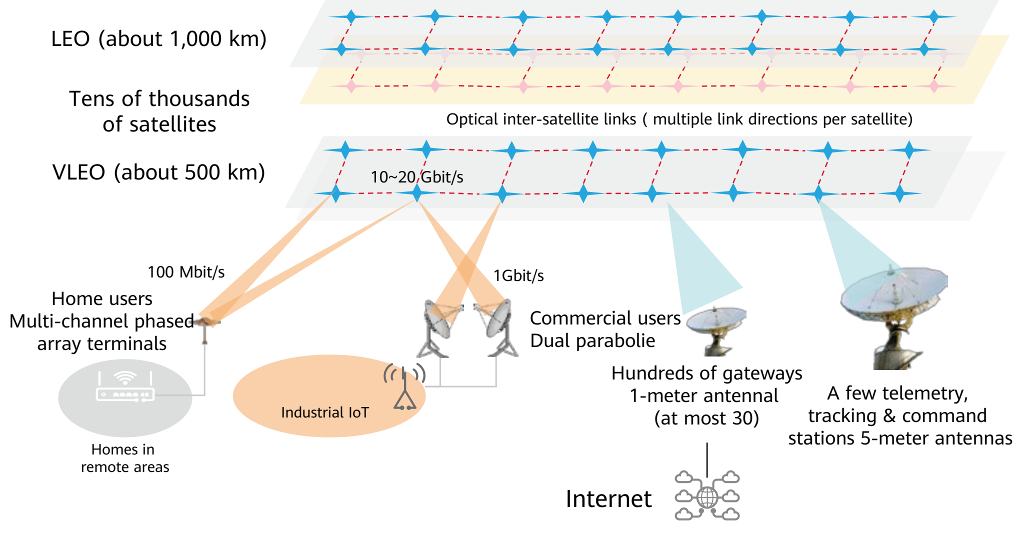
In the terabit era, datacom equipment will need to have Ethernet interface technology that supports speeds of 800 Gbit/s or even 1.6 Tbit/s to meet service development needs. Unlike 200G/400G Ethernet, 800G Ethernet is a nascent technology that has yet to be standardized. From a technical standpoint, there are two routes that will take us to 800G: continuing evolution of existing pluggable optics modules and the adoption of new co-packaged optics (CPO) modules. Both module types will have a place in the future market, but pluggable optics modules with a capacity of over 800G are expected to encounter power and density problems, so CPO modules will likely become the preferred choice.

Moreover, enabling a transmission capacity of more than 100 Tbit/s per system will require technical breakthroughs in WDM equipment, including high-baud-rate electro-optic modulator materials, spatial division multiplexing (SDM) transmission systems and modules, and new optical amplifier technology that goes beyond C band to L band and S band.

3) Satellite Communications NTN: Effective Supplement to Terrestrial Network Coverage

LEO satellite broadband mainly serves homes and enterprises in remote areas, and ships at sea. It can be used for backhaul and combined with cellular networks and wireless local area networks (WLANs) on the ground to provide both broadband and narrowband coverage for villages or enterprises in remote areas. (Figure 6 Satellite communications network)

Figure 6 Satellite communications network



For satellite-terrestrial transmission, broadband CPEs and handheld NTN terminals must be able to efficiently access satellite networks. To make this possible, we need to study new air interface technologies to overcome the deep fading, high latency, ultra-high Doppler shift, and highly dynamic nature of satellite networks. We also need to explore key air interface technologies, such as time-frequency synchronization technology for random access and high-speed handovers over air interfaces, as well as optimized encoding, decoding, waveform, modulation, and multiple access technologies for satellite-terrestrial links. These advancements will enable highly reliable access, efficient multiple access and wireless transmission, and high-speed mobility management.

To improve the coverage capability and network spectral efficiency of satellites, there is a lot of research that needs to be done. Specific areas of research include:

- High-performance multi-antenna beamforming technology and ultra-large-aperture and high-gain multi-antenna technology, to enable spatial multiplexing for ultra-high beam concurrency and high-speed beam switching, in order to support the access of high-performance broadband CPEs and smart handheld terminals likely to be defined in 3GPP Release 20

- Technologies to mitigate interference between the beams of an individual satellite, as well as inter-satellite interference, to improve spectrum multiplexing rates and spectral efficiency

- Unified multi-user scheduling of time, frequency, space, and power domain resources of satellite-terrestrial links in a multi-layer LEO satellite constellation, to fully and efficiently utilize network resources.

- Large-bandwidth satellite-terrestrial lasercom technology, to meet increasing feeding bandwidth requirements, along with solutions for mitigating atmospheric turbulence during laser transmission

Inter-satellite transmission requires satellites at different orbital heights to form multi-layer constellations, with each layer networking through inter-satellite links. Inter-satellite links are established on demand between satellites in the same orbit, at the same layer, and at adjacent layers, forming a cubic space network. Inter-satellite links will use lasercom and terahertz technologies to support a speed higher than 100 Gbit/s. This will require research on adapting industrial products to aerial settings, making phased array antennas more compact, and enabling dynamic inter-satellite lasercom tracking and pointing.

The network management and control domain comprises an operation and control center, network management center, gateway, and converged core network. In order to perform the tasks of satellite network management, user management, and service support, we need to research flexible and efficient dynamic routing protocols between gateways and constellation networks, and hyper-distributed converged core networks that support intelligent switching of multi-layer satellite constellations.

3.2.2 Deterministic Experience

The ability of communications networks to provide deterministic experiences is key to supporting online office and learning, as well as meeting the security and reliability needs of production environments.

