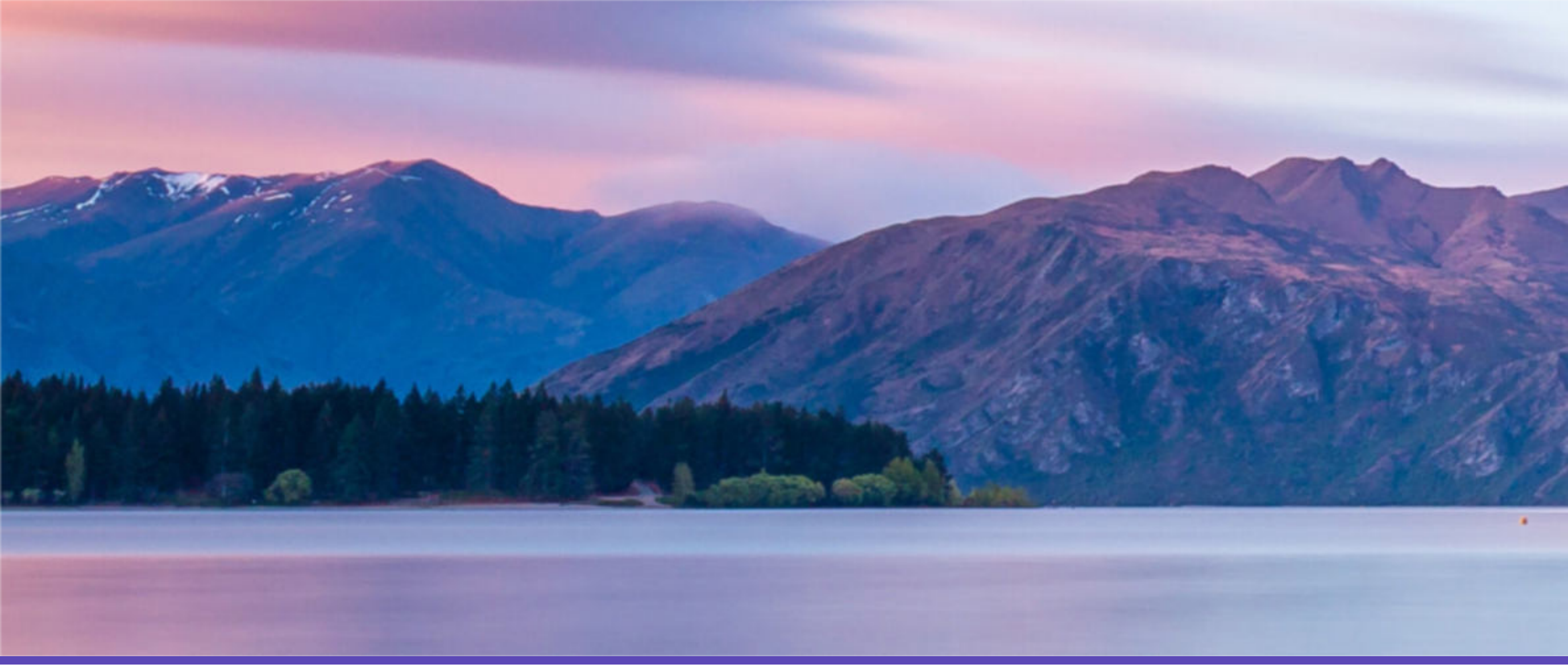
F5G Advanced Industry White Paper



Byliners

China Unicom	Xiongyan Tang, Guangquan Wang, Zelin Wang, He zhang, Yan Shao, Xiangkun Man, Yue Sun, Shikui Shen, Shan Dong
CAICT	Li Ao, Qian Liu
CMCC	Han Li, Dechao Zhang, Junwei Li, Yunbo Li
Bharti	Praveen Maheshwari
BUPT	Jie Zhang, Yongli Zhao, Zhiguo Zhang
CEEDI	Xu Zhang
CEPREI	Yanfei Hu
CSU	Ying Li
CTTC	Raul Muñoz
e&	Mohamed al Marzooqi
Fiber Home	Songtao Chen, Shaoyong Peng, Hongliang Li, Yuzhou Sui
Globe Telecom	Emmanuel Lazaro R. Estrada
HUST	Mengfan Cheng, Qi Yang
HUAWEI	Jingji Wang, Qian Gong, Xiaohua Lu, Chun Sun, Xianlong Luo
ITEI	Dan Liu
Orange	Philippe chanclou
ONA	Ruili Zhang
Post Luxembourg	Olivier Ferveur
PT Telkom	NA
Qishuai Digital Technology	Qichang He, Xianming Gao
University of Patras	Ioannis Tomkos
Union SHENZHEN Hospital	SuiSong Zhu
VTAL	Evandro Bender
ZTE	Lairong Luo, Chuanzhu Liu, Haijun Zhang, Mingsheng Li, Meng Wang

CONTENTS

Preface

In February 2020, the European Telecommunications Standards Institute (ETSI) released the fifth-generation fixed network (F5G) standard and proposed the vision of "Fiber to Everywhere". After more than two years of development, F5G has achieved rapid development from standards organizations to industry applications, with nearly 100 members, more than 1000 documents published, and 13 work items (WIs) set up for technical research, which greatly promotes the standardization of F5G applications. The establishment of the World Broadband Alliance (WBBA) at the end of 2021 marks a new beginning of F5G from standards to industrial applications. In September 2022, ETSI released the F5G Advanced standard white paper to promote the continuous evolution of the F5G industry.

F5G networks are being rolled out worldwide and starting to play an important role in home broadband, public services, and industry convergence. Major economies worldwide have formulated or are formulating F5G gigabit broadband strategies and related policies, and we are witnessing accelerating commercial deployment and industry convergence related to F5G.

Four forces drive fixed networks to continuously evolve and enter the F5G Advanced era:

- Fiber networks connect the real world and virtual world, and the network bandwidth evolves from 1 Gbps to 10 Gbps.
- Optical networks extend from the ICT industry to vertical industries, helping these industries go digital.
- Fibers carry communication as well as sensing services to generate greater value.
- Fiber networks evolve to greener architectures, improving energy efficiency 10 fold.

In the next 10 years, gigabit access will be widely used, 10G access will be put into large-scale commercial use, and enterprise cloudification and digital transformation will go deeper. The intelligent era of Internet of Everything (IoE) is coming and fixed networks are facing unprecedented opportunities.

Based on new scenarios and applications, this white paper explores architecture evolution and new network capabilities, focuses on key requirement scenarios such as home, enterprise, computing network, and green optical network, and defines the industry objectives, core features, key network indicators, evolution paths, and key technical capabilities of F5G Advanced. It aims to provide requirement references and technology trends for F5G Advanced, explore new directions for network evolution, build industry consensus, and jointly move towards the new era of F5G Advanced.

F5G Review and Evolution to F5G Advanced

1. F5G Development Review

In February 2020, the European Telecommunications Standards Institute (ETSI) officially defined the fixed network generations for the first time based on core technologies such as 10G PON+fiber to the room (FTTR) for broadband access, Wi-Fi 6, and single-wavelength 200G for optical transmission + optical cross-connect (OXC). In addition, ETSI released the Fifth-Generation Fixed Network (F5G) standard and proposed the industry vision of "Fiber to Everywhere". The essence of the vision is to promote fiber-based broadband on the access side to achieve gigabit rates, while building an all-optical base on the transport side to provide premium transmission for various industries. Once released, the standard and vision quickly garnered wide attention and stimulated discussion within the fixed network industry. Meanwhile, the number of ETSI members increased to approximately 100 within two years, more than 1000 articles were released, and over 60 F5G workshops were held. The F5G standard has also been accepted by other standards organizations and adopted in industry applications. In addition, the World Broadband Alliance (WBBA) was established at the end of 2021, marking the start of F5G commercialization.

Since then, the F5G fiber-based digital base has benefited various industries, enabling the digitalization of homes, enterprises, utility services, and social governance. According to a research report released by the Chinese Academy of Social Sciences, F5G can increase China's GDP by 0.3% each year from 2020 to 2025. F5G is the cornerstone of the digital economy and has become a core strategy for global ICT infrastructure development. In Europe, the EU released the 2030 Digital Compass: the European way for the Digital Decade and Guidelines on Very High Capacity Networks (VHCN) to guide the construction of gigabit fiber networks in European countries in terms of policies, funds, and supervision. In China, the 14th Five-Year Plan clearly proposes to fully deploy gigabit fiber networks, accelerate gigabit city construction and 200G/400G network upgrade, and formulate a three-year action plan to ensure target achievement. In addition, more than 20 countries have released top-level plans for fiber broadband, such as Thailand's Giga Thailand, Egypt's Decent Life, Morocco's NBN 2025, Nigeria's NNBP 2025, and Cote d'Ivoire's National Broadband Implement Plan, accelerating worldwide fiber broadband deployment. For another example, India's "Digital India" plan aims to build a digital society and knowledge economy in nine fields, such as high-speed broadband and ubiquitous mobile access, and promote the comprehensive digital transformation of Indian society.

In consumer scenarios, which feature high bandwidth, low latency, and ubiquitous connections, F5G can incubate new products, applications, and services to better meet the ever-increasing ICT requirements of consumers.

In the production domain, optical fibers are extending from homes to campuses, factories, and machines. The fiber-in-and-copper-out development becomes the new trend of network construction. Fiber-To-The-Office (FTTO) has been deployed in more than 15,000 education, healthcare, and financial institutions. Fiber-To-The-Machine (FTTM) has been applied in more than 100 projects, covering safe production of coal mines, remote port control, and all-optical transportation intersection. F5G features environmental protection, simplified architecture, large bandwidth, deterministic low latency, and high security and reliability, greatly assisting digital transformation in various industries and improving productivity of traditional industries.

According to statistics from global operators, 100 million fiber to the home (FTTH) users, 70 million gigabit broadband users, 800,000 FTTR users, and 20,000 fiber to the office (FTTO) and fiber to the machine (FTTM) enterprise customers were developed from the year 2020 to 2021. In other words, the F5G industry ecosystem is flourishing.

2. Four Driving Forces for the Evolution to F5G Advanced

Unlike previous generations of communications networks, the F5G gigabit optical network is regarded as an important part of the new information infrastructure, forming the information "artery" of economic and social development. It plays an important role in enabling development of the digital economy and facilitating digital transformation across various industries. Within this context, the EU proposed the 2030 Digital Compass plan and formulated the gigabit all-optical strategy. China also takes gigabit optical network + convergent industry applications as an important goal. From the industry evolution perspective, F5G needs to address the following challenges:

UHD immersive experience requires higher-bandwidth and lower-latency networks. As technologies develop and metaverse applications emerge, the development of industries such as VR, AR, XR, and optical field display is greatly promoted. According to Huawei's research and third-party consulting reports, more than 1 billion users will experience the immersive virtual world through XR and interact with the physical world by 2030. Building a virtual world with immersive experience and natural interaction experience requires a bandwidth of 1 Gbps to 10 Gbps and a latency of 5 ms to 20 ms. In addition, to ensure the concurrent experience of multiple home and enterprise users, bandwidth needs to be increased by 10 times. All these pose new challenges to existing F5G gigabit network capabilities.

