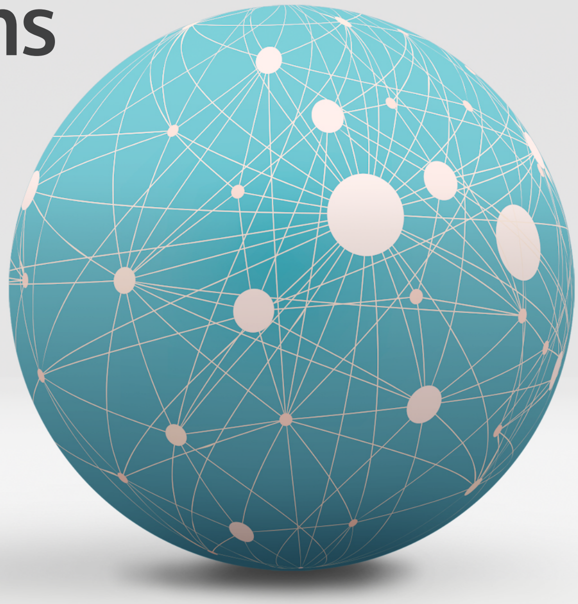
Communications Network 2030



Building a Fully Connected,
Intelligent World

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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 services, big data, and Artificial Intelligence (AI), and more than 90% of European 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 data, software, computing, and networking capabilities over the next decade in order to help maintain the US's competitiveness in the digital economy.

The intelligent development of industries first requires companies to upgrade their networks. In its Industrial Internet Innovation and Development Action Plan (2021–2023), the Chinese government put 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 Digitising 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.

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

A survey conducted by GSMA shows that B2B, cloud, and IoT services that target industry, finance, health, energy, and agriculture will be the most promising areas for carriers worldwide to fully unleash the potential of their connectivity portfolios.

In the world of 2030, many amazing things that we can only dream of today will be a reality.

With highly sensitive biosensors and intelligent hardware connected through broadband networks, we can obtain and track the indicators of our physical health in real time, and securely store massive amounts of health data in the cloud. This will allow us to proactively manage our own health and reduce our dependence on doctors, thus 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, so networks must become more intelligent. Over the next decade, how can we innovate

in software technology to 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 and self-driving vehicles 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.

Future Network Use Cases

Since Samuel Morse invented the electric telegraph in 1837, communications networks have come a long way, moving from connecting individuals and homes to connecting organizations. 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, to connect multiple perception, display, and computing resources 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 5.5G/6G, from F5G to F5.5G/F6G, and from IPv4/Multiprotocol Label Switching (MPLS) to IPv6+, and the autonomous driving network will evolve from L2 to L5. In addition, new use cases will continue to emerge.

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.,

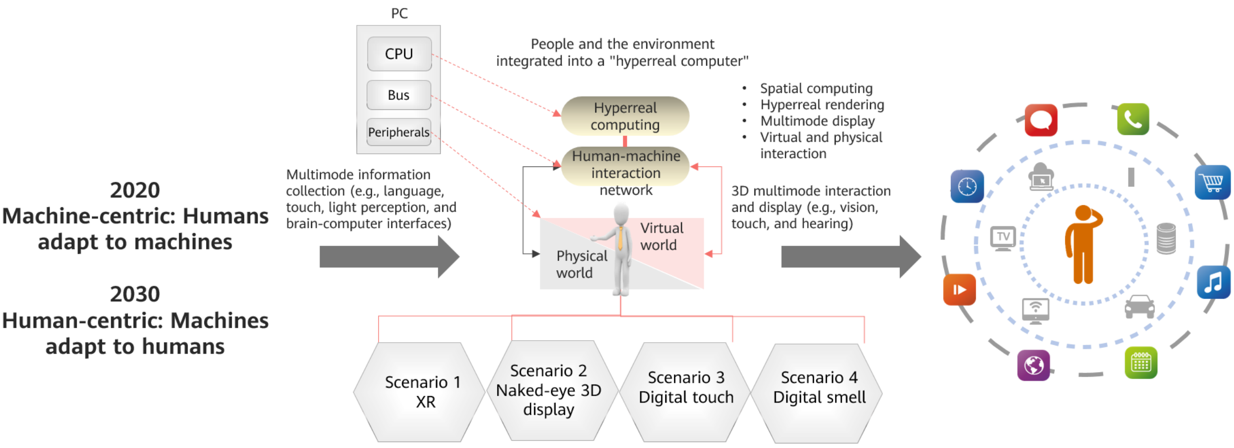
smart screens, smart home appliances, intelligent vehicles, and smart exoskeletons) will be able to understand natural language, gestures, and eye movement, and even read human brain waves, enabling more intuitive integration between the virtual and physical worlds and bringing a hyperreal sensory experience to human-machine interaction. (Figure 1 Hyperreal human-machine interaction experience)

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, and digital smell.

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

Figure 1 Hyperreal human-machine interaction experience



(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 more portable AR-enabled contact lenses, which are expected to go to market in about two years. With the wide adoption of 5G, 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)

Currently, XR is still at the stage of partial immersion. Today, a typical XR experience involves 2K monocular resolution, 100°–120°

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° 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	

FOV, 100 Mbit/s bitrate, and 20 ms motion-to-photon (MTP) latency. If all content is rendered in the cloud, 20 ms of MTP latency is the threshold above which users start to report feelings of dizziness.