1) 20 ms, 5 ms, and 1 ms Latency Assurance for Differentiated Service Requirements

Over the course of this decade, the Internet traffic model will undergo a fundamental shift from today's top-down content traffic generated primarily from online services, retail, and entertainment to bottom-up data traffic from pervasive intelligent applications deployed across various industries. Intelligent machines will generate massive amounts of data, and this data will need to be processed in data centers. This decade will see a push toward the coordinated development of electricity and computing power to enable society-wide green computing power. Therefore, the networks of the future will need to be able to support more centralized operations of data centers. That will entail meeting differentiated latency requirements, with the acceptable latency for backbone, inter-city, and intra-city network services being 20 ms, 5 ms, and 1 ms, respectively.

In addition, networks will need to schedule resources in real time at the network layer based on service attributes in order to make computing power greener and more efficient.

In addition to meeting differentiated latency requirements at the network architecture and system levels, the industry also needs to research E2E deterministic latency.

Computing power and data components are progressively moving edgeward. Wireless access latency now accounts for 30% to 60% of network latency. Reducing wireless access latency has become the focus for enhancing session experience. However, wireless air interface sharing leads to resource sharing by multiple user devices, making it difficult to guarantee real-time performance and high speeds. To solve this problem, multi-carrier aggregation and multi-antenna spatial multiplexing technologies need to be developed to optimize carrier configurations and increase air interface capacity. These technologies, together with differentiated and hierarchical scheduling policies, will improve the bandwidth of services under latency constraints on multi-band carriers and provide deterministic experience for applications.

Furthermore, an intelligent closed-loop experience assurance mechanism needs to established so that intelligent core networks can implement real-time experience awareness and scheduling, ensuring deterministic service experience.

The optical access networks we have today feature PON technology, which is based on time division multiplexing (TDM). PON uses uplink burst to prevent collisions, making it ill-suited to scenarios requiring low latency. Frequency division multiplexing (FDMA) needs to be explored to allow concurrency of multiple optical network terminals (ONTs) and guarantee low latency by addressing fundamental issues.

For wide area networks (WANs), the current best-effort forwarding mechanism needs to be changed, protocols at the Physical (PHY) and Medium Access Control (MAC) layers need to be improved, and new technologies including SRv6, In-situ Flow Information Telemetry (IFIT), lossless WAN remote direct memory access (RDMA), and deterministic IP need to be integrated to ensure on-demand, E2E latency.

2) E2E Slicing: Logical Private Networks and Services That Are More Adaptable to Vertical Industries

E2E slicing provides vertical industries with customized private network services that run independently and are isolated from each other. This is a key area we can work on in order to serve vertical industries. E2E slicing is a network virtualization technology with Service Level Agreement (SLA) assurance. Through network slicing, different logical or physical networks can be isolated from the network infrastructure to meet the SLA requirements of different industries and services. Types of slicing include wireless slicing, transport network slicing, and core network slicing. When a carrier provides a slice to a customer, the carrier also provides E2E management and services.

Wireless slicing: It can be further classified into hard slicing and soft slicing. Hard slicing is achieved through resource isolation, such as through static resource block (RB) reservation and carrier isolation for specific slices. Soft slicing is achieved through resource preemption, such

as quality of service (QoS)-based scheduling and dynamic RB reservation. Currently, the bitrates of different network slices can be guaranteed based on priorities. The next step in the development of network slicing is to explore the most appropriate wireless protocols for the PHY, MAC, Radio Link Control (RLC), and Packet Data Convergence Protocol (PDCP) layers. For example, we could have a PHY layer with a low-latency coding scheme for slices that support ultra-reliable low-latency communication (URLLC) services, or a MAC layer with an optimized hybrid automatic repeat request (HARQ) mechanism.

Transport network slicing: This is achieved through physical isolation or logical isolation. Physical layer isolation technologies include optical-layer fine-grain OTN (fgOTN), allowing different services to be carried through different wavelengths or through fgODU within a single wavelength. Flexible Ethernet (FlexE) at the MAC layer is also used to isolate services by scheduling timeslots. Physical layer and logical layer isolation complement each other in terms of technology, providing both deterministic and flexible network capabilities for transport networks. Further research is needed in the industry to explore the integration of technologies such as congestion management mechanisms, latency-oriented scheduling algorithms, and highly reliable redundant links for FlexE, TSN, and deterministic networking (DetNet), as well as PON+OTN/IP E2E slicing capabilities. This can deliver deterministic latency and zero packet loss for physical slicing, as well as low-granularity FlexE interfaces.

Core network slicing: In 5G standalone (SA) architecture, microservices are the smallest modular components of core network functions. In the future, microservices will need to be flexibly orchestrated into different slices based on service requirements, and flexibly deployed in different parts of the network based on differentiated latency and bandwidth requirements.

E2E management and services: 3GPP has defined an E2E network slicing management function (NSMF), which streamlines network slice subnet management functions (NSSMFs) to enable E2E automatic slicing. This can facilitate elastic slice service provisioning and capacity expansion or reduction. Moving towards 2030, the SLA awareness, precision measurement and scheduling of slicing need to be further researched in the industry to achieve automated closed-loop slicing control. In addition, customers in vertical industries must be able to flexibly customize slicing services on demand. More efforts are needed to study how to meet industry customers' Create, Read, Update, and Delete (CRUD) requirements for slices, and how to coordinate the configuration of slices, private networks, and edge services.

3) Higher than 99.999% Availability for Industry Production Control Systems to Enable Enterprises to Migrate All Systems to the Cloud

Traditional enterprise management and production systems are human-centric and built based on the ISA-95 pyramid model, such as enterprise resource planning (ERP), manufacturing execution system (MES), supervisory control and data acquisition (SCADA), and programmable logic controller (PLC) systems. As enterprises become intelligent, these systems will be built on human-thing collaboration, and we will see the wide adoption of a new flattened architecture for cloud, edge, things, and humans.

Currently, enterprises are primarily migrating their ERP and MES systems to the cloud, which do not have real-time requirements and require the availability of the cloud and network to be just 99.9%. By 2030, however, enterprises will be migrating all of their systems to the cloud, including systems that require higher than 99.9999% availability for the cloud and network (and edge), such as SCADA and PLC.