Digitalization of industries such as manufacturing, energy, and transportation requires further improvements in real-time performance and network reliability. F5G drives optical networks into the industrial field. With the acceleration of industrial digitalization and intelligent upgrade, as well as the large-scale development of applications such as ultra-HD video backhaul (such as machine vision) and remote motion control, 20 μs latency, 20 ns jitter, zero packet loss, and 99.9999% reliability connections are required. However, the current serial bus latency is higher than 100 μs, and the latency and jitter are accumulated site by site, which cannot meet the service requirements. Therefore, a new field bus is required to meet the strict requirements of industrial control. Energy and transportation production networks have stringent requirements on network security, reliability, and latency. With the development of high-bandwidth services such as HD video backhaul, hard pipes with 1 Gbps bandwidth, 1 ms latency, and 99.999% reliability must be provided for each site to carry and enable the automatic and intelligent upgrade of operational technologies (OTs), accelerating the digital transformation of industrial production networks.

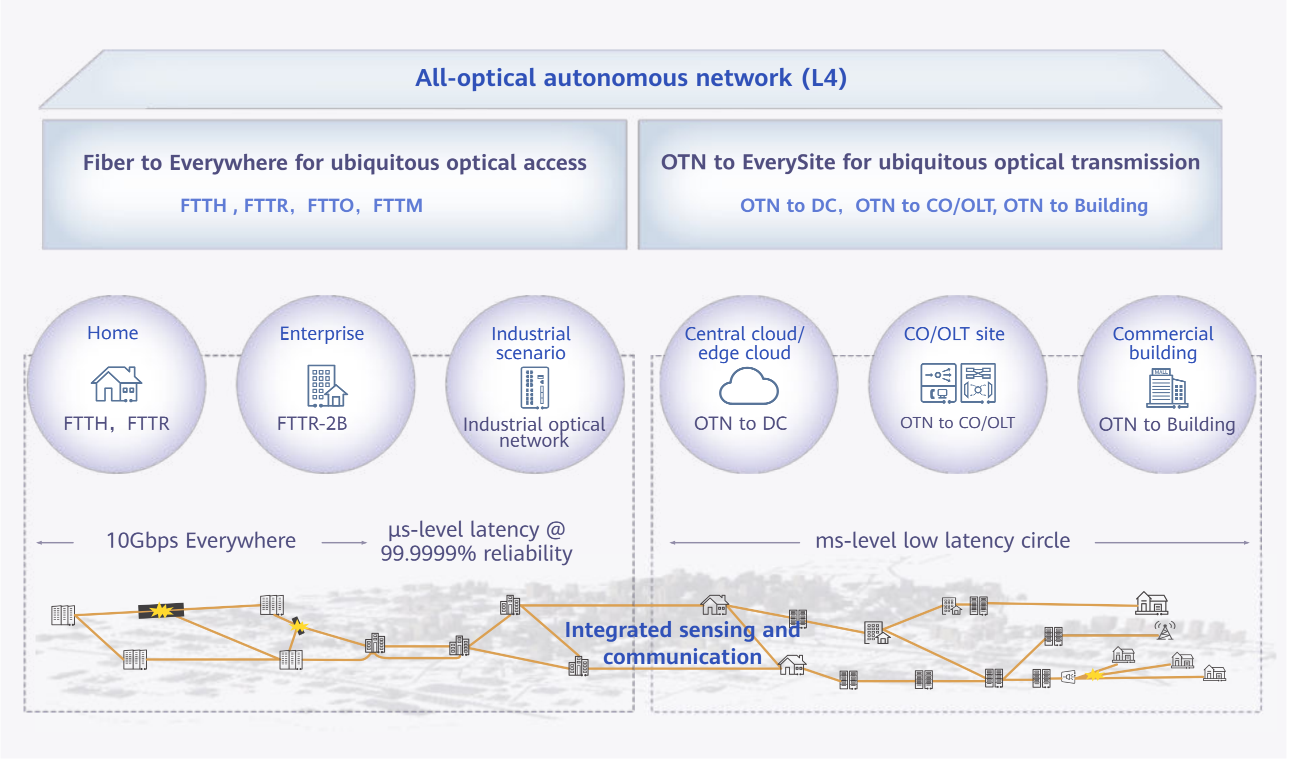
Ubiquitous optical cable networks require digitalized management and enhanced environment awareness capabilities. With the in-depth deployment of Fiber to Everywhere in F5G, optical fibers are further extended to end users and devices, the number of connections increases by 10 times, and the total length of deployed optical fibers increases by 20%. Operators have massive dumb cable resources, which make management and maintenance complex. Digital technologies are required to accurately locate optical cable positions and identify faults, achieving digitalized and visualized management. Moreover, the large-scale deployment of F5G in industries promotes the ubiquitous use of optical cables in enterprise scenarios. In addition to satisfying enterprise communication requirements, optical fibers can be used to sense parameters such as vibration, temperature, and stress. By accurately sensing external environments, optical fibers play a key role in the online inspection of oil and gas pipelines.

Accelerating enterprise digitalization and cloudification requires simplified, green, and low-carbon network architectures. With the acceleration of enterprise cloudification and digital transformation, services are centrally deployed on the cloud, traffic is mainly aggregated from terminals to data centers, and high-bandwidth applications, such as 8K and XR, drive the compound annual growth rate (CAGR) of network traffic to exceed 26% in the next 10 years, requiring network bandwidth to increase by more than 10 times. However, the existing multi-layer hop-by-hop forwarding network architecture faces challenges in terms of latency and power consumption. Green all-optical networks with one-hop transmission, all-optical grooming, and simplified and flat architecture are required to improve network energy efficiency by 10 times to better meet enterprises' requirements for digital development.

F5G Advanced Industry Objectives and Characteristics

F5G Advanced focuses on optical fibers, OTN sites, and Wi-Fi spectrum. It is deeply integrated with homes, industry applications, and optical sensing, and it helps in the realization of the Internet of Everything (IoE) by building all-optical bases for transmission and access networks. The goal is to achieve "ubiquitous all-optical infrastructure" like water and electricity; realize the industry vision of "Fiber to Everywhere, OTN to EverySite, integrated sensing, and all-optical autonomous networks".

Figure | F5G Advanced industry objectives



The details are as follows:

The access-side bandwidth will evolve from 1 Gbps to 10 Gbps, and ubiquitous fiber networks (Fiber to Everywhere) need to be deployed as the digital foundations for connecting the real and virtual worlds.

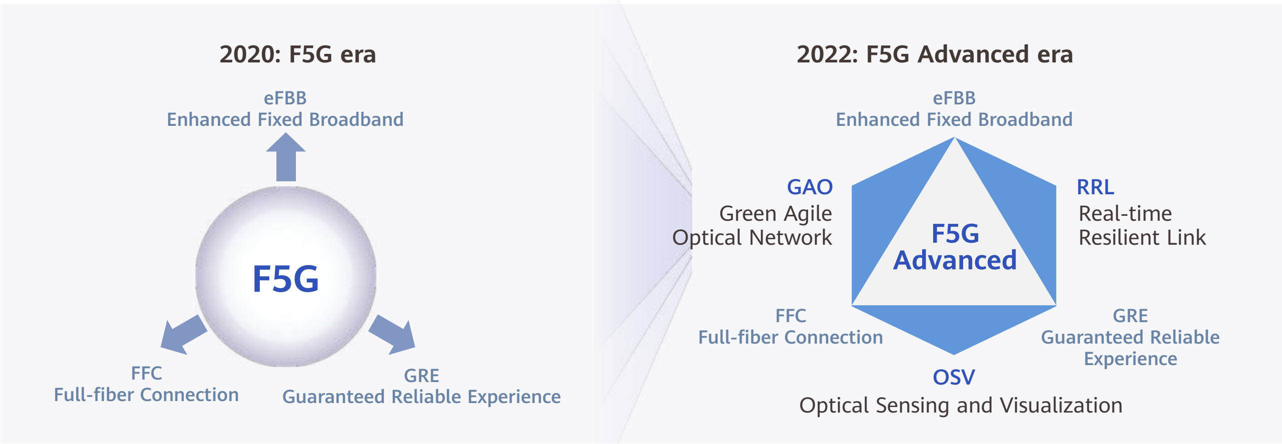
In addition, OTN needs to be extended downward to buildings, communities, sites, and data centers (DCs), and needs to support one-hop access to the cloud to realize OTN to every site and build premium and differentiated all-optical bearer networks that help various industries achieve digital transformation.

Ubiquitous optical cable networks can be managed in digital mode to sense the environment, integrate communication and sensing, unleash the infinite potential of optical fibers, and facilitate the digitalization and unmanned inspection of various pipelines, thereby improving the efficiency of resource management.

Evolving from automation to intelligence, an all-optical autonomous network accelerates differentiated product operation. Through the upgrade to an L4 autonomous network, the all-optical bases of transport and access networks can be intelligently managed, home broadband experience can be self-optimized, and private lines and premium computing capabilities can be quickly accessed.

Based on these industry objectives, the main difference between F5G Advanced and F5G is that the former defines green agile all-optical networks, real-time resilient links for industrial manufacturing, and optical sensing and visualization based on F5G features that are continuously expanding. The specific features are as follows:

Figure | Evolution from F5G to F5G Advanced and continuous expansion of industry characteristics



- Enhanced Fixed Broadband (eFBB): from gigabit access to 10G home, 10G campus, and 100T networks, achieving 1 Gbps to 10 Gbps Everywhere (line bandwidth doubled from 200G/400G to 400G/800G)
- Green Agile Optical Network (GAO): OTN to every site, building a green agile all-optical network with one-hop transmission and 10-fold energy efficiency improvement
- Full-fiber Connection (FFC): building digital foundations for smart homes, enterprise-home collaboration, and all-optical campuses to increase premium connections
- Real-time Resilient Link (RRL): building all-optical production networks with 99.9999% ultra-high reliability and μs-level deterministic low-latency to help various industries go intelligent
- Guaranteed Reliable Experience (GRE): home broadband changing from visible fault locating to experience self-optimization, and fast access to private lines and computing networks
- Optical Sensing and Visualization (OSV): from communication to sensing, unleashing unlimited potentials of fiber networks

F5G Advanced Application Scenarios

1. To Home: Immersive XR and Smart House, Building Smart New Lives

1.1 Immersive XR + Whole-House Intelligence, Enabling Premium Home Life

With the improvement of terminal capabilities and large-scale deployment of gigabit networks, home services evolve toward multi-screen, diversified, and intelligent features, enabling smart lifestyles. From one perspective, services are evolving from 4K to 8K to XR. According to a third-party consulting report, the XR industry will witness rapid development in the next five years, and by 2030, over 1 billion users will enjoy an immersive experience of the virtual world. For example, in work scenarios, users will wear headsets at home to create a virtual environment and interact with customers and colleagues as if they are meeting in person. Additionally, in online learning scenarios, more education resources will be shared over the Internet. Students will use AR glasses to observe chemical reactions more vividly. In daily life scenarios, XR will enable people to hold virtual parties and chat remotely. From another perspective, the number of terminal connections will increase by more than 10 times. Whole houses will become intelligent, and various terminals will interact with each other to provide smart care services. For example, when you return home after work, your favorite lights, music, fragrance, and TV programs will turn on automatically, and the smart bed, smart pillow, and bedroom lighting and sound effect systems will collaborate to make you feel comfortable. 3D light sensing can accurately detect human postures and connect with cameras to provide smart care for the elderly.