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. If all rendering is still conducted in the cloud, MTP latency will need to be kept below 5 ms. If technology is developed to support the local rendering of environment-related content that could easily make users dizzy, the latency will be specifically linked to the types of content. For content that requires only weak interaction (such as a streamed video), 20 ms of MTP latency is acceptable. For content that requires strong interaction like games, less than 5 ms MTP latency will be needed.

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

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 large-scale adoption would require real-time capturing of user location and dynamic adjustment.

Table 2 Network requirements of naked-eye 3D display

Technical System	Technical Index	Lenslets (2021–2025)	SLMs (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 for objects with a size of 10 x 10 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

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)

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 are already showcasing their 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 gigabit-level 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 cm2. 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.

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)

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,

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	2 Mbit/s
	Avatar-User	Video	99.999%	10–20	1–100 Mbit/s
		Audio	99.9%	10–20	512 Kbit/s
		Tactile feedback	99.999%	1–10	20 Mbit/s (100 DOFs)
Hyerfine interaction	Avatar-User	Tactile feedback	99.999%	1–10	1–10 Gbit/s (Electronic skin)
Active cognitive capability: The network layer also needs to support services such as dynamic performance monitoring, task awareness, and 3D mapping.					

Reference: IEEE 1981.1 Tactile Internet

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.

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.

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

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, 3D display, and holograms will all be used both at home and in cars. 8K and 16K smart screens will be gradually adopted at home and MR will be widely used in cars.

With 5G, F5G, and Wi-Fi 6, mobile and fixed broadband basically enters the 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 4 Network requirements for delivering a consistent experience at home, in the office, and on the go)

Over the next decade, common home and office services will include smart screens, multi-screen collaboration, 3D, holographic teaching, and XR. As true-to-life holographic meetings will not be widely adopted by 2030, the mainstream broadband requirements of home and office services will stand at 1 to 10 Gbit/s of bandwidth and less than 5 ms of 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.

Services like multi-screen collaboration, 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

Table 4 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%

availability greater than 99.999% and positioning precision of 10 cm.

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.

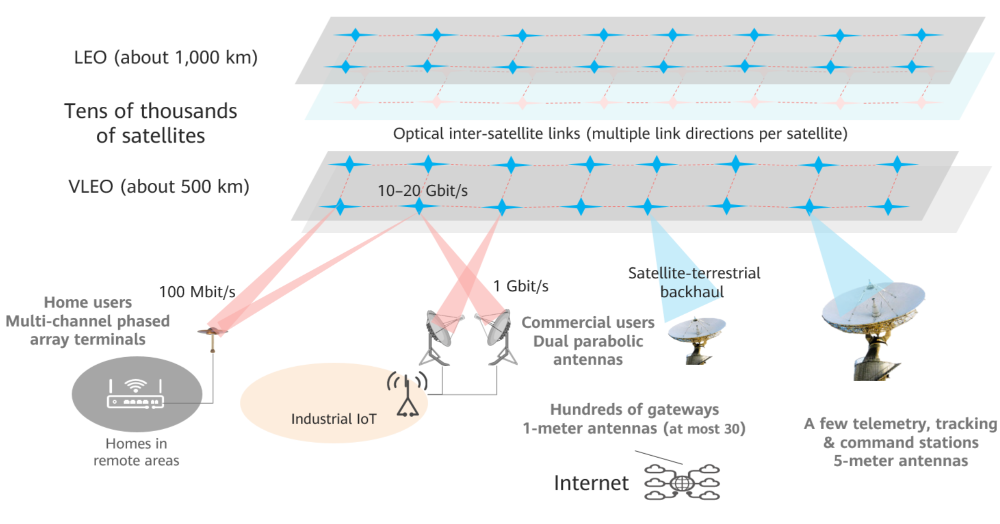
Satellite Broadband Internet: Continuous Broadband Coverage from Ground to Air

Over the next 10 years, connected drones will be more widely adopted, helping create new markets worth tens of billions of US dollars. We will see an increase in intra-city passenger transport in the skies above our cities, supported by tens of thousands of low-earth orbit (LEO) broadband satellites. Satellite broadband will be commercially available on a large scale, which will help turn space tourism and deep-sea exploration into popular leisure activities. Broadband will become an indispensable part of our life; the increased diversification of our leisure activities and the growing demand for unmanned operations in intelligent industry and agriculture mean that broadband will be needed everywhere, from land to sea and sky. A comprehensive broadband network from ground to air will deliver new experiences to people and power the full intelligent transformation of industries. (Figure 2 Satellite broadband network)

Due to spectrum resource constraints and communications disruptions, the actual peak capacity of a single LEO satellite is about 10–20 Gbit/s. Suppose a global satellite network is supported by 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. The actual effective capacity of the satellite network will be around 100 Tbit/s, considering at least half of the areas passed over by satellites are areas where demand for broadband is minimal (e.g., seas and deserts). Outside of areas covered by cellular networks, satellite broadband providers can use multi-channel phased array antennas to deliver hundred-megabit broadband to consumers and use dual parabolic antennas to deliver gigabit broadband to enterprise customers. They could also transmit data over optical inter-satellite links to hundreds of gateways around the world where they can connect to the Internet. Such a satellite network would be equivalent to a quasi-4G network, providing three-dimensional global coverage and latency of less than 100 ms.