Moving forward, improving radio access network availability will be a major area of research. 5G can already meet the basic reliability requirements of URLLC scenarios such as ports and mines, in which availability has reached 99.99%. In the future, AI technologies will be introduced to improve the availability of mobile networks to 99.999% by better predicting channel fading characteristics, identifying envelope channel changes, increasing the number of URLLC connections supported by a single unit of spectrum, and enabling intelligent prediction, interference tracking, and E2E collaboration.

A data center is generally limited by the site scale and power supply, preventing computing hardware from being continuously expanded. Distributed training in collaboration with other data centers can effectively break computing bottlenecks, and will be the trend of computing development in the future. The reliability of network connections must reach 99.9999% or higher to ensure efficient and reliable model training and greatly reduce the time and cost caused by data transmission interruption or retransmission.

4) Ubiquitous Differentiated Experience Assurance

In the future, immersive communication, multi-modal communication, cloud gaming, and cloud phones will take off, gaining wide popularity. These services have additional requirements on bandwidth and latency, starkly different from those of common applications such as video and web. As such, an intelligent differentiated experience assurance mechanism is required to provide differentiated assurance based on user types, terminal types, application types, busy/idle hours, and scenarios/areas. This is necessary to meet network requirements of new applications while maximizing network efficiency.

3.2.3 AI-Native

1) ADN: Continuous Evolution Toward AN Level 4+

ADN is an advanced stage of network automation that aims to use an intelligent, simplified network architecture driven by data and knowledge in order to deploy a self-fulfilling, self-healing, self-optimizing, autonomous network. Such a network will be able to provide new services, deliver a superior user experience, implement fully automated O&M, and maximize resource and energy efficiency.

ADN is still in the development phase transiting from Level 2 to Level 3 and possesses partially and conditionally autonomous capabilities. These capabilities allow the system to achieve closed-loop O&M for certain units in particular external environments based on the AI telecom foundation model. ADN will evolve toward Level 4+, achieving closed-loop automation for a diverse range of services throughout the entire network lifecycle in a more complex cross-domain environment. (Table 8 ADN levels)

Table 8 ADN levels

Level	LO: Manual O&M	L1: Assisted O&M	L2: Partial Autonomy	L3: Conditional Autonomy	L4: High Autonomy	L5: Full Autonomy
Service	N/A	Single use case	Single use case	Multiple use cases	Multiple use cases	Any use cases
Execution	Manual	Manual/ Autonomous	Autonomous	Autonomous	Autonomous	Autonomous
Awareness	Manual	Manual	Manual/ Autonomous	Autonomous	Autonomous	Autonomous
Analysis/ Decision	Manual	Manual	Manual	Manual/ Autonomous	Autonomous	Autonomous
Intent/ Experience	Manual	Manual	Manual	Manual	Manual/ Autonomous	Autonomous

Reference: TMF 2020

To support the evolution of ADN toward Level 4+, we need to study the following key technologies:

The management and operation layer: This layer unifies data modeling to decouple data from functions and applications and ensures data consistency across layers. On this layer, the network's digital twin is built to analyze and manipulate the physical network through simulation. In this regard, research should focus on the following technologies:

- Objective-based adaptive decision-making architecture: The traditional function-oriented architecture must evolve toward a multi-objective decision-making architecture to offer system capabilities that are adaptable to complex and unpredictable environments. For instance, channel-, module-, device-, and network-level energy saving requires collaborative optimization algorithms with multiple objectives (including time, space, frequency, and power objectives). These algorithms must take both user throughput and overall energy saving performance into account. In the future, multi-objective optimization involving network and terminal energy saving needs to be achieved in addition to reassuring multi-user deterministic SLAs.

- Model-driven and data-driven hybrid architecture: The model-driven architecture requires detailed risk analysis and identification of harmful incidents in the design phase. Its advantages include being trustworthy, explainable, and applicable to critical tasks. The first step of the evolution toward ADN is machines using situational awareness and adaptive decision-making capabilities in the data architecture to replace humans in complex and uncertain scenarios. However, this high-performance architecture has suboptimal explainability, relies on the training sample space, and cannot be easily generalized for different NEs or scenarios.

- Semantics-based intent: In ADN, autonomous systems interact with each other through intent-based interfaces in a simplified manner, and differentiated internal implementation processes are shielded from the outside, which enables an out-of-the-box feature. Autonomous systems are decoupled from each other by focusing only on achieving the objectives, regardless of the implementation methods. There are four types of intent: user intent, business intent, service intent, and resource intent.

- Network digital twin: In terms of data awareness, research on high-performance networks should strive for near-zero-error measurement. At the modeling and prediction layer, a high-precision approximate simulation model needs to be constructed for research on how to provide high-performance, SLA-supported simulation that has theoretical guarantee based on network calculus and queuing theory. In terms of control management, the issues of resource allocation and optimization of giant network systems need to be resolved by exploring the theory of fast and slow control structure.

In addition to the advancement of software systems, building Level 4/Level 5 capabilities into ADN also requires that network architecture, protocols, equipment, sites, and deployment solutions be simplified, so as to offset the complexity of network connectivity with a simplified architecture.