Services such as immersive XR and whole-house intelligence will pose higher requirements on network bandwidth and latency. In that regard, F5G Advanced provides new capabilities such as 50G PON and supports FTTR Wi-Fi 7 to implement carrier-class Wi-Fi experience assurance, such as 1–10 Gbps seamless coverage, latency within milliseconds, and seamless roaming. F5G Advanced also enables dizziness-free immersive interactions, privacy-protected healthcare, and premium smart life experience. New business models and services will appear, opening market space worth trillions of dollars.

1.2 Homes Evolve from Entertainment Centers to Multi-service Centers, Calling for Enterprise–Home Collaboration

Due to factors such as the COVID-19 pandemic, homes have evolved from entertainment centers to multi-service centers, where online education, remote office, and live broadcast have become important services. As many people now work from home, rigid demands have developed for services such as smooth HD video conference, convenient file transmission, low-latency remote access, and physical layer permission control and isolation.

These changes pose higher requirements on network bandwidth, latency, encryption, and isolation, calling for service quality that is on par with that of private lines. F5G Advanced can provide differentiated end-to-end (E2E) pipes, one-hop cloud access for high-value services, and isolation for OTN enterprise private lines. In this way, the service quality of home broadband can be guaranteed, and users can enjoy services such as enterprise-home collaboration and live broadcast broadband. This will change consumer traffic to business traffic, maximizing the value of broadband networks.

1.3 Autonomous Premium Broadband Network Enables Operators to Shift from Selling Bandwidth to Monetizing Experience

With the rapid development of gigabit optical broadband and increase in users, the diversified and personalized requirements of home services increase sharply, posing higher requirements on fiber broadband networks. AI and big data technologies are introduced to broadband networks to enable operators to shift from selling bandwidth to monetizing experience, improving user loyalty and meeting customized service requirements. The Autonomous Networks white paper released by the TM Forum defines the L0–L5 autonomous network classification standards. Along these lines, multiple operators recently released white papers, aiming to achieve L4 autonomous networks by 2025. These networks will feature highly automated perception, analysis, decision-making, and execution, achieving zero-wait service provisioning, zero-touch maintenance, and zero-trouble services.

F5G Advanced introduces new technologies such as big data and AI to build E2E digital O&M capabilities for home broadband services, implementing highly automated network awareness, analysis, decision-making, and execution, as well as smart hierarchical broadband operation. From one perspective, these features enable real-time visualization and self-healing of low-quality experience, helping operators shift from complaint-driven passive O&M to experience-driven proactive optimization, and from offline traditional marketing to online precision marketing. From another perspective, high-value service experience is automatically optimized. To do this, gold, silver, and copper pipe services of different assurance levels are provided and dynamically diverted to the cloud, implementing self-optimization of STA-level service experience. F5G Advanced can help operators improve optical broadband service quality and user experience, improve user satisfaction, and accelerate the development of new services.

2. To Enterprise: FTTO/FTTM Integrates IT and OT, Enabling Enterprises Digitalization

2.1 Immersive XR Applications Create Brand-New Experience in Office, Learning, and Telemedicine Services

Enterprise digitalization is accelerating. In office, school, and hospital scenarios, XR is widely used, data is migrated to the cloud, and cross-region intelligent collaboration is gradually becoming the mainstream. For example, in hospital scenarios, smart vital sign detection terminals are widely used to provide healthcare for the elderly and make premium medical services accessible to all. Medical check data such as 3D CT is migrated to the cloud in real time, enabling doctors to remotely monitor the health status of patients using 360-degree HD videos. Additionally, XR is widely used in smart classrooms to create an immersive experience. In enterprise scenarios, the goal of digital office is to make users feel like their colleagues are present in the same space, achieving more natural and efficient communication. Immersive XR delivers this kind of experience. You can observe the faces of meeting participants and communicate through eye contact and body language, like you would without a screen.

Services such as enterprise 8K live broadcast, XR office, and XR smart classroom pose higher requirements on networks. F5G Advanced provides new capabilities such as 50G PON and FTTR Wi-Fi 7 to achieve 1–10 Gbps seamless coverage and deterministic latency within milliseconds. 100 GB design files can be uploaded and downloaded in minutes, and 3D CT images can be viewed in seconds, delivering optimal network experience to enterprise and industry customers.

2.2 Industrial Optical Network Builds an Optical Base for the Industrial Internet

Industry digitalization is picking up speed as the social economy develops, and industrial manufacturing is developing toward digital, intelligent, unmanned, and flexible operations. 3D machine vision quality inspection, cloud-based PLC, and centralized control applications will become the mainstream in future industrial manufacturing. However, applications such as 3D quality inspection, cloud-based PLC, and remote control over the industrial Internet pose higher network requirements, such as uplink bandwidth of 1–10 Gbps, 99.9999% reliability, deterministic latency within milliseconds, and production network expansion in minutes.

In the F5G Advanced phase, industrial optical networks will bring benefits such as energy saving, stable anti-interference, high bandwidth, flexible capacity expansion, long-distance coverage, deterministic μs-level latency and jitter, and E2E hard pipe isolation to ensure industrial-grade premium networks. The benefits will boost services such as unmanned ports, flexible and intelligent factory production lines, and 3D AI quality inspection. These industrial optical networks will serve as the optical base for the industrial Internet and further unleash the productivity of various industries.

2.3 Intelligent Transformation of Industries: Evolution to Green, High Reliability, and Deterministic Quality

With deepening intelligent transformation, the traditional energy and transportation industries are developing toward cloudification, videos, and IoT. Take electric power as an example. Clean and low-carbon energy has become a global trend; however, with new application scenarios such as PV power, wind power, and digital IoT substations, electric power companies need a new power system network that provides the following capabilities: 1. Accurate data collection and precision control for the distribution network (from telemetering to teleindication) to reduce the annual power outage duration and schedule complex grid-tied power devices, such as rooftop PV panels and charging piles. 2. µs-level timing and partial discharge — especially during lighting strikes — for hundreds of sensors in a substation and thousands of sensors in each digital converter station as substations go digital. 3. Deterministic latency lower than 5 ms and hard isolation to ensure smart terminals and video surveillance do not affect production service stability as grid-tided and distribution network terminals increase exponentially.

Compared with traditional networks, future power communication networks will require more connections, more reliable communication quality, and lower deterministic latency within milliseconds to ensure the 100% security and reliability of collection and control services. This is the only way that new power systems can meet peak cut requirements. In the F5G Advanced era, the optical service unit (OSU) technology based on hard slicing provides E2E hard pipes as micro private lines to ensure the communication quality of terminals. OSU can not only deliver high OTN bandwidths, but also carry small-bandwidth services with guaranteed latency to avoid bandwidth waste. With these benefits, OSU is the optimal technical path for network upgrade and evolution.

In long-distance transmission scenarios for industries like coal mines, highways, and railways, isolated information points are connected by optical fibers to implement data aggregation and sharing and promote the development of digital applications.

2.4 Communication and Sensing Integration: Unleashing the Full Potential of Optical Networks

As fibers are dumb resources, the collection of information from optical networks to locate and demarcate faults has always been an industry pain point, especially after massive optical cables are deployed. In the F5G Advanced era, the intelligent digital optical path technology is introduced to implement E2E visualization of the ODN topology and optical power, allowing meter-level precision diagnosis. This helps operators build a digital optical cable network that features real-time visualization, precise perception, and efficient O&M, significantly improving O&M efficiency.

In addition to transmitting signals, optical fibers perform well when sensing temperature, vibration, and stress. Realizing that fiber sensing is green, efficient, and intrinsically safe, various industries have started utilizing fiber sensing technologies in production activities. For example, in the traditional oil and gas and rail transportation fields, long-distance inspection needs to be performed manually, which is costly (up to CNY20,000/km/year), time-consuming, and labor-intensive, but does not produce accurate results in real time. Fiber sensing is ready for commercialization in the F5G Advanced era, and it can work with intelligent algorithms to support pipeline detection (for example, in the oil and gas industries) and perimeter security protection (for example, in airports) to achieve 99% accuracy and meter-level precision, realize unmanned inspection around the clock and early detection and warning of intrusion events, considerably improve the inspection efficiency, and effectively reduce pipeline accidents.

In the future, fiber sensing will be able to work with spectrum detection technologies to measure the concentration of microelements and gases. For example, spectral gas sensing will be used to detect flammable and explosive gases in urban underground corridors and harmful gas leakage in refineries. It will not only generate warnings in advance, but also indicate the distribution of toxic and harmful gases in real time, helping first responders determine the leakage source in seconds and develop rescue plans. Based on the fourth-generation atomic spectrum laser induced breakdown spectroscopy (LIBS), fiber sensing can replace the traditional X-ray fluorescence and gamma ray methods, enabling real-time, radiation-free, and high-accuracy element content detection in the metallurgy and mining industries.

3. To Computing: High-Bandwidth, Deterministic, and Schedulable Transmission Capacity, Achieving Premium Computing

3.1 High-Bandwidth, Deterministic, Schedulable, and Fast and Flexible Access Required for Computing Power to Reach End Users

High bandwidth requirements for computing hub interconnection: Driven by national policies such as new infrastructure construction and digital transformation and enterprises' requirements for cost reduction and efficiency improvement, data centers in China have developed rapidly in recent years. To put it into perspective, by the end of 2021, the total number of racks used in data centers across China exceeded 5.2 million, with a compound annual growth rate (CAGR) over 30% the past five years. The number of racks in large-scale data centers is increasing rapidly, accounting for 80% of the total. According to the hub cluster construction plan released by some provinces and cities, the 10 hub clusters will have over 5 million racks. The western hub clusters are mainly used to meet the national computing power requirements, with outbound bandwidth exceeding 80%. In eastern cluster hubs, the outbound bandwidth will reach 35%. The east-data-west-computing project will require a much higher backbone network bandwidth. Predictions indicate that after the planned number of racks are deployed, the backbone network bandwidth will increase to 3000 Tbps or higher for computing power interconnection.