Currently, terminal antennas for LEO satellite

Figure 2 Satellite broadband network



broadband are large, meaning they are ill-suited to mobile scenarios for individuals. Current satellite broadband networks mostly serve homes in remote areas, enterprises, and ships. Some carriers have combined satellite broadband, which is used for backhaul, with cellular networks and WLAN networks on the ground to provide both broadband and narrowband coverage for villages or enterprises in remote areas. With wider adoption of satellite broadband, we may see it applied to mobile scenarios (terminals) such as connected cars and small personal devices. Satellite broadband will deliver a seamless, continuous broadband experience beyond home Wi-Fi and urban cellular networks, meeting the network requirements of people and things.

Industrial Internet: A New Type of Network for Intelligent Manufacturing and Human-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. An 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 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 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.

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 billions of connected devices will include not only pressure, photoelectric, and temperature and humidity sensors, but also a large number of intelligent cameras, intelligent cars, drones, and robots. 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+, and industrial optical networks, allowing companies 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 5 Network requirements of intelligent enterprises)

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 100 ms. In addition, it will be necessary to ensure the security and trustworthiness of industrial networks.

Computing Power Network: Orienting Towards Machine Cognition and Connecting 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

Table 5 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	Visualized	Manageable	Operable
Smart healthcare	16K remote diagnosis	10					1 Gbit/s										
	Monitoring & nursing	2K															
	Holographic remote surgery	5					10 Gbit/s										
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 End-to-end Network Slicing

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.

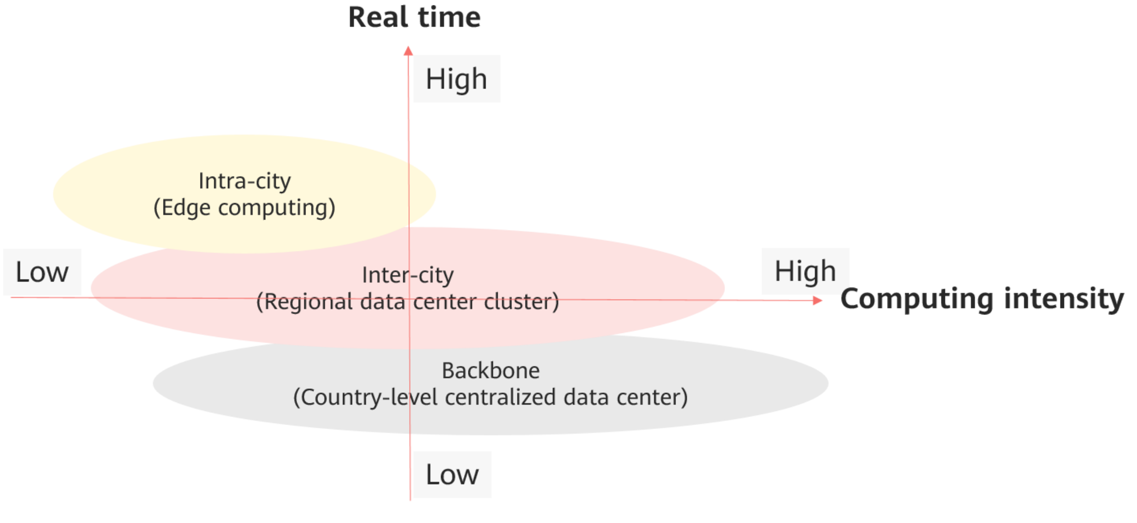
- Supporting the storage and sharing of data among communications and computing nodes in the network.
- Supporting precision time and geolocation stamping.
- Providing strong protections for data security, privacy, and integrity.
- Providing a data brokerage between IP and non-IP nodes, with the data brokerage being accessible through multiple networks.

As the miniaturization of chips approaches its physical limits, the computing industry can no longer rely on Moore's law for rapid development. Economic bottlenecks are encountered when manufacturing CPUs with more than 128 cores in smart devices. 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. Machine cognition requires a new type of network in which data analytics and processing can be performed on the edge, and not all data needs to be transmitted 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 100 ms, data may be sent to a centralized data center. In use cases with lower latency tolerance (from 10 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 cognition to focusing on machine cognition.

Figure 3 Three levels of computing resources for machine data services



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, 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.

Cognitive Network: Evolution Towards Advanced Levels of Intelligence

In the academic community, technological advances are often personified to help us understand them more easily. In 1877, German philosopher Ernst Kapp first put forward the concept and theory that "tools and instruments produced by human hands conform to already existing organic structures" in the Elements of a Philosophy of Technology. In 1964, in his book Understanding Media, Marshall McLuhan proposed that mechanical technologies extended our bodies in space and that electric technology extended our central nervous system. In 1995, in The Global Brain Awakens, Peter Russell stated that the various connections were making the earth an embryonic brain and the earth is awakening. The analogies used to describe the tools and technologies humans have created have shifted from body to nerve and to brain as the digital world has advanced towards advanced levels of intelligence.

Communications networks have existed in one form or another for about two centuries. Today, the telegraph and analog telephone networks of the 19th century have long since been superseded by more advanced digital networks.