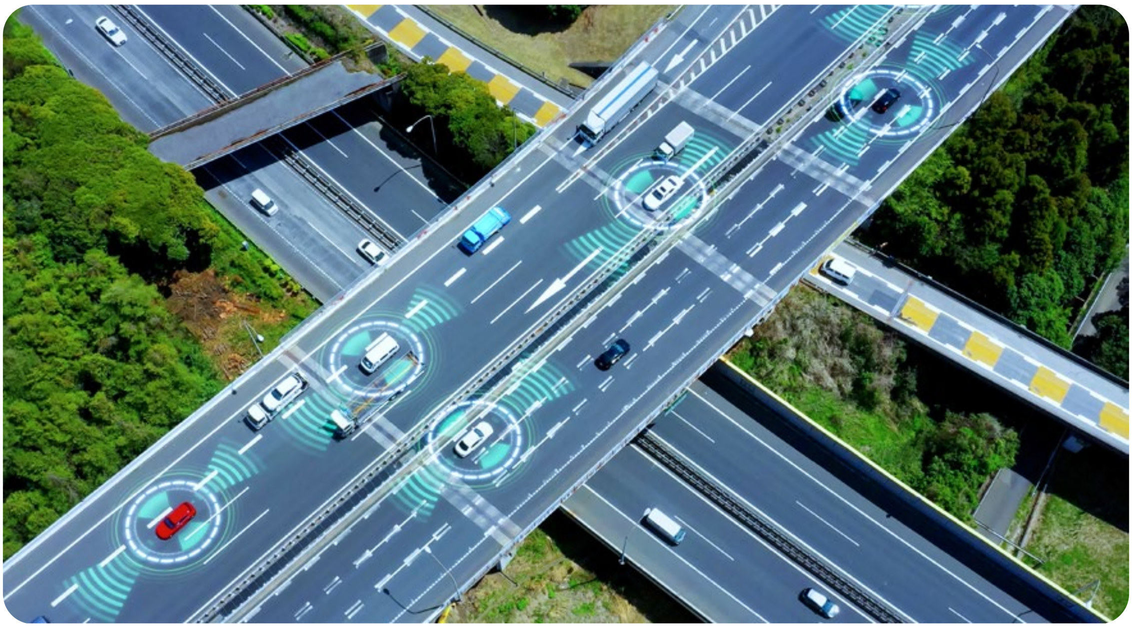
2) AI-Native Edge: Reconstructing the Intelligent Edge with Cloud Native and AI Technologies

Within the architecture of the communications network of 2030, the cloud core network will build an AI-native edge by combining the flexibility and openness afforded by a cloud-native architecture and the service-aware capabilities of AI.

The AI-native edge needs to support AI-based service awareness capabilities. Networks for individual consumers will provide efficient encoding and decoding, optimized transmission, experience assurance, and coordinated scheduling capabilities for full-sensing, holographic communications services. In addition, such networks will provide terminals with computing power offloading for foundation model applications. Private networks for industries can enhance the scheduling framework, and provide service assurance for various industries based on deterministic operating systems. For example, during machine vision processing, the Multi-access Edge Computing (MEC)-based 5G to Business (5GtoB) + AI inference service uses the AI-powered image feature recognition function on the edge to reduce the bandwidth requirements of the backbone network and improve real-time service performance.

The AI-native edge needs to support mesh interconnection and horizontal computing power scheduling. As networks connect to multi-level computing power resource pools, they should be able to sense various resources in order to use computing power efficiently.

To develop computing power awareness, the first thing to do is explore how to measure and model



the computing power requirements of AI services. There are various types of computing chips on a computing power network, such as CPUs, GPUs, application-specific integrated circuits (ASICs), TPUs, and NPUs. The computing power of each type of chips needs to be accurately measured in order to identify the service types to which they can be applied.

Second, computing nodes of a computing power network need to send their computing power resource information, computing power service information, and location information to network nodes. To enable the network to sense multi-dimensional resources and services such as computing power and storage, new computing power routing control and forwarding technologies need to be developed. These could include IPv6 Enhanced-based computing power status advertising, computing power requirement awareness, and computing power routing and forwarding.

Third, in addition to being able to sense computing power, networks should also be able to flexibly adapt to different IoT device scenarios. Huawei predicts that IPv6 adoption must exceed 90% by 2030 to ensure all things that can be connected are connected. It is thus necessary to develop innovative technologies for hierarchical IPv6 address architecture and ultra-large-scale high-speed addressing and forwarding. These technologies should be compatible with both traditional IP networks and lightweight protocols, so as to ensure the global accessibility of data and computing.

As smart home and enterprise advance rapidly, the extension of new capabilities such as sensing, storage, computing, and control based on the FTTR connectivity foundation and AI needs to be continuously studied to further improve users' smart home experiences. For example, AI-based whole-house Wi-Fi optimization, natural language search of photos using FTTR+NAS, family album, voice recognition, and semantic understanding are implemented.

3.2.4 HCS: A New Area Emerging from Communications Technologies

From 1G to 5G, communications and sensing have been independent of each other. For example, a 4G communications system is only responsible for communications, and a radar system is only responsible for functions such as speed measurement, sensing, and imaging. This separation wastes wireless spectrum and hardware resources, and the separation of functions often results in high latency for information processing.

As we approach the 5G-A or 6G era, the communications spectrum will expand to include millimeter wave, terahertz, and visible light. This means the communications spectrum will soon overlap with the spectrum previously reserved for sensing systems. HCS facilitates unified scheduling of communications and sensing resources. Technically, HCS can be broken down into the following three types:

1) Wireless Sensing

HCS is one of the three new use cases proposed for 5G-A, particularly in scenarios such as connected vehicles and drones. With Release 16, precise positioning functionality can already achieve meter-level accuracy for commercial use cases, and future releases are expected to hone this accuracy further, to the centimeter level. As wireless networks move toward higher frequency bands, such as millimeter wave and terahertz, HCS will be applied in areas such as smart cities, weather forecasts, environmental monitoring, and medical imaging.

Wireless HCS technology is still in its infancy and more research is needed to develop foundational theories such as optimal compromise. More research needs to be devoted to electromagnetic wave propagation in complex channel environments; spatial target reflection, scattering, and diffraction modeling; and spatial sparsity sensing modeling. Work needs to be done to improve the performance and energy efficiency of radio frequency (RF) chips and components. There is also a need for further research into extremely large antenna array (ELAA) structure, and efficient distributed cooperative sensing algorithms such as active radar illumination, environmental electromagnetic control, multi-point cooperative transmitting and receiving, target imaging, scene reconstruction, and channel inversion.