Deterministic low latency for computing power interconnection: Multi-level collaboration is required between east-data-west-computing and data centers, and data center interconnect (DCI) networks must be stable and reliable with low latency. For example, active-active services in data centers require latency as low as 1–2 ms. According to the Computing Hub Implementation Solution for the National Integrated Big Data Center Collaborative Innovation System released by the National Development and Reform Commission of China (NDRC), to ensure proper allocation of cold, warm, and hot services, the E2E unidirectional network latency between data centers must be within 20 ms in principle.

Flexible scheduling capabilities for cloud-edge collaboration between all-optical transmission

networks: As predicted by Gartner, approximately 75% of enterprise data will be generated and processed outside data centers by 2025. Edge computing is widely used in scenarios such as smart transportation, security surveillance, and the industrial Internet, undertaking many real-time tasks that require fast data processing. However, a large amount of processed data still needs to be aggregated from edge nodes to the central cloud for further big data analysis, mining, data sharing, and algorithm model training, and new algorithm models need to be pushed to edge nodes to promptly implement updates. In addition, massive data stored on edge nodes needs to be backed up in the cloud to prevent data loss caused by edge node faults. Therefore, efficient collaboration is required between clouds, between clouds and edges, and between edges. In this regard, the all-optical transmission network serves as a bridge for connections and must provide highly flexible scheduling capabilities to meet cloud-edge collaboration requirements.

Convenient, flexible, agile, secure, and reliable transmission networks for users to access computing networks: Government, finance, schools, and enterprises are usually distributed in different areas of cities. The all-optical transmission network must provide access assurance for these organizations to obtain computing services when necessary. Some core enterprise services require high security and low latency, while some dynamic services require flexible scheduling, quick response to changes, and prompt resource provisioning and releasing.

In the F5G Advanced era, the all-optical transmission network must provide high bandwidth, deterministic low latency, flexible scheduling, and agile access to computing services.

3.2 Autonomous Networks for Premium Access to Computing Services

E2E resource coordination for nationwide scheduling of computing power: In the computing network era, computing power needs to be scheduled nationwide. This requires central coordination of computing resources and poses challenges to the original hierarchical management by province and city. The three major operators in China have approximately 15,000 to 20,000 OTN devices in large provinces, approximately 7000 in medium-sized provinces, and approximately 3000 in small provinces. In the next five years, each operator will have approximately 300,000 to 500,000 OTN devices in China. These massive devices require centralized management and control, E2E transmission capacity scheduling, as well as O&M capabilities such as complex alarm management and analysis, fault locating and demarcation, and potential fault analysis.

After hub computing power, provincial computing power, and municipal edge computing power are deployed, users' computing power requirements can be met by different computing power resources. As the brain of the computing network needs to match resources with requirements based on latency, bandwidth, and computing power, the management and control system of the all-optical transmission network must effectively collaborate with the brain of the computing network to select resources and establish network connections.

At the early stage of F5G Advanced, the network-wide transmission capacity is visualized to support flexible scheduling of network resources and improve the efficiency of network resource allocation. During the growing stage of F5G Advanced, network resources will be flexibly scheduled with highly reliable service capabilities, such as intelligent scheduling within seconds, 99.999% availability, guaranteed bandwidth, and low latency. As F5G Advanced matures, millions of network nodes will be centrally managed and flexibly scheduled nationwide, enabling efficient computing power allocation for projects like east-data-west-computing.

4. Green All-Optical Base, Improving Bearer Network Energy Efficiency 10-Fold

Facing massive data transmission and carbon neutralization requirements, high-efficiency and energy-saving technical solutions are required for networks. On the bearer network, optical fiber transmission is most energy efficient and the first choice to achieve premium transmission and carbon neutralization. In 2C scenarios, optical fiber transmission can be extended to base stations to fully meet the access bandwidth and latency requirements of 5G and future 6G. In 2H scenarios, optical fiber transmission can be used to replace copper cable transmission, reducing energy consumption by 75% and meeting users' future digital home experience. In 2B scenarios, optical fiber connections extended to offices and factories greatly reduce the power consumption of signal transmission, and provide a high bandwidth and low latency to improve user experience.

When the network evolves to the F5G Advanced phase, an optical network needs to achieve green and low carbon emission from four dimensions. First, change the optical spectrum from the C-wave band to the L-wave band, greatly improving the single-fiber capacity and reducing the power consumption per bit. Second, improve the hardware energy efficiency of devices by means such as liquid cooling, intelligent temperature control, and tidal bandwidth algorithm. Third, reconstruct DC centers to improve the site energy efficiency. Fourth, change the traditional optical-layer architecture deployed in FOADM mode which is labor intensive and inefficient in resource, equipment room space, and energy usage to the OXC solution which simplifies the deployment at the core and aggregation optical layers. In addition, the OXC solution pools metro WDM resources to enable a single aggregation site to connect to multiple access rings through one pooled board, implementing multi-ring sharing, improving wavelength resource utilization, reducing optical-layer complexity, and realizing automatic wavelength planning. Based on the two technologies, an end-to-end all-optical simplified target network can be constructed to enable one-hop access to the cloud and unified bearing of multiple services. In this way, energy consumption is optimized in the network architecture, and the energy efficiency of the entire network is improved by more than 10 times.

Multiple energy-saving innovations have been developed to realize green operation. A board can enter the sleep mode in off-peak hours to save energy. The optical network energy efficiency can be dynamically optimized at multiple layers, from slots, boards, to ports and interfaces. Links can be set up rapidly and resiliently in minutes at the optical layer and in seconds at the electrical layer for easy service access. The bandwidth can be adjusted from Mbps to Tbps losslessly in milliseconds to achieve precision operation and control.

F5G Advanced Evolution Path

1. To Home: FTTx Evolution, Building Whole-House Intelligence

Global operators develop FTTH networks in three phases to expand service boundaries and improve service quality.

In the first phase, all-optical networks are green with low carbon, high bandwidth, high stability, and low latency features, and they provide advanced services and applications for users. All-optical networks are becoming a key strategy for green and digital transformation in countries. Governments and operators worldwide continuously reduce the TCO of FTTH construction and accelerate the construction by guiding optical fiber policies, planning integrated optical cable networks, reusing various resources such as base stations and backhaul optical fibers on live networks, and introducing digital pre-connection ODN technologies.

In the second phase, as services and broadband packages are upgraded to 500 Mbps to 10,000 Mbps, valuable services such as 4K/8K/VR, online office/education, and live broadcast are developed. By building planning, construction, acceptance, and maintenance capabilities, optical fibers are extended to rooms, and the combination of 10G PON and FTTR builds a gigabit home network with true gigabit experiences, ultra-low latency, whole-house coverage, and seamless roaming.

In the third phase, with the development of XR, 8K, cloud gaming, and multi-terminal access, the true gigabit home network evolves to the smart home, where various terminals are interconnected through all-optical base Wi-Fi 7. To carry latency-sensitive services such as VR and 8K, the home base must have deterministic low latency, zero interference, and multi-spectrum Wi-Fi. The typical characteristics of this phase are as follows: Network bandwidth is upgraded to 50G PON, and Wi-Fi 7 implements wide-spectrum access. The network is upgraded to support the L4 autonomous network. With network experience visualization in seconds, proactive locating in minutes, and online precise marketing, service experience self-optimization and assurance as well as network-level fault self-healing are achieved.

2. To Enterprise: Digital Upgrade of Enterprise WANs and Intranets, Achieving Integrated Sensing and Communication

With the popularization and development of applications such as industry intelligentization, video access to the cloud, and unattended remote control, industry WANs require high bandwidth, high reliability, and small-granularity hard pipes. Industry WANs with SDH technologies as the core will be upgraded to next-generation OTN networks. The OTN OSU technology uses 10M timeslot granularities and fixed timeslot multiplexing, while supporting 4000 connections per 100G to achieve one-hop transmission of key service data with high security, high reliability, and low latency.

Within enterprises, intranets generally carry enterprise office, video, surveillance, collection, and production system interconnection services, and fiber to the desktop (FTTD) and fiber to the machine (FTTM) are promoted to create seamless optical network coverage. In this context, existing 10G PON networks can be upgraded to support 50G PON and FTTR Wi-Fi 7. With the help of network hard slicing and deterministic bearer technologies, a unified optical network can be built to provide up to 10 Gbps of bandwidth, low latency within milliseconds, and zero interference for end access in enterprise intranets.

Oriented to integrated sensing and communication, device ports, boards, modules, and management and control functions are upgraded in the F5G Advanced phase to utilize the optical fiber sensing function for oil and gas pipeline inspection and perimeter security protection in key areas such as airports. In this way, the sensing positioning can achieve commercial-level application capabilities, such as 99% accuracy and meter-level precision. The advantage of integrated sensing and communication is that it helps industries build intrinsic sensing capabilities and further expand applications.

3. To Computing: Upgrade from Premium Private Lines to Premium Computing Networks

In the premium private line phase, the core concept is to implement high-quality service bearing; provide 99.999% network availability, low latency, low jitter, and visualization capabilities for private line customers; and support service provisioning within minutes. Premium private lines are not just used by high-end customers such as governments, as their reach now extends to an increasing number of large, medium-sized, and small enterprises. The typical characteristic of premium private lines is E2E OTN networking, which extends OTN coverage to end users within 500 m to 1 km to achieve fast access. In addition, 400G is deployed on backbone networks, 100G+ is widely deployed on metro networks, and OXC is increasingly deployed at the backbone core layer to enhance the low latency capabilities of private line networks. Moreover, 1–5–20 ms three-level latency circles (1 ms within city, 5 ms from city to regional clusters, and 20 ms between hubs) are constructed on private line networks.

In the second phase, a premium computing network is built. This is the initial phase of a computing power network, and its core concept is "collaboration". As the bearing base of premium computing power, an optical network is still an independent unit, meaning optical and computing networks are orchestrated and scheduled separately. However, optical networks start coordinating deployment and operation. Through their collaborative service portal, resource scheduling is implemented to meet user requirements for one-stop service provisioning. On-demand computing network programming flexibly schedules ubiquitous computing power resources, reduces application response latency, improves system processing efficiency, and achieves mutual promotion and win-win development of computing networks. The typical characteristics are as follows: OTN implements on-demand coverage on the CO side in the premium private line phase, implements fast service access to OTN sites within 300 m, realizes the1–5–20 ms latency circles, introduces the computing power sensing function, and can quickly identify the computing power destination and directly access the computing power end through one hop to the cloud using transmission networks. As for the rate increase on the backbone side, backbone networks are upgraded to 400G and 800G to meet the large-capacity transmission requirements brought by centralized computing power. On the management and control side, the upgrade to an L4 autonomous network is supported. The network-wide transmission capacity visualization, resource pooling, automatic provisioning within seconds, and management and control for ultra-large networks with millions of NEs comprehensively enable premium transmission networks with guaranteed bandwidth and latency.