Over the past 50 years, mobile communications, optical communications, and data communications networks have evolved continuously to remain relevant. These network types, together with optical cables, equipment rooms, and sites, form a robust network trunk.

The biggest evolutionary step taken in the last decade is the development of what the academic community could understand as being the network's nervous system. The human nervous system comprises basic systems that can initiate automatic stress responses and feature closed-loop control, as well as more advanced systems that support thinking, analysis, and cognition (i.e., the brain). The current shift from the software-defined network (SDN) to the autonomous driving network (ADN) is analogous to the evolution of a basic nervous system for networks.

Over the next 10 years, the network nervous system

will evolve along the following two tracks. The first is HCS, e.g., wireless sensing, Wi-Fi sensing, and optical sensing. The second is the development of a "brain" – the digital twin of the physical world that allows autonomous inference and decision making. This is how networks will evolve towards advanced levels of intelligence and feature cognitive intelligence.

Cognitive intelligence is both an engineering and a mathematical issue. To qualify as having cognitive intelligence, a system must be able to sense status changes internally and externally in real time and manage itself through autonomous analysis and prediction.

The construction of cognitive intelligence consists of two dimensions: time and function.

Time: A network may predict changes in the future (T3) by learning historical information (T1 and T2). For example, an L5 ADN will be able to accurately predict performance degradation based on historical performance records and warnings.

Function: A network may predict changes in its functions (information C) by learning function-related information in different environments (information A and information B). For example, a cognitive wireless system may predict user service changes by identifying changes in user locations and channels, and in cyber security, a network may predict changes in the security situation based on detection of abnormal behaviors at the packet level.

The concept of cognitive networks is not new. Some renowned universities, research institutes, and companies have been doing related research for years, but few breakthroughs have been made. Cognitive technology was first used in wireless networks. In 2004, the IEEE established the IEEE 802.22 Working Group and developed the first wireless standard based on cognitive technology. Recent years have seen AI breakthroughs in many industries. Self-driving cars have already driven millions of miles in the real world, completely autonomously. In production quality control, AI vision has significantly cut inspection times. In agriculture, the efficiency of intelligent apple pickers is more than double that of human workers. The communications industry is also exploring the use of AI in networks. We hope that over the next 10 years, the combination of AI and digital twin technology will lead to breakthroughs in cognitive networks, and prediction and judgment of network status will be significantly improved though analysis and inference of multi-dimensional data.

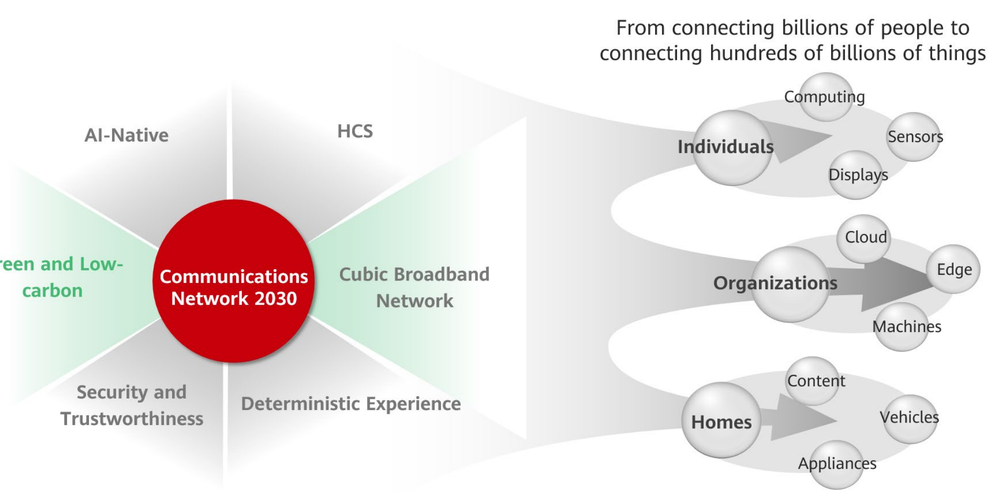
As part of the digital world that is about to awaken, communications networks will have both harmonized sensing capabilities and cognitive intelligence, evolving to a higher form with a robust trunk, sensitive perceptions, and an agile "brain".

Vision for Future Networks and Their Defining Features

Vision for Future Networks

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



Defining Features

The communications networks of 2030 will have six defining features enabled by 15 key technologies, and each key technology will rely on research on multiple technological fronts. (Figure 5 Defining features of the communications network of 2030)

Cubic Broadband Network

The coming decade will see continuous improvement in network performance. Today's gigabit access enabled by 5G, F5G, and Wi-Fi 6 for homes, individuals, and organizations will evolve toward 10 gigabit capacity enabled by 6G, F6G, and Wi-Fi 8. Huawei predicts that the average monthly data use on wireless cellular networks per person will increase by 40-fold to 600 GB in 2030. In addition, gigabit or higher fiber broadband household penetration and 10 gigabit fiber broadband household penetration are expected to reach 55% and 23%,