2) Wi-Fi Sensing

IEEE 802.11bf defines Wi-Fi sensing standards applicable to indoor, outdoor, in-vehicle, warehouse, and freight yard scenarios, among others. It covers functionalities such as high-precision positioning, posture and gesture recognition, breath detection, emotion recognition, and perimeter security. Moving forward, more research needs to be directed at both the PHY layer (i.e., new signals, waveforms, and sequences) and the MAC layer (e.g., compromise between measurement result feedback and sensing precision for sensing scenarios based on channel state information [CSI] or signal-to-noise ratio [SNR]). Synchronization and coordination between nodes for single-, dual-, and multi-station radar systems is another problem to address. The last issue concerns collaborative sensing across multiple protocols, including 802.11az, 802.11be, and 802.11ay.

3) Optical Sensing

Optical sensing can be divided into fiber-based sensing and laser radar ("lidar") sensing. Fiber-based sensing is more often seen in energy, electricity, government, and transportation sectors where it is used to sense changes in temperature, vibration, and stress to inform fire monitoring and warning, equipment and pipeline fault diagnoses, and environmental and facility stress monitoring. Lidar sensing is more commonly seen in homes and vehicles, providing functions such as spatial environmental sensing, high-precision positioning, and posture or gesture recognition. Currently, fiber-based sensing tends to have a high false alarm rate in complex environments. More research should be directed at reducing the false alarm rate by introducing AI and big data analytics. For lidar sensing, the 3D panoramic modeling algorithm technology needs to be improved to enable multi-radar coordinate system registration based on lidar sensing data.

Huawei predicts that by 2030, gigabit and higher-speed Wi-Fi networks will reach a penetration rate in global enterprises of 98% (84% for 10-gigabit and higher). In addition, the penetration of 5G private networks in medium/large enterprises will reach 35%. While providing broadband services for enterprises, communications networks will use HCS capabilities to gather static information (e.g., spatial environments, communications blind spots, and obstacles) and dynamic information (e.g., positions, motion tracks, postures, and gestures of people, and the movement of vehicles and objects) to perform data modeling. Coupled with simulation technologies based on the idea of digital twins, the data can help identify and predict changes, empowering numerous industries. HCS represents a new frontier of communications technologies and has huge development potential.

3.2.5 Security and Trustworthiness: A Six-Layer Framework for a New Security Foundation

The networks of the future are on course to be varied, diverse, ubiquitous, and cloud-based, and ToB and ToC services are likely to be converged. These trends will increase network exposure to attacks and further blur traditional network security boundaries. Reactive defense measures such as border isolation and add-on security capabilities will prove insufficient in the face of constantly evolving network attack methods. Therefore, the network security systems of the future must be capable of native, secure, trustworthy, intelligent, and flexible proactive defense.

Security and trustworthiness cover six layers: trustworthiness of components (chips and operating systems), equipment security, connectivity security, management security, federated trustworthiness, and data trustworthiness. Equipment security, connectivity security, and management security fall under network security, while component trustworthiness, data trustworthiness, and federated trustworthiness fall in the trustworthiness realm. The two focus on different aspects but interact in many ways. Ensuring security and trustworthiness requires systemic efforts, involving hierarchical security and trustworthiness technologies such as cross-platform trustworthiness operating systems and chips, endogenous network security, cloud security "brain", multi-intelligent-twin and cross-domain trustworthiness federation, and differential data privacy processing. (Figure 7 Six-layer network security and trustworthiness framework)

1) Component Trustworthiness

Credible data sources are the basis for security and trustworthiness. The Trusted Execution Environment (TEE) at the component (chip and operating system) level is a widely recognized and used solution. Moving forward, chip-level trustworthiness computing technologies will be introduced to network elements (NEs). This will help build a secure and trustworthy running environment for software and hardware based on the underlying NEs, thereby enabling level-by-level verification of chips, operating systems, and applications to ensure data authenticity.

2) Equipment and Connectivity Security

Communications protocols and network equipment can be modified to embed trustworthiness identifiers and password credentials in IPv6 packet headers. Network equipment can verify the authenticity and legitimacy of requests based on

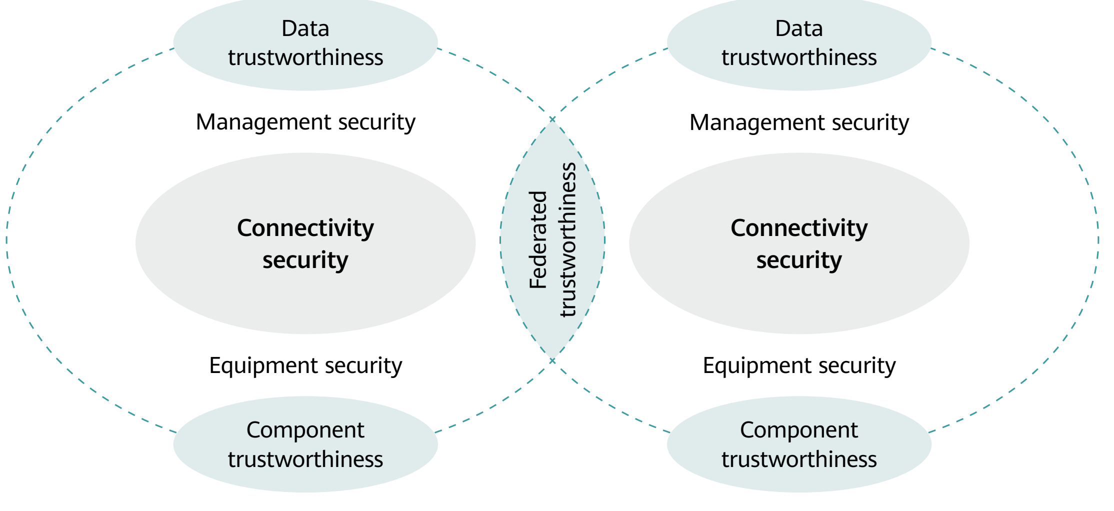


Figure 7 Six-layer network security and trustworthiness framework

identifier authentication, preventing identity theft and spoofing and building fine-grained access authentication and source tracing capabilities.