4. Green All-Optical Base: Upgrade and Reconstruct Old Devices, Optimize the Architecture by Replacing Electrical Components with Optical Ones, and Extend WDM to Metro and Access Networks to Build All-Optical Bases

To evolve to F5G Advanced, the green optical transmission base needs the following upgrades:

As more industries go digital, massive old services and devices need to be incorporated and retired. More than 2 million old SDH devices are running on the live network around the world. With the gradual migration of 2G and small-granularity private line services, SDH devices need to be upgraded to optimize equipment room usage. As technologies such as MS-OTN and small-granularity OSU become mature, OTN will definitely replace SDH devices. According to the case of a city in China, after more than 200,000 SDH lines were migrated to OTN, 1.66 million kWh of electricity was saved each year, which is equivalent to planting more than 70,000 trees each year. The electricity fee is reduced by nearly one million CNY. Further more, the SDH-to-OTN upgrade saves more than 90% of equipment room resources.

To cope with the sharp increase in energy consumption caused by rapid traffic growth, operators need to continuously reduce the per-bit power consumption on the bearer network. In addition, operators need to optimize the network architecture and build all-optical target networks by introducing OXC (replacing optical components with electrical ones) to reduce the network-wide energy consumption. Backbone-layer traffic evolves from electrical-layer grooming to optical-layer grooming, enabling the network to feature a 3D-mesh all-optical connection architecture. The discrete ROADM evolves to a unified OXC platform that implements higher than 400G bandwidth all-optical 32-degree to 64-degree grooming and C120 to C120+L120, significantly reducing the energy consumption of backbone traffic forwarding at the electrical layer.

OTN gradually extends from the metro core layer to metro aggregation layer and CO equipment rooms. With an optical-electrical convergence network architecture, the levels of hierarchical electrical-layer grooming on metro networks are reduced. Driven by XR, 8K, cloud computing, and cloud storage services, OTN optical transmission is further extended to service access sites and deployed in equipment rooms, outdoor cabinets, and pole sites. The distance between optical transmission devices and users can be less than 300 m, achieving all-optical access of premium services within the vicinity. Services are transmitted in one hop from the access layer to the core layer/DC at the optical layer. An E2E all-optical network is deployed from the backbone network, metro network, to access network. Optical and electrical resources are pooled and allocated on demand. In this way, the energy efficiency of the entire network is improved by 10 times, making networks greener.

10 Key Technologies of F5G Advanced

1. 400 Gbps and 800 Gbps or Higher Ultra-broadband

As "East Digital West Computing" project comes into full play in China, it has become an imperative task to optimize the interconnection network between the east and west and the direct network between hub nodes. DC network construction is also in full swing outside China. Therefore, the transmission port rate of transmission networks needs to be continuously doubled, and the single-fiber capacity needs to be doubled over the same transmission distance to support large-capacity transmission on backbone networks.

400G metro standards have been released to define 200G at C80 and 400G at C40. In this context, 400G long-haul transmission standards were initiated at the end of 2021 and will be released in 2024. As for 800G standards, several standard organizations are discussing client-side modules, and line-side and system standards will be put on the agenda as the industry continues to develop.

To meet this requirement, the optoelectronic industry needs to prepare key technologies in the optical module, spectrum, optical fiber, and system commissioning fields.

- The port rate of optical modules needs to be increased from 200 Gbps to 400 Gbps and 800 Gbps, and the same or similar transmission capability needs to be maintained. Therefore, the high-performance codec algorithm, FEC algorithm, and non-linear compensation algorithm need to be studied.
- In the 400G phase, OAs will be expanded from the original C band to C+L band to double the spectrum. In this case, the capacity can be doubled at the same spectral efficiency. When the spectral efficiency reaches bottlenecks, the technology evolution path of a wider spectrum can be further explored for the 800G generation.
- New optical fibers, including G.654E fibers with a large effective area and low nonlinearity, multi-core and few-mode optical fibers, and hollow-core optical fibers can be researched and explored.

2. E2E Wavelength Switching OXC

Currently, large-scale ROADM/OXC networks have been deployed at the backbone layer around the world, and optical-layer grooming is being gradually extended to the metro aggregation and access layers. Compared with traditional optical-layer planes, all-optical networks implement one-hop transmission of services at the wavelength level, reducing complex electrical-optical conversions. Like direct trips between high-speed railway stations, all-optical networks feature non-blocking transmission with ultra-low latency. In addition, all-optical grooming —functioning as a "high-speed overpass" — efficiently grooms service traffic, and significantly improves the grooming efficiency. As services develop in the future, all-optical network grooming and all-optical cross-connect units will also face various challenges. Specifically, backbone transmission is evolving toward higher-rate ports, faster grooming, and wider spectrum, and metro networks require more flexible deployment, lower costs, and simplified O&M, which have become the new norms for dynamic development of the metro optical layer. To address the technical challenges of OXC, research needs to be conducted on a low-cost solution with few ports, 64-degree or higher solution with many ports, and C+L-band integrated WSS.

3. Agile Service Provisioning Protocol

The agile service provisioning protocol provides simplified and efficient control for all-optical service cloudification and computing.

- Service protocol: It controls service routes and separates control and forwarding.
- Connection protocol: Control signaling is forwarded along with the data channel. The forwarding performance is decoupled from the number of pipes, and high-performance massive connections can be quickly established.

In the 2B/2H cloud access service scenario, users need to access multiple clouds at one or more points. An OTN edge node needs to detect the destination addresses or VLANs of service packets and automatically map them to corresponding OSU/ODUk pipes. In addition, the OTN edge node detects service application types and traffic, calculates the required bandwidth based on the application traffic model, and automatically triggers bandwidth adjustment for the corresponding OSU pipe. OTN edge nodes use service protocols to forward private network addresses of enterprises through controllers, greatly reducing the operation complexity of intermediate NEs on the network.

A fiber cut affects thousands or even tens of thousands of small-granularity OSU services, as well as the restoration performance. To mitigate this issue, the automatically switched optical network (ASON) path computation unit pre-computes a preset restoration path and configures the preset resources on each node of the path. As such, when a fiber cut occurs, the connection protocol is forwarded along with the data channel to quickly activate bandwidth and achieve fast restoration within 10 ms.

4. Optical Service Unit (OSU)

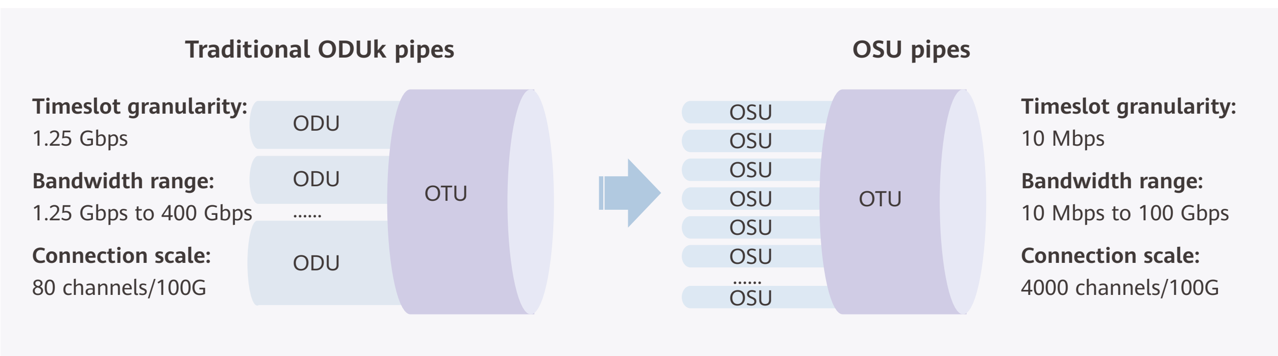
OSU is a network technology used by OTN networks to evolve to large-scale and small-granularity private line bearer scenarios on metro networks. It uses smaller timeslot granularities (on the Mbps level), supports massive elastic hard pipe connections, and provides guaranteed, deterministic low latency as well as comprehensive E2E OAM functions, thereby meeting the high-quality requirements of private line bearer scenarios on metro networks.

China and international standards organizations are actively researching and formulating OSU standards. For instance, China Communications Standards Association (CCSA) has initiated OSU standards and defined technical solutions. Currently, the technical solutions have a stable definition. Meanwhile, ITU-T initiated the G.OSU standard and discussed scenario requirements as well as technical directions. At the ITU-T SG15 plenary meeting in September 2022, ITU-T reached a consensus on the corresponding technical directions, laying a foundation for OSU standard formulation.

The key OSU technologies and features are as follows:

- Massive connections: 10,000 connections per 100G are supported; therefore 100,000 connections can be achieved on a metro network.
- Flexible bandwidth adjustment: Hitless pipe bandwidth adjustment is supported based on service requirements.
- Transparent transmission of clock signals: CBR services can be transparently transmitted to meet the clock performance requirements of customer services.
- Service awareness and mapping: Service awareness is supported to encapsulate and map service flows to OSU pipes.
- Stable and low latency: The latency during electrical-layer pass-through processing of large-granularity services is stable and within 10 µs.

Figure | OSU pipes



5. 50G PON

In September 2021, ITU-T approved and released the 50G PON standard. 50G PON is widely recognized as the mainstream next-generation PON technology in the industry. The 50G PON system defined in the ITU-T standard uses the point-to-multipoint architecture and time division multiplexing (TDM) technology. The first version supports 50 Gbps in the downstream direction and 12.5 Gbps or 25 Gbps in the upstream direction, while the future enhanced version will support 50 Gbps in both the upstream and downstream directions. Additionally, 50G PON introduces the digital signal processor (DSP) to compensate for component performance, improving access bandwidth by five times compared with 10G PON. 50G PON also features higher service support capabilities. Specifically, it supports technologies such as single-frame multi-burst, registration window elimination, Co-DBA (reduces transmission latency and jitter), and PON slicing (provides deterministic service quality).

The release of the standard promotes the maturity of the 50G PON technology and industry, with predictions pointing to the commercial use of 50G PON by 2025. Intergenerational network upgrade and smooth evolution have always been the key concerns of the industry. As network evolution is a gradual process, a technical solution for the coexistence of 50G PON and PON over the same live optical distribution network (ODN) needs to be developed. In this regard, the multi-PON module (MPM) solution for a single PON port at the CO is a key research direction. To improve 50G PON deployment efficiency, CO devices must support the same optical power budget and port density as devices on the live network. That said, it is still technically challenging to support an optical power budget greater than 29 dBm and high-density PON boards. As such, the research directions include new high-power lasers, high-sensitivity receiver chips, and low-complexity DSP algorithms.