Figure 5 Defining features of the communications networks of 2030

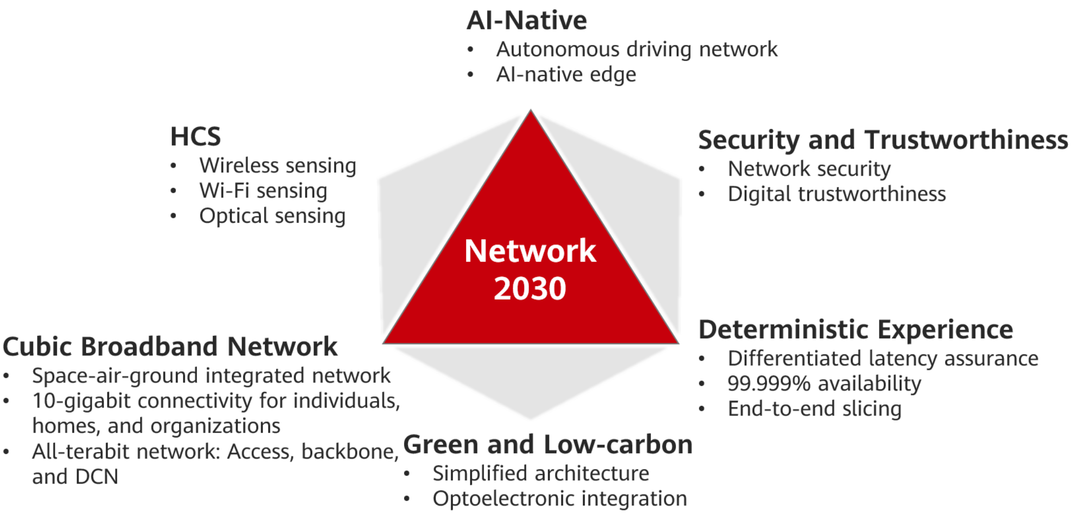
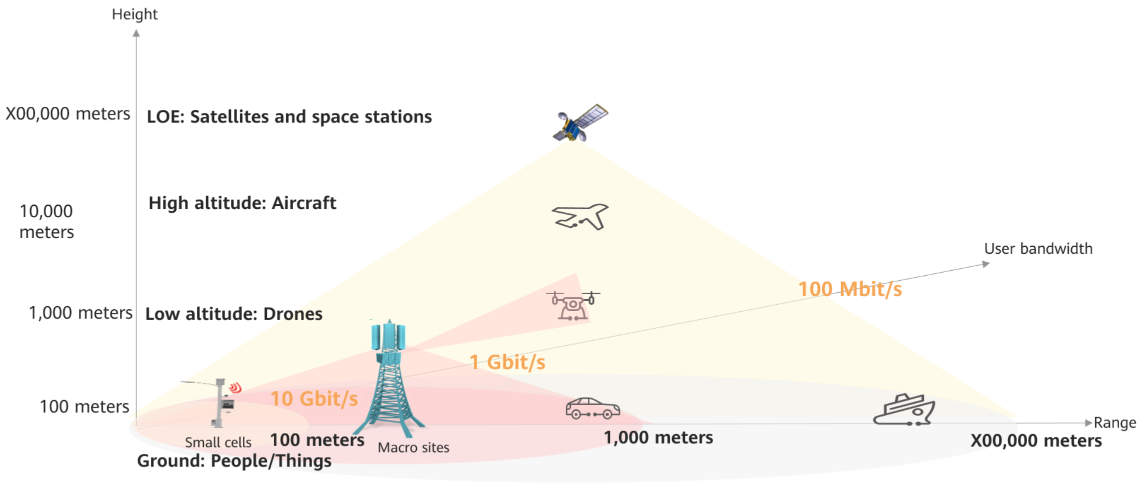


Figure 6 Cubic broadband network



respectively, and the average monthly fixed 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 integrated networks connecting the ground, air, and space.

1) Space-Air-Ground Integrated Network: Seamless and Continuous Broadband Experience

Moving forward, broadband coverage will extend beyond the ground, encompassing the air and even space. These networks will connect devices at various heights, such as drones flying less than 1 kilometer above the ground, aircraft 10 kilometers above the ground, and LEO spacecraft hundreds of kilometers above the ground. A cubic network will consist of small cells with a coverage radius of 100 meters, macro sites with a range of 1–10 kilometers, and LEO satellites with a range of 300–400 kilometers, which will provide users with continuous broadband experiences of 10 Gbit/s, 1 Gbit/s, and 100 Mbit/s, respectively. (Figure 6 Cubic broadband network)

For satellite-terrestrial access, devices must be able to easily access terrestrial and space networks. Before we can make that happen, there is still a lot of research that needs to be done. For example, we need to develop:

- New air interface technologies with deep fading, large latency, and highly dynamic performance
- Intra-satellite and inter-satellite beamforming technologies that can evenly allocate active user equipment (UE) to different beams for load balancing and more efficient resource utilization
- Anti-interference technologies for higher spectrum multiplexing rates
- Frameworks that support fast decision making in response to massive volumes of switching requests and complex switching, as well as mobility management frameworks for limited numbers of ground stations

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 between satellites in the same orbit, on the same layer, and on adjacent layers, forming a cubic space network. Inter-satellite links will use lasercom and terahertz technologies to support bandwidth of more than 100 Gbit/s. This will require research on adapting industrial products to aerial settings, making phased array antennas more compact, and enabling dynamic laser tracking and pointing.