3) Management Security

First, future networks need to adopt a service-based security architecture that integrates cloud, network, and security, so that security functionalities are provided as components and microservices, and can be centrally orchestrated and agilely deployed. Second, as the user base grows and complexity increases, security policies are growing exponentially to the point where the conventional manual approach to planning and management can no longer keep up. More research is needed on traffic and service self-learning and modeling technologies, model-driven risk prediction and security policy orchestration technologies, and security policy conflict detection and automatic optimization technologies.

4) Federated Trustworthiness

To meet the security and trustworthiness requirements across networks and clouds, blockchain technology will be used to build a trustworthy service system for basic digital resources (including connectivity and computing) for future networks. Distributed accounting, consensus mechanisms, and decentralized key allocation will help ensure the authenticity of resource ownership and mapping relationships and prevent anonymous tampering, illegal hijacking, and other security and trustworthiness issues. The centralized trust model of today's mobile communications network infrastructure results in problems such as excessive permissions of central nodes and single-point authority failures. This kind of infrastructure may pose risks to network security, reliability, and equality, and is not up to the task of serving as a secure and trustworthy foundation for the networks of tomorrow. The infrastructure of next-generation networks must be decentralized, transparent, and auditable, and support trusted identity management.

5) Data Trustworthiness

Networks process user data at user access nodes and service-aware nodes. Therefore, user data passing through the network must be made opaque to the network, so as to ensure user information security. Research should go into technologies that enhance encrypted transmission of user IDs and communications data, as well as pseudonymization and homomorphic encryption technologies that make user information fully invisible to the network.

With the development of quantum technologies, new quantum algorithms that compromise the security of the public key cryptosystem are very likely to emerge with future networks. Quantum computers search for and decompose things much faster than classical computers. A quantum computing breakthrough could render all existing public key cryptographic algorithms useless. Even increasing the parameter length would offer little defense in a post-quantum world. Therefore, networks will need to introduce post-quantum cryptographic algorithms to defend against quantum attacks. Similarly, quantum computers will also reduce the security of symmetric cryptographic algorithms. Symmetric cryptographic algorithms will need to be hardened to support the encryption and decryption of data when throughput and concurrency are high.

3.2.6 Green and Low-carbon

The escalating global energy crisis and climate crisis are driving the demand for low-carbon development around the world.

Several leading operators in Europe have set themselves the clear goal of reducing their carbon emissions by 45% to 55% by 2030, compared with 2020 levels. They have also raised specific requirements for their equipment suppliers to reduce carbon emissions at the organization and product levels. Equipment vendors can meet these requirements and help operators achieve low-carbon goals by moving toward simplified architecture, optoelectronic integration, and system energy saving and multi-dimensional energy efficiency.

1) Simplified Architecture: Low Carbon Realized by Simplifying Foundation, Cloud, and Computing Networks

Traditional networks are divided by technical specialty, resulting in the fragmentation of O&M services. This model is increasingly difficult to adapt to the development of automated and intelligent networks. In the future, networks need to be reconstructed based on the nature of the services they carry, building a simplified three-layer network architecture consisting of foundation, cloud, and computing networks.

The foundation network is used for connectivity at the equipment port level. It adopts an IP+optical simplified architecture and provides end-to-end networks covering access (wired/wireless), bearer, and core layers, based on the 100% fiber-to-site optical foundation that supports optical cross-connect (OXC) or ROADM. The foundation network provides high-bandwidth, low-latency, and high-reliability broadband services. It also enables green, low-carbon networks based on all-in-one full-spectrum antennas, Wi-Fi 7/Wi-Fi 8 10-gigabit campus networks, intelligent bearer network with high transmission capacity, fully converged core networks, simplified protocols, and simplified O&M.

The cloud network is used for connectivity between the cloud and devices at the tenant level, and is overlaid on the foundation network using E2E slicing technology. It enables agile and open virtual networks that provide SLA assurance, and uses a network for multiple purposes to increase network utilization and save network energy.

The computing network is used for connecting data and computing power at the service level and providing computing power routing services and trustworthiness assurance for data processing. It is constructed based on distributed and open protocols. Through flexible scheduling of data, the computing network enables green, centralized multi-level computing power infrastructure that has a reasonable layout. Hyper-converged Ethernet is used in data centers. Some ultra-large-scale intelligent computing centers evolve to all-optical switching+hyper-converged Ethernet, while IP+ all-optical switching is used between data centers.

The three networks are interdependent. The computing network depends on the cloud network to enable agile building of virtual pipes and open interfaces that can be provisioned on demand, so as to provide real-time, elastic connections between data and computing power. The computing network also needs the support of the foundation network to enable its most important features: low latency and high bandwidth.

2) Optoelectronic Integration: Profoundly Changing the Architecture and Energy Efficiency of Communications Network Equipment

In the communications network industry, optical technologies have traditionally been relatively independent from other specialized technologies such as wireless communications and datacom. However, as networks develop toward higher bitrates, higher frequencies, and greater energy efficiency, traditional electronic technologies will soon encounter sustainable development bottlenecks, such as in distance and power consumption. The solution to this is optoelectronic integration.

In the next decade, the development of new products, such as optical input/output chips and CPO, will improve electronic components' high-speed processing capabilities and reduce their power consumption. Coherent optical technologies will be applied to extend the transmission distance of high-speed ports on datacom equipment. New types of antennas that directly connect to optical fibers will be used to reduce the weight and power consumption of base stations. Microwave communications will be superseded by laser communications to support high-speed data transmission between LEO satellites. To meet the communications requirements of underwater mobile devices, wireless coverage will be replaced by visible light which achieves higher penetration than radio waves. Due to its higher transmittance, far infrared light technology will be used to detect brain waves more accurately.