6. Wi-Fi 7

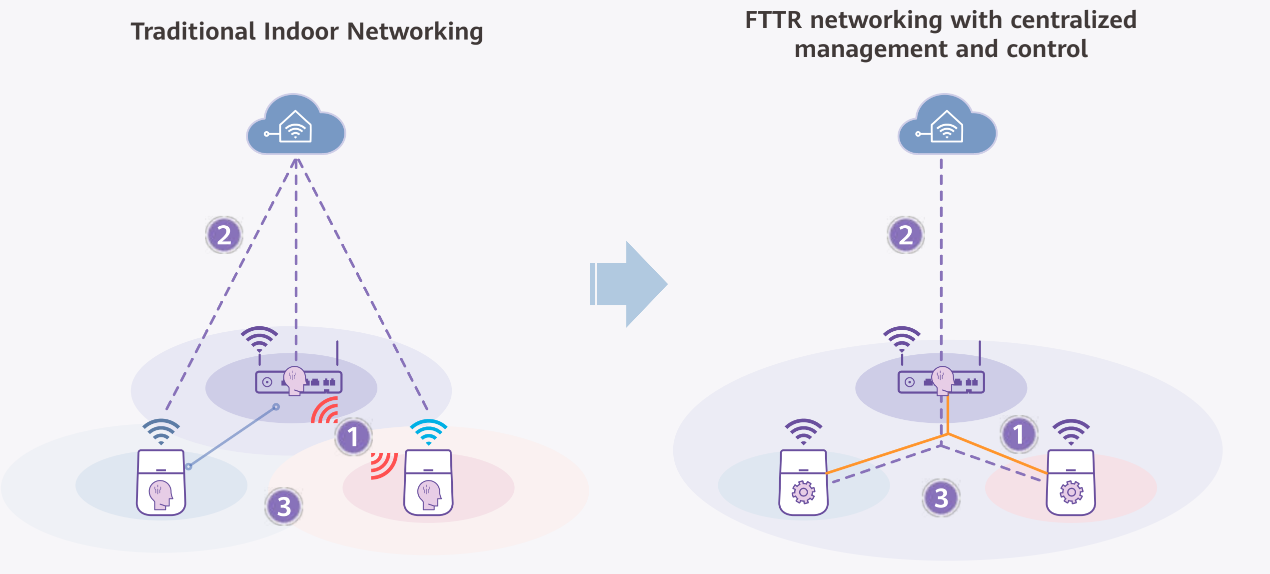
Wi-Fi 7 (IEEE 802.11be) is an upgrade of Wi-Fi 6 and Wi-Fi 6E. Draft 2.0 of Wi-Fi 7 will be finalized in 2022, and the standard will likely be released by the end of 2024. Wi-Fi 7 can provide a peak data rate over 30 Gbps, which is approximately three times faster than the peak data rate of Wi-Fi 6. In addition, Wi-Fi 7 is backward compatible with previous-generation Wi-Fi devices.

To meet the requirements of new applications in the future, Wi-Fi 7 features multiple enhancements compared with Wi-Fi 6, for example, higher access throughput and lower access latency. To improve the access rate, Wi-Fi 7 uses 2.4 GHz, 5 GHz, and 6 GHz spectrum resources and introduces multiple technologies, such as the 320 MHz frequency band and 4K quadrature amplitude modulation (QAM). To reduce latency, Wi-Fi 7 adopts technologies such as multi-link operations and multi-user resource unit (Multi-RU), while exploring the coordination and scheduling mechanism between multiple APs. That said, a lot of research is still needed to fully utilize the capabilities of Wi-Fi 7. The Wi-Fi 7 320 MHz ultra-wide spectrum is in the 6 GHz wireless frequency band; however, this frequency band may not be commercially available in some countries or regions. In this case, the millimeter band is a possible choice. Due to the use of 6 GHz or higher frequency bands and new mechanisms with higher complexity, highly integrated, miniaturized, and low power consumption RF components, antennas, and supportive algorithms are the key research directions.

7. FTTR Networking with Centralized Management and Control

As its name suggests, FTTR extends optical fibers to every room in a home or small enterprise to ensure premium service experience in indoor environments. FTTR consists of three parts: master FTTR unit (MFU), slave FTTR units (SFUs), and indoor fiber network. An MFU is deployed at the access point of a house or SME, and multiple SFUs are connected to the MFU using optical fibers based on service requirements and network planning to provide wired and wireless gigabit network coverage for each room.

Figure | FTTR networking with centralized management and control



Traditional Indoor Networking

1. Unstable megabit backhaul over copper lines or Wi-Fi
2. Complex O&M due to independent devices
3. Experience Fluctuation due to competition between multiple Wi-Fi APs

FTTR networking with centralized management and control

1. One-network for smart connection base (full-fiber connection, stable ultra-gigabit)
2. Simplified O&M on one network (Centralized management on master FTTR unit)
3. Stable experience on one network (central coordination of optical and Wi-Fi networks)

A key feature of FTTR is the indoor distributed fiber network. Optical fiber networking features ultra-large bandwidth, stable anti-interference, and low energy consumption. It supports one-off deployment and long-term evolution, making it an ideal choice for indoor networking. To adapt to diverse deployment scenarios and improve deployment and maintenance efficiency, technical innovations have been made around elegant and tensile optical fibers, power over fiber (PoF) cables, and onsite termination.

Stable and premium experience is the key goal of FTTR. To this end, FTTR needs to address major issues of traditional indoor Wi-Fi networks, such as lack of control and stability. For this, it uses a centralized one-network management and control architecture in combination with multi-layer enhancements such as service and connection collaboration, optical and Wi-Fi collaboration, and centralized Wi-Fi control. It also enables precise collaboration of Wi-Fi APs on the entire network from multiple dimensions — such as frequency domain, time domain, and space domain — to provide consistent and stable connection experience and zero-packet-loss roaming on the entire network. Continuous exploration and research are required to balance service experience requirements with device resource limitations, thereby obtaining the optimal optical and Wi-Fi collaboration mechanism and centralized Wi-Fi management and control algorithm.

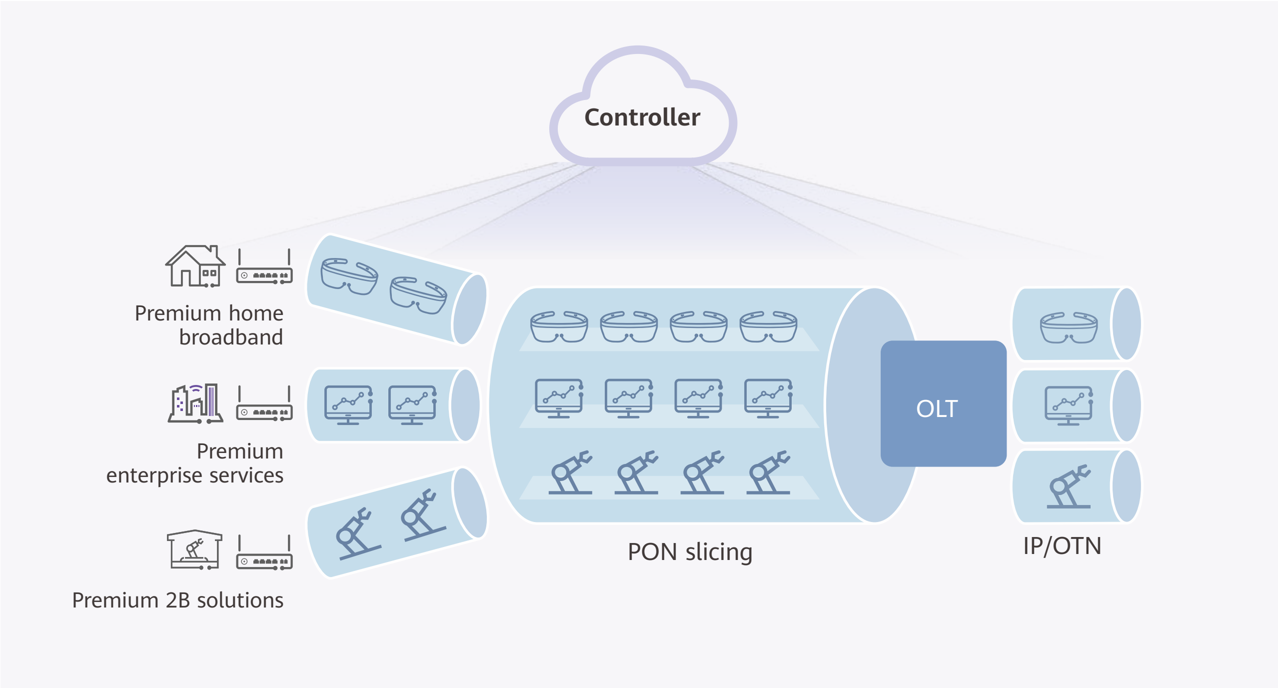
The fundamental idea of FTTR is that only one network is needed for a whole house and O&M is simplified. One FTTR network is simplified into one management point to support one-click service provisioning and intelligent O&M. The FTTR one-network O&M framework and management model need to be jointly studied and defined by the industry. For one thing, premium FTTR connections are the cornerstone of smart applications for homes and SMEs. For another, widely distributed optical fibers and devices have sensing and computing capabilities, making them key data generation sources and data processing resources. Indeed, FTTR has great potential to provide smart services in the future to increase network values.

8. PON Multi-Dimensional Slicing

To ensure experience and guarantee SLAs, E2E slicing is implemented on the Wi-Fi air interface, ONU Ethernet port, and OLT network-side egress. Slices are created dynamically, and resources are allocated on demand based on committed, visible, and manageable SLA requirements to enable integrated service bearing over a single fiber. In addition, technologies — such as home and enterprise Wi-Fi network optimization and optical access network time and frequency multiplexing — are used to meet millisecond-level and microsecond-level deterministic low latency requirements.

E2E slicing involves the egress of the ONU and OLT on the access side. Slices of each device on the network are properly combined to implement dynamic slice creation and on-demand resource scheduling. E2E industry private network slicing enables a multi-purpose network to provide differentiated bearer services for different industry users.

Figure | PON multi-dimensional slicing



There are three types of slices on a PON access network: management slices, resource slices, and resource slices. A management slice is a slice of management resources, used for precise access control. In multi-tenant scenarios, each tenant can customize views based on service requirements, and visualize and manage only their own network resources. Resource slicing is the basis of access network slicing. ONUs and Ethernet ports must be allocated to a dedicated network, which each must have an independent forwarding domain. Traffic slicing is mainly used to classify applications to implement deterministic and differentiated SLAs.

Latency and jitter of Wi-Fi interfaces are key bottlenecks in home/campus office scenarios. Wi-Fi 7 uses the OFDMA technology, multi-user resource allocation, and multi-link collaboration algorithm to implement integrated slicing by multiplexing air interface time and frequency. This effectively reduces Wi-Fi air interface conflicts, reduces service forwarding latency and jitter, and achieves deterministic millisecond-level latency, meeting requirements of services such as XR Pro.