The network management and control domain consists of an operation and control center, network management center, earth station, and integrated core network. It performs the tasks of satellite network management, user management, and service support. In this domain, we need to research new dynamic routing protocols between ground-based earth stations and constellation networks, and hyper-distributed convergent core networks that support intelligent switching of space-air-ground integrated networks.

2) 10-Gigabit Connectivity for Individuals, Homes, and Organizations

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

To deliver 10-gigabit home broadband, 200G passive optical network (PON) technology will likely be used for optical access. 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 needs to focus on flexible use of the sub-100 GHz spectrum bands and continuous evolution of massive multiple-input multiple-output (MIMO). 3GPP Release 16 has defined two frequency ranges, FR1 and FR2, for 5G new radio (NR), covering all spectrum bands for International Mobile Telecommunications (IMT) between 450 MHz and 52.6 GHz. Research for Release 17 is still underway, and one important focus of this research has been the use of spectrum above 52.6 GHz for 5G NR. This points to industry consensus on fully utilizing spectrum below 100 GHz for 5G.

To make 10-gigabit campus networks possible, more research is needed on next-generation Wi-Fi technologies that support millimeter-wave and high-density MIMO. Theoretically, Wi-Fi 7 standards that are currently being defined 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.

3) All-terabit Network: Access, Backbone, and DCN

Taking into account the growing broadband requirements of individuals, homes, and enterprises, as well as the need to connect people and things, 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 network, from access and backbone to data center networks. 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 and 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.

In addition, enabling long-distance transmission capacity of more than 100 Tbit/s per fiber will require technical breakthroughs in backbone WDM equipment, including materials science breakthroughs in high-baud electro-optic modulation and the development of new optical amplifier technology that goes beyond C-band to L-band and S-band.

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) 100 ms, 10 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 100 ms, 10 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 end-to-end deterministic latency.

Real-time wireless access services require high instantaneous rates over the air interface. However, due to the spectrum constraints caused by the multiplexing of multiple pieces of UE on a single carrier, it is difficult to guarantee real-time performance. Moving forward, multi-carrier aggregation technologies need to be developed so that carrier configuration is decoupled from transmission, improving the bandwidth of services under latency constraints on multi-band carriers.

For cloud-based wireless core networks, real-time operating systems (OSs) are needed to enhance deterministic scheduling frameworks and ensure real-time service performance.

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 such as time-sensitive networks (TSNs) and deterministic IPs need to be integrated to ensure on-demand, end-to-end latency.

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

End-to-end 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. End-to-end 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 end-to-end 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 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 isolation technologies can be optical-layer hard pipes, which carry different services through different wavelengths or through the optical channel data unit-k (ODUk) within a single wavelength. Flexible Ethernet (FlexE) at the MAC layer is also used to isolate services by scheduling timeslots. Logical isolation technologies mainly include SRv6 Slice-ID, traffic engineering (TE), and virtual private network (VPN) at the IP layer. Logical service isolation is implemented through labeling and network equipment resource reservation. 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). This can deliver bounded 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.

End-to-end management and services: 3GPP has defined an end-to-end network slicing management function (NSMF), which streamlines network slice subnet management functions (NSSMFs) to enable end-to-end 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) 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 greater than 99.999% 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 end-to-end collaboration.

AI-Native

1) Autonomous Driving Network (ADN): Continuously Evolving Toward L4/L5 Advanced Intelligence

The ADN represents an advanced stage in the development of the network nervous system. Based on data- and knowledge-driven intelligent, simplified networks, the ADN is automatic, autonomous, self-healing, and self-optimizing. It enables new services that offer optimal customer experiences, autonomous O&M, and the most efficient resource and energy utilization.

Currently, the development of the ADN has reached the L2 to L3 stages, with partial and conditional autonomy. The system uses AI models to enable closed-loop O&M for specific units in specific external environments. In the future, the ADN will continue to evolve toward advanced intelligence to achieve closed-loop autonomy for multiple services throughout the lifecycle in more complex cross-domain environments. (Table 6 Levels of the ADN)

Research aimed at supporting the evolution to the L4/L5 ADN should focus on the following key directions.

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 architecture centered on function implementation will evolve into an objective-based decision-making architecture, capable of handling complex and unpredictable environments. Key challenges in this regard include resolving potential conflicts

Table 6 Levels of the ADN

Level	L0: 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

between multiple objectives of the system, increasing the environment's predictability, and ensuring collaboration between different autonomous systems, or between autonomous systems and humans.

- 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. In the data-driven architecture, machines will gradually replace human operators for situation awareness and adaptive decision making, and become able to handle complex and uncertain scenarios. This will mark the first step toward the ADN. The advantage of this architecture is its high performance, and its disadvantages include poor explainability, limitations of training sample space, and the fact that it is currently only applicable to non-critical tasks.

- Semantics-based intent: In an 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.