Optoelectronic integration is the way forward for structured improvement of equipment energy efficiency. CPO chips based on optical buses are expected to be in commercial use by 2025. Some academic institutions are researching optical cell switching technology that could potentially replace electrical switching networks. Equipment-level optoelectronic integrated products using optical buses and optical cell switching technology are expected to be developed by 2030. Further into the future, chip-level products that combine optical computing, optical random access memory (RAM) cores, and general-purpose computing cores will also emerge.

Optoelectronic integration technology at the network, equipment, and chip levels can continuously improve the energy efficiency of communications equipment, and meet the green network objective of increasing network capacity without increasing energy consumption.

3) System Energy Saving and Multi-dimensional Energy Efficiency: Building Energy-Efficient High-Performance Networks

Energy efficiency has always been crucial to high-quality network construction. As networks evolve, service scenarios are becoming more complex and service types are diversifying, necessitating scenario-specific energy saving strategies and differentiated service assurance. Meanwhile, networks and equipment systems are also becoming increasingly complex, driving the need for a highly energy-efficient E2E system that covers everything from software to hardware, from main equipment to auxiliary devices, and from single-point optimization to overall optimization. Such a system would be expected to improve energy efficiency from three perspectives: energy flow, service flow, and control flow.

Energy flow: By reducing energy losses throughout the energy chain from supply to transmission to use, energy efficiency can be significantly improved. Energy supply efficiency can be improved by optimizing power supply architecture (such as adopting a modular power supply architecture) and simplifying the topology. Line transmission losses can be reduced by decreasing the types of voltages and the number of voltage conversion classes. Energy utilization efficiency of loads can be boosted through partitioned power supply and dynamic shutdown. In addition to iteratively optimizing the conversion efficiency of each individual link, the overall conversion efficiency of the energy chain can be maximized through cross-link collaboration.

Service flow: Resources will need to be accurately allocated on demand and elastically scaled in real time based on the mapping between services, resources, and energy consumption. This is essential to meet the experience assurance requirements of a diverse range of services and adapt to the dynamic changes of services in time and space. In addition, the depth, speed, precision, and flexibility of equipment shutdown will need to be improved to approach the goal of "0 Bit 0 Watt".

Control flow: A complete energy efficiency optimization, control, and evaluation mechanism is required for dealing with dynamically-changing complex systems. By implementing hierarchical autonomy at the network, site, equipment, and chip levels, we can improve the energy efficiency of each level. We can also maximize the energy efficiency of an entire system through cross-layer collaboration such as software-hardware synergy and device-pipe-chip synergy, as well as vertical integration. Any evaluation of efficiency needs to take into account both service volume (such as traffic and coverage area) and service quality (such as user-perceived speed, latency, and reliability). To strike a balance among service volume, service quality, and energy consumption, we need to develop intelligent multi-objective comprehensive optimization capabilities at the network and equipment levels. These capabilities are important for building energy-efficient high-performance networks.

3.3 Summary and Technology Outlook

By 2030, we will be living in a multi-network and multi-cloud world. Billions of people and hundreds of billions of things will be connected to an intelligent world of hyperreal experiences where multiple clouds coexist, including public, industry, and telecom clouds. Connections will be supported by cubic networks consisting of 10-gigabit personalized home networks, high-quality 10-gigabit campus networks, 10-gigabit individual networks, and global satellite networks.

In future communications networks, energy efficiency will be continuously improved through optoelectronic integration at the network, equipment, and chip levels in the foundation network. The cloud network will use E2E virtual slicing to connect the breakpoints of specialized networks on top of the foundation network, so as to provide differentiated capabilities guaranteed by SLAs for different tenants. The computing network will provide high dynamic connectivity between data and computing power through innovation in IP network protocols, meeting the requirements of intelligent services. Green, low-carbon networks will be enabled by a three-layer simplified network architecture and three-layer optoelectronic integration.

Future communications networks will support deterministic service experiences critical to the intelligent transformation of industries. Users will be connected to multi-level computing resources: 1 ms latency will be guaranteed for data transmission within cities, 5 ms latency within city clusters, and 20 ms latency through backbone networks. The networks will also provide greater than 99.999% availability, and develop secure, trustworthy network capabilities to support the migration of all systems to the cloud across industries.

Future communications networks will support AI-native. By combining NE status data with AI and innovating in algorithms, the networks will approach the theoretical limit and turn non-determinism into determinism, improving network performance. With the combination of network O&M data and AI, big data analytics, and closed-loop optimization, the networks' automation and all-scenario service capabilities will be comprehensively improved. With the AI-native edge, the networks will also be able to sense diversified service requirements of various industries, thereby improving service experiences.

Future communications networks will support HCS. Wireless, optical, and other multimodal sensing technologies will allow networks to collect environmental data and combine it with digital twin technology to provide industries with the brand-new service capabilities enabled by HCS.

Over 20 years ago, IP technology started reshaping the forwarding architecture of communications networks. Over 10 years ago, cloud technology began to profoundly influence the network management control architecture. Over the next 10 years, AI will be embedded into all layers of the network architecture, driving the networks to evolve toward advanced intelligent twins. To support the development of intelligent networks in the future, networks' computing capabilities will be enhanced, and optoelectronic integration will be adopted to enable green, low-carbon communications networks.

In conclusion, the architecture of the communications network of 2030 will evolve towards cubic broadband networks, deterministic experience, AI-native, HCS, security and trustworthiness, and green and low-carbon networks.

04

Recommendations

William Gibson, famous science fiction novelist and author of Neuromancer, once said, "The future is already here. It's just not evenly distributed yet." AR, the key technology for integrating the virtual and real worlds, was invented by the Royal Navy 60 years ago, and used for the sighting devices of fighter aircraft. Later, MIT established in the 1980s the Media Lab, which is dedicated to changing the way humans interact with computers and delivering personalized digital experiences.