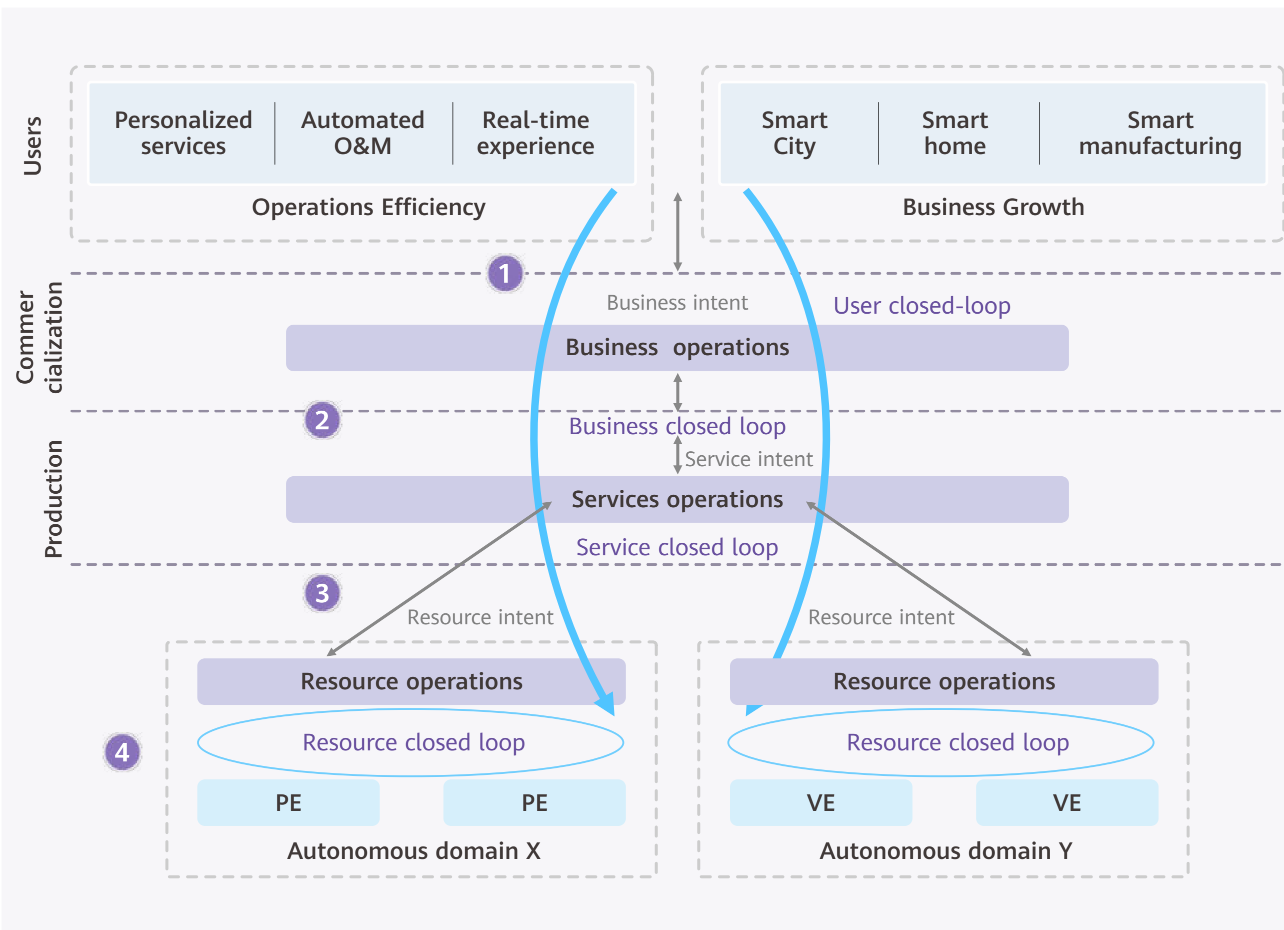
The TDM forwarding plane is added to the optical access network, forming a dual-plane forwarding architecture. The jitter compensation mechanism, single-frame multi-burst technology, independent registration channel technology, and collaborative DBA technology are introduced to implement microsecond-level low-latency forwarding and service jitter at the service forwarding layer, helping industries such as industrial remote control and precision manufacturing go intelligent.

9. Native Intelligence for Autonomous Networks

The Autonomous Networks Project (ANP) of the Telecom Management Forum (TM Forum) defined the overall architecture and classification standards of autonomous networks, while the European Telecommunication Standards Institute (ETSI) researched and standardized how to implement E2E automatic management of networks and services, as well as how to apply AI technologies in autonomous networks from the perspective of resource facing services (RFSs). Currently, related projects and working groups of the TM Forum, ETSI, and China Communications Standards Association (CCSA), and other related standards organizations have established a collaborative organization to jointly research and standardize autonomous networks, in addition to promoting the implementation of standards for autonomous network technology in different fields such as optical networks.

The TM Forum has launched the Autonomous Network White Paper, which defines the system architecture of autonomous networks, as shown in the following figure.

Figure | PON multi-dimensional slicing



Key technologies that support optical autonomous networks mainly cover the following five technical directions:

1） Visualized transmission capacity

Allocate integrated weights to multiple factors such as the network usage and latency based on real-time detection of the computing power-network status to calculate paths that not only meet SLA requirements of different services and but also evenly use network resources. Oriented to the dynamic trend of computing power-network services, introduce AI technologies to automatically learn the distribution characteristics, duration modes, and growth trends of computing power-network services, to optimize the multi-factor path computation capability. Oriented to integrated computing power-network scheduling, concurrently calculate routes from users to all optional computing nodes for the upper-layer system to intelligently determine a computing power-network scheme based on network transmission capability measurement data.

2） Automatic service provisioning in seconds

Integrate the automatic optical service provisioning capabilities of device vendors' network management and control systems through automatic interfaces between BSS/OSS subsystems, to support application-driven automatic service provisioning in seconds. Enable the system to automatically set the service source and sink addresses, port types of user devices, as well as the bandwidth, protection, and latency requirements, automatically calculate paths that meet latency and protection requirements and allocate resources, create server paths for services or reuse existing server paths, and create E2E connections. In this way, manual provisioning in days or weeks is replaced with automatic provisioning in seconds, thereby improving service provisioning.

3） Ultra-large network management and control

Deploy a two-level architecture consisting of the super and domain controllers. The domain controller is used for single-domain service scheduling; the super controller for cross-domain service scheduling. The two controllers collaborate to implement flexible scheduling of a large network with millions of NEs.

4） Personalized services

Deploy intelligent OLTs to identify more than 70 OSS labels in four categories for online users, such as poor-QoE, experience status, home networking, and poor-QoE bottlenecks. In this way, BSS systems can implement personalized services more accurately over gigabit/FTTR networks, changing from potential customer identification in weeks to real-time recommendation.

5） Real-time experience assurance

Provide VIP users with dedicated assurance capabilities such as E2E dynamic topology visualization, fault diagnosis, and experience optimization, to accurately sense and locate possible suspension, disconnection, and slow response issues. Complaint-triggered response and locating are replaced with routine assurance, assuring user experiences.

10. Harmonized/Integrated Communication and Sensing

- **Key optical cable digitalization technologies**

It is difficult for NEs in an optical communication system to monitor the health and status of dumb resources such as optical cable networks. Operators have long lacked effective digital management methods for port occupation status and fiber patch cord connections in optical distribution frames (ODFs) in equipment rooms and outdoor fiber distribution terminals (FDTs). As advanced technologies such as sensors, AI, and big data become popular, digital information collection and processing tools developed for various handheld terminals, intelligent device boards with optical fiber quality monitoring and optical cable status awareness capabilities, and advanced and efficient computing and machine vision algorithms can now be used to provide operators and other optical cable network owners with real-time and accurate digital recording, audit, and synchronization of massive dumb resources such as passive facilities, optical fibers, and optical cables. At the same time, for the backbone and distribution optical cable sections of the local network of an operator with the highest proportion of the total mileage of optical cables, based on the innovative breakthroughs in bottom-layer optoelectronic components and basic materials, some equipment vendors have made optical route resources of a gigabit optical network visible and manageable from end to end, setting a clear path for O&M development in the access section of an optical cable network in the future.

- **Key optical fiber sensing technologies**

Optical fiber sensing uses the physical properties of light as it travels along a fiber to detect changes in vibration, temperature, strain, and other parameters. This technology utilizes the fiber itself as the sensor to create thousands of continuous sensor points along the fiber, and so is also called distributed optical fiber sensing. The principle is to use a standard or specific fiber to implement measurement using Raman, Rayleigh, and Brillouin distributed optical fiber sensor techniques.

Unlike traditional electromechanical and electronic sensors, optical fiber sensors feature anti-electromagnetic interference, corrosion resistance, easy integration, intrinsic safety, long distance, and high precision. Thanks to these advantages, optical fiber sensing has been widely used in large-scale engineering projects. It also has a large number of mature application cases in various industries, such as oil and gas pipeline intrusion detection, perimeter detection for large campuses and rail transits, security detection for large civil engineering structures such as bridges and dams, and security detection for railways such as tunnels.

Application scenarios of optical fiber sensing are further enriched thanks to the continuous performance improvement of narrow-linewidth light sources, the mature application of new technologies such as the multi-carrier technology, pulse code, and special sensing fibers, as well as automatic event identification using the big data generated during AI-powered optical fiber sensing processing. These trends also continuously improve the KPIs including the coverage distance and sensing precision of optical fiber sensing and event identification accuracy.

- **Key Wi-Fi sensing technologies**

Radio waves are the best sensors. Leveraging the sensing function of Wi-Fi 7, radio waves have the benefits of low cost, continuity, and non-infringement on user privacy, in addition to supporting valuable applications such as indoor positioning, motion detection, and breathing frequency detection. Wi-Fi sensing technologies usually use the change patterns of signal arrival time (for example, IEEE 802.11az) and channel state information (for example, IEEE 802.11bf) of a signal propagation path to sense existence or motion information of a person or an object in a coverage area.

Affected by the operating environment, Wi-Fi signals may suffer from interference, fading, and multipath effects during transmission, which limits the precision and accuracy of Wi-Fi sensing and identification. Much research in the industry has focused on continuously improving the precision and accuracy of Wi-Fi sensing and identification based on the characteristics of Wi-Fi signal transmission. To improve Wi-Fi sensing precision, signal waveforms and sequences that match refined personal features can be designed for signals to reflect slight changes in personal features. Alternatively, the multiple-input multiple-output (MIMO) antenna technology can be used to obtain more multi-dimensional radio channel information. In addition, using millimeter waves that have shorter wavelengths is also a potential direction. To improve Wi-Fi sensing accuracy, environment anti-interference technologies can be enhanced to prevent statistical features from being overwhelmed by interference. Alternatively, technologies for cross-AP synchronization and coordination can be explored to obtain more accurate and richer information over the entire network.