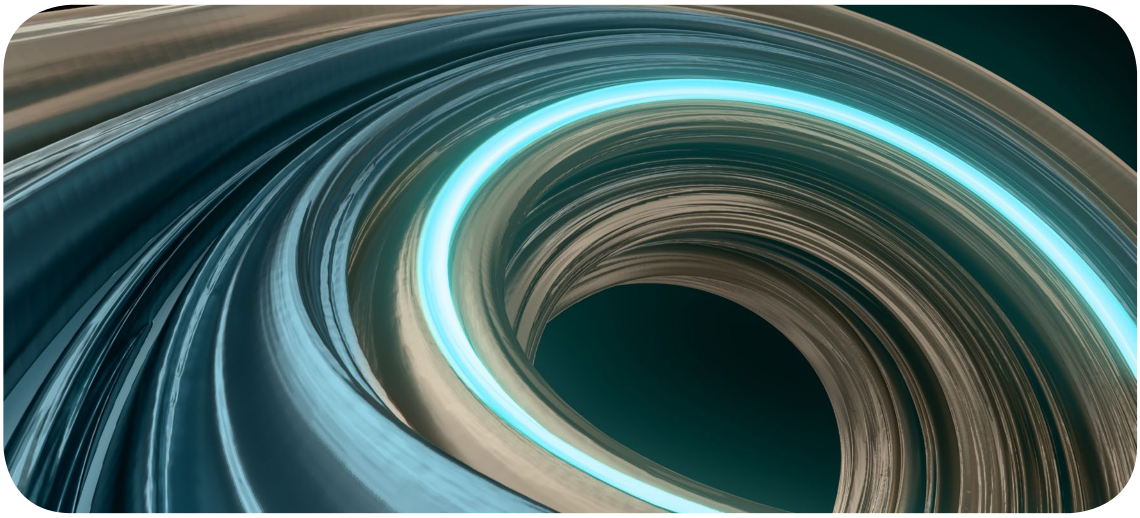
The NE layer: AI should be used not only for O&M, but also for reconstructing NE algorithms and functions so as to deliver AI-native NEs. Through AI-based, real-time analysis and processing of real-time status data of NEs, the ADN can dynamically compensate and optimize parameters, improve the algorithm accuracy of network equipment, and achieve intelligent ultra-broadband, such as cognitive wireless networks and cognitive optical networks. To this end, the equipment's computing power needs to be improved tenfold.

In addition to the advancement of software systems, building L4/L5 capabilities into the 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.



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 MEC-based 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, 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+-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.

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 5.5G 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:

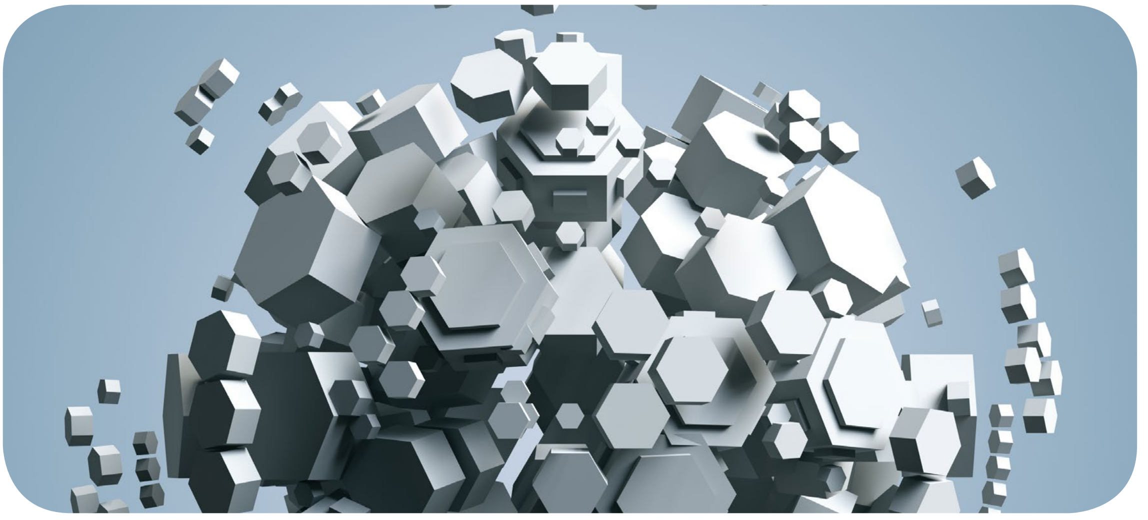
Wireless sensing: HCS is one of the three new use cases proposed for 5.5G, particularly in scenarios such as connected vehicles and drones. With Release 16, precise positioning functionality can already achieve meter-level accuracy for commercial use cases, and future releases are expected to hone this 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 in the industry for basic theories such as optimal compromise. As of now, the potential of channel modeling above 0.3 terahertz remains untapped. More research needs to be devoted to far-field and near-field terahertz propagation modeling; spatial target reflection, scattering, and diffraction modeling; and spatial sparsity sensing modeling. In addition, more research is needed on high-performance, low-power radio frequency (RF) chips and components, the structure of super-large terahertz array antennas, 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.

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.

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, 10 gigabit Wi-



Fi network penetration in enterprises will reach 40%, and F5G private network penetration in medium/large enterprises will reach 42%. 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.

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

Today, the very concept of security is changing. It is no longer about centralized protection or a bolted-on feature. Rather, there is a new expectation that security should be an endogenous feature of a network and part of the network's architecture. Beyond that, as we move from the consumer Internet to the industrial Internet, networks require not only security but also trustworthiness.

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)

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.