Communications technology and computing technology share the same origin. Less than five years after IBM launched its first personal computer in 1981, the world's first router was invented. Compared with computers, the main distinguishing features of communications equipment are enhanced optical and wireless functions, and network protocol interfaces.

Cloud, AI, and optical, the three key technologies influencing the development of future communications networks, are also reshaping the computing industry. While we may be more familiar with cloud and AI, optical technologies have also been profoundly influencing the computing industry over the past decade. Currently, the industry is focusing on two research areas of optical computing. One is replacing electronic components with optical components to develop optoelectronic integrated computers. The other is using optical parallel processing to build an optical neural network which will increase computing power by 100 times while consuming very little power. The

application of optical technologies in computing will also play a part in realizing a green, low-carbon network architecture.

Currently, we cannot find an accurate keyword to represent the target network. 6G/F6G/Net6G may be the keyword based on the improvement of network capabilities from ubiquitous gigabit networks to 10-gigabit cubic networks (5G-A/F5G-A/Net5.5G). Industrial Internet may be the keyword based on the shift of network application scenarios from consumer Internet to industrial Internet. At the same time, computing power network may be the keyword based on the shift in the nature of services from human-oriented cognition to machine-oriented cognition that supports massive amounts of user data and multi-level computing power services.

In addition, optical network may be the keyword based on the evolution of the underlying technology from electronic technologies to optical technologies. The cognitive network or digital twin network may be the keyword based on the improvement of network intelligence from L3 to L4+ ADN.

The next decade in communications networks will open up huge space for imagination while also bringing an abundance of uncertainties. All players in the industry need to work together to explore new technology directions and jointly make the vision for the communications network of 2030 a reality.

Appendix A: Acronyms and Abbreviations

Abbreviation/Acronym	Full Spelling
3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
5G SA	5G Standalone
5GtoB	5G to Business
ADS	Advanced Driving System
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AMR	Automated Mobile Robot
ADN	Autonomous Driving Network
AN	Autonomous Networks
API	Application Programming Interface
AR	Augmented Reality
B2B	Business to Business
CAICT	China Academy of Information and Communications Technology
CCSA	China Communications Standards Association
CPO	Co-Packaged Optics
CPU	Central Processing Unit
CRUD	Create, Read, Update, Delete
CSI/SNR	Channel State Information/Signal-to-Noise Ratio
DCNN	Deep Convolutional Neural Network
DetNet	Deterministic Networking
E2E	End to End
ERP	Enterprise Resource Planning
ELAA	Extremely Large Antenna Array
ELAA-MM	Extremely Large Antenna Array-Massive MIMO

Abbreviation/Acronym	Full Spelling
F5G	5th Generation Fixed Network
FDMA	Frequency Division Multiple Access
fgOTN	Fine-grain OTN
FlexE	Flexible Ethernet
FOV	Field Of View
FPS	Frames Per Second
FR1/FR2	Frequency Range_1/Frequency Range_2
FSD	Full Self-Driving
FTTR	Fiber To The Room
FSA	Flexible Spectrum Access
GenAI	Generative AI
GPU	Graphical Processing Unit
GSMA	GSM Association
HCS	Harmonized Communication and Sensing
HBF	Hybrid Beamforming
IMT	International Mobile Telecommunications
IETF	Internet Engineering Task Force
IFIT	In-situ Flow Information Telemetry
IoT	Internet of Things
ISA-95	International Society of Automation 95
ISAC	Integrated Sensing and Communication
ITU-T	International Telecommunication Union-Telecommunication Standardization Sector
LEO	Low-Earth Orbit
MAC	Media Access Control
Massive MIMO	Massive Multiple-Input Multiple-Output
MEC	Multi-access Edge Computing
MES	Manufacturing Execution System

Abbreviation/Acronym	Full Spelling
MIIT	Ministry of Industry and Information Technology
MR	Mixed Reality
MTP	Motion-to-Photon
MBSC	Multi-Band Serving Cell
NPU	Neural Processing Unit
NSB	US National Science Board
NSMF	Network Slice Management Function
NSSMF	Network Slice Subnet Management Function
NTN	Non-terrestrial Network
ONT	Optical Network Terminal
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PLC	Programmable Logic Controller
RDMA	Remote Direct Memory Access
PON	Passive Optical Network
PPD	Pixel Per Degree
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
OXC	Optical Cross-Connect
O2I	Outdoor-to-Indoor
RAM	Random Access Memory
RB	Resource Block
RLC	Radio Link Control
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RTT	Round-Trip Time

Abbreviation/Acronym	Full Spelling
RF	Radio Frequency
SCADA	Supervisory Control And Data Acquisition
SDM	Spatial Division Multiplexing
SLA	Service Level Agreement
SLM	Spatial Light Modulator
SDL	Supplemental Downlink
SUL	Super Uplink
TDM	Time Division Multiplexing
TSN	Time Sensitive Networking
TTM	Time to Market
TVR	Time-Variant Routing
URLLC	Ultra-Reliable Low-Latency Communication
U6G	Upper 6 GHz
VR	Virtual Reality
WDM	Wavelength Division Multiplexing
WAN	Wide Area Network
Wi-Fi 6	Wireless Fidelity 6
WLAN	Wireless Local Area Network
XR	eXtended Reality

Appendix B: Notes on Version Updates in 2024

Huawei makes continuous efforts to explore the intelligent world through in-depth exchanges with renowned scholars, valued customers, and key partners in the industry. The intelligent world is rapidly evolving, with new technologies and scenarios emerging faster than ever, leading to dramatic changes in industry-related parameters. In response, Huawei systematically updated its *Communications Network 2030* released in 2021 to envision the scenarios and trends in 2030 and adjust related forecast data.

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