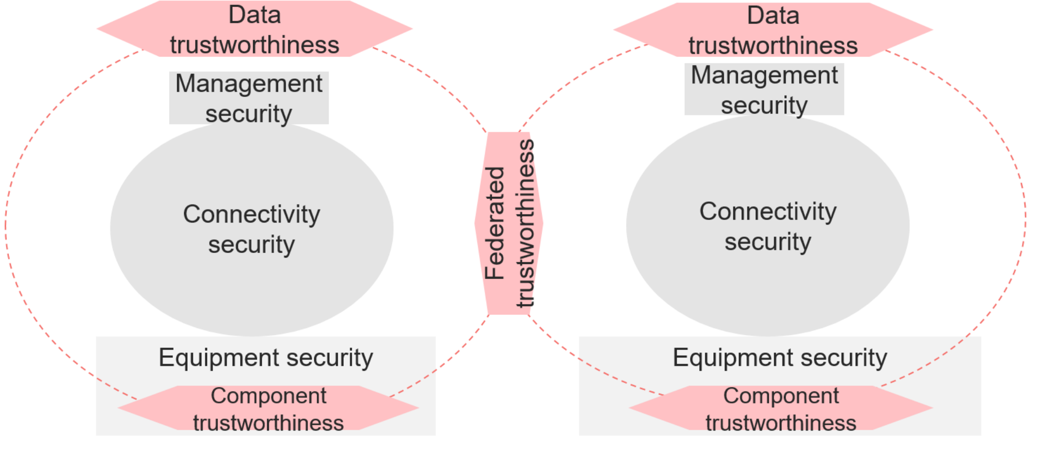
Equipment and connectivity security: Communications protocols and network equipment can be modified to embed trustworthiness identifiers and password credentials in IPv6 packet headers. Network equipment can verify the authenticity and legitimacy of requests based on identifier authentication, preventing identity theft and spoofing and building fine-grained access authentication and source tracing capabilities.

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.

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.

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

Figure 7 Six-layer network security and trustworthiness framework



invisible to the network.

Green and Low-carbon

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 provides access (wired/wireless), switching, and core networks from end to end, 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, and enables green, low-carbon networks with simplified O&M based on all-in-one full-spectrum antennas, fully converged core networks, and simplified protocols.

The cloud network is used for connectivity between the cloud and devices at the tenant level, and is overlaid on the foundation network using end-to-end 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 provides 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.

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 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) 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, 10-gigabit industrial 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 end-to-end 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, 10 ms latency within city clusters, and 100 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.

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 may be the keyword based on the improvement of network capabilities from ubiquitous gigabit networks to 10-gigabit cubic networks. 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 L5 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

3GPP	3rd Generation Partnership Project
5G	5th Generation of mobile communication
5G NR	5G New Radio
5G SA	5G Standalone
5GtoB	5G to Business
6G	6th Generation of mobile communication
ADSL	Asymmetric Digital Subscriber Line
AI	Artificial Intelligence
AMR	Automated Mobile Robot
ADN	Autonomous Driving Network
API	Application Programming Interface
AR	Augmented Reality
ASIC	Application-Specific Integrated Circuit
B2B	Business to Business
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
DoF	Degrees of Freedom
E2E	End to End
ERP	Enterprise Resource Planning
F5G	5th Generation Fixed Network
F6G	6th Generation Fixed Network
FDMA	Frequency Division Multiple Access

FlexE	Flexible Ethernet
FOV	Field Of View
FPS	Frames Per Second
FR1/FR2	Frequency Range_1/Frequency Range_2
GPU	Graphical Processing Unit
GSMA	GSM Association
HCS	Harmonized Communication and Sensing
IMT	International Mobile Telecommunications
IoT	Internet of Things
IOWNGF	Innovative Optical and Wireless Network Global Forum
IPv6+	IPv6 enhanced innovation
ISA-95	International Society of Automation 95
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
MR	Mixed Reality
MTP	Motion-to-Photon
NPU	Neural Processing Unit
NSMF	Network Slice Management Function
NSSMF	Network Slice Subnet Management Function
ODUk	Optical channel Data Unit-k
ONT	Optical Network Terminal
PDCP	Packet Data Convergence Protocol
PHY	Physical Layer
PLC	Programmable Logic Controller
PON	Passive Optical Network
PPD	Pixel Per Degree
QAM	Quadrature Amplitude Modulation

QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAM	Random Access Memory
RB	Resource Block
Real-Time OS	Real-Time Operating System
RLC	Radio Link Control
SCADA	Supervisory Control And Data Acquisition
SDN	Software-Defined Network
SLA	Service Level Agreement
SLM	Spatial Light Modulator
SRv6 Slice-ID	SRv6 Slice Identifier
TDM	Time Division Multiplexing
TE	Traffic Engineering
TOPS/W	Tera Operations Per Second/Watt
TPU	Tensor Processing Unit
TSN	Time Sensitive Networking
URLLC	Ultra-Reliable Low-Latency Communication
VLEO	Very Low-Earth Orbit
VPN	Virtual Private Network
VR	Virtual Reality
WDM	Wavelength Division Multiplexing
Wi-Fi 6	Wireless Fidelity 6
Wi-Fi 7	Wireless Fidelity 7
Wi-Fi 8	Wireless Fidelity 8
WLAN	Wireless Local Area Network
XR	eXtended Reality

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