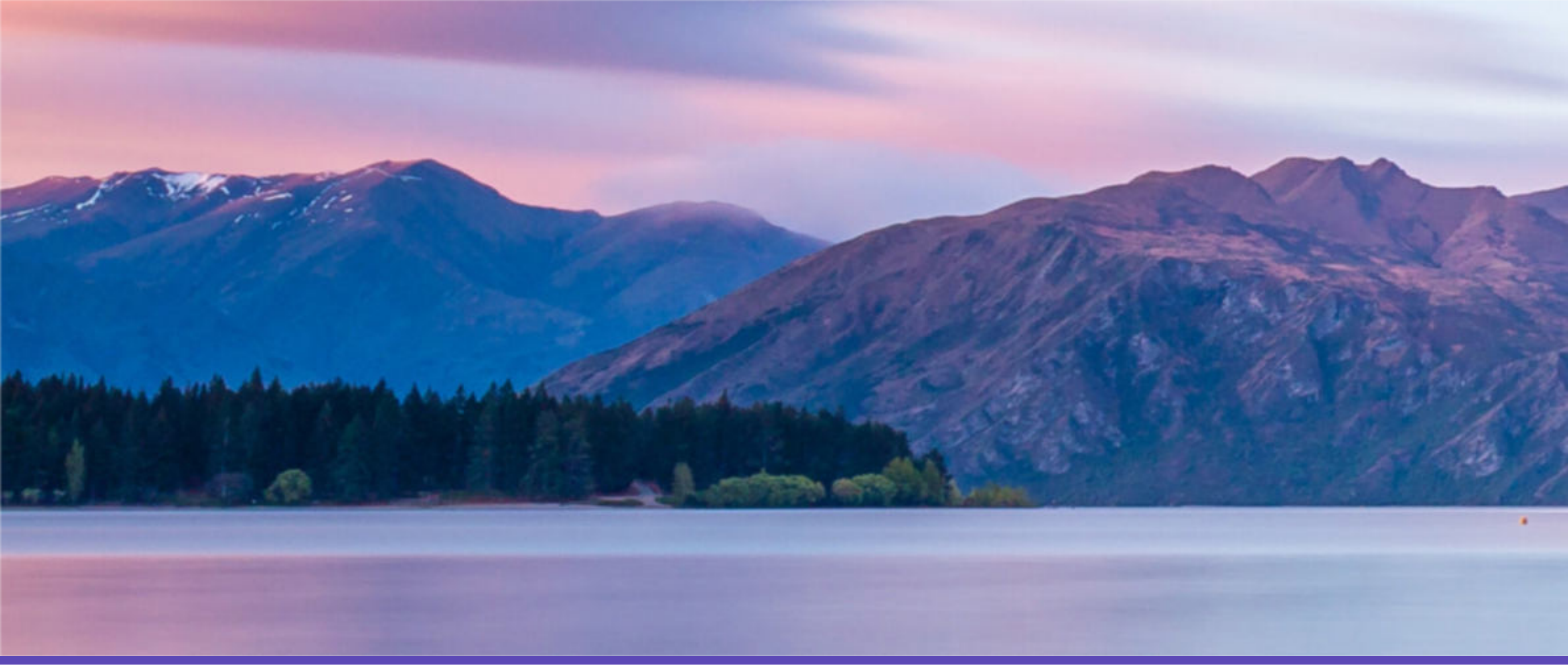
Summary and Prospects

Optical communication is always in a state of continuous innovation and development. In the first phase, F5G standards have been put into commercial use. But F5G technologies are still developing. At the meeting on September 16, 2022, the ETSI officially named the next phase: F5G Advanced. It defines new goals and capabilities for the future development of F5G. With the wide application of F5G in various industries, new opportunities and service requirements are generated for homes, enterprises, and industries. Evolution to F5G Advanced is required to enrich applications, promote innovation, and build a sustainable fixed network industry. Let's join hands to stride into F5G Advanced and usher in a new era of fiber to everywhere.

Acronyms and Abbreviations

AI	artificial intelligence
DCI	Data Center Interconnect
ETSI	European Telecommunications Standards Institute
F5G	the Fifth-Generation Fixed Network
FlexO	Flexible Optical Transport Network
FTTH	fiber to the home
FTTR	fiber to the room
FTTO	fiber to the office
GPON	gigabit passive optical network
MPM PON	Multi-Processing Module passive optical network
$NEE_{Network}$	network energy efficiency index
HPC	high-performance computing
ICT	information and communications technology
oDSP	optical digital signal processing
OT	Operation Technology
OLT	optical line termination
ODN	optical distribution network
ONU	optical network unit
ONT	optical network terminal
OSU	optical service unit
OSUflex	optical service unit flex
ROADM	reconfigurable optical add/drop multiplexer
OXC	optical cross-connect
OSS	operations support system
PLC	production line control
SLA	Service Level Agreement
TM Forum	telecommunication management forum
VR	virtual reality
WI	Work Item
WBBA	World Broadband Association

F5G Advanced
产业白皮书



贡献者

中国联合网络通信集团有限公司	唐雄燕、王光全、王泽林、张贺、邵岩、满祥锟、孙越、沈世奎、董姗
中国信息通信研究院	敖立、刘谦
中国移动通信集团有限公司	李晗、张德朝、李俊玮、李允博
Bharti	Praveen Maheshwari
北京邮电大学	张杰、赵永利、张治国
中国电子工程设计院有限公司	张旭
工业和信息化部电子第五研究所	胡妍飞
中南大学	黎胤
CTTC	Raul Muñoz
e&	Mohamed al Marzooqi
烽火通信科技股份有限公司	陈松涛、彭绍勇、李洪亮、隋玉洲
Globe Telecom	Emmanuel Lazaro R. Estrada
华中科技大学	程孟凡、杨奇
华为技术有限公司	王景吉、龚倩、陆小华、孙春、罗贤龙
机械工业仪器仪表综合技术经济研究所	刘丹
Orange	Philippe Chanclou
绿色全光网络技术委员会	张锐利
Post Luxembourg	Olivier Ferveur
PT Telkom	NA
企帅数字科技	何敞昌、高显明
University of Patras	Ioannis Tomkos
Union SHENZHEN Hospital	Suisong Zhu
VTAL	Evandro Bender
中兴通讯股份有限公司	罗来荣、刘传珠、张海军、李明生、王孟

目录 CONTENTS

序言

2020年2月欧洲电信标准化协会（ETSI）正式发布F5G提出了“光联万物”产业愿景。经过2年多发展F5G从标准组织到行业应用都实现了快速的发展：会员数近100家、提交了1000+篇的文稿、成立了13个WI进行技术的研究等极大的带动了F5G在行业应用的标准化工作。2021年底WBBA的成立开启了F5G从标准走向产业新开端，2022年9月ETSI发布了F5G Advanced标准白皮书推动F5G产业持续向前演进。

F5G网络正在全球加速推进，从产业发展驱动角度看，F5G在促进家庭信息消费，赋能社会民生及行业融合应用方面产生了重要的支撑作用。当前全球的主要经济体都已经或正在推出F5G千兆宽带战略及相关政策，F5G的商用部署及行业融合应用也呈现出规模化态势。

四大动能驱动产业持续演进，进入F5G Advanced时代：

- 光纤网络联通现实世界向虚拟世界，需要网络支持业务从1G到10G演进
- 从电信级向工业级演进，深化行业的数字化能力
- 从通信向感知演进：挖掘光纤网络的无限潜能
- 光纤网络走向更绿色的网络架构，实现10倍能效提升

下一个十年，千兆接入全面普及、万兆接入规模商用， 企业云化、数字化转型持续深化，万物互联的智能时代正加速到来，固定网络面临前所未有的历史机遇。

本白皮书立足新场景新应用，对架构演进及网络新能力进行了探索，重点讨论了家庭、企业、算网及绿色光网络等关键需求场景，定义了F5G Advanced的产业目标、核心特征、关键网络指标、演进路径及关键技术能力，旨在为F5G Advanced发展提供可参考的场景需求和技术走向，为网络演进探索新的方向，促进产业形成共识，共同迈向F5G Advanced新时代。

F5G回顾与F5G Advanced演进

1. F5G发展回顾

2020年2月，欧洲电信标准化协会（ETSI）正式发布F5G，提出了“光联万物”产业愿景，以宽带接入10G PON+FTTR、Wi-Fi 6、光传送单波200G+OXC为核心技术，首次定义了固网代际。其内涵是在光网的接入侧提升光纤化宽带化水平实现千兆速率，承载侧利用全光底座实现千行百业的品质承载。F5G固定代际标准及光联万物的愿景一经提出迅速成为产业界热议的焦点，ETSI的标准2年多从标准组织到行业应用都实现了快速的发展，会员数近100家，提交了1000+篇的文稿，成立了13个WI进行技术的研究，召开了60+场次的周边组织研讨，极大的带动了F5G在行业应用的标准化工作，2021年底WBBA的成立开启了F5G从标准走向产业新开端。

同时光联万物，F5G服务千行百业，构筑家庭数字化、企业数字化以及公共服务和社会治理数字化的联接底座带来的经济效益也逐步成为全球产业共识 。中国社会科学院做的一份研究报告显示，2020-2025年间F5G平均每年能拉动中国GDP增长0.3个百分点。F5G是数字经济的基石，已成为国家ICT基础设施发展的核心战略。在欧洲，欧盟发布“2030数字十年计划Europe's Digital Decade”和“VHCN指导方针”，从政策、资金、监管等方面牵引欧洲各国千兆光纤网络建设。在中国，“十四五规划”明确提出全面部署千兆光纤网络，加快千兆城市建设和200G/400G升级，并制定3年行动计划确保目标达成。此外，有20+国家发布光纤宽带顶层规划，如泰国“Giga Thailand”、埃及“Decent Life”、摩洛哥“NBN 2025”、尼日利亚“NNBP 2025”、科特迪瓦“National Broadband Implement Plan”，加快了光纤宽带部署。印度“Digital India”，围绕“高速宽带、移动泛在接入”等9个领域打造数字社会和知识经济，推动印度社会的全面数字化转型。

在生活领域，一方面F5G以其大带宽、低时延、泛联接的特征满足对网络和信息服务的新需求；另一方面，F5G孵化新产品、新应用和新业态，加快供给与需求的匹配度，不断满足消费者日益增长的多样化信息产品需求。

在生产领域，光纤从家庭走向园区，走向工厂和机器，光进铜退正成为新的建网趋势。FTTO全光园区已在超 过15,000家教育、医疗、金融机构部署。FTTM全光工业网已在超过百家煤矿井下安全生产、港口超远控、交通全 光路口创新应用。F5G以绿色环保、极简架构、大带宽、确定性低时延、安全可靠等特性，助力千行百业数字化转型，极大地释放了传统行业的生产力。

从全球运营商的统计数据来看，从2020年-2021年，FTTH新增用户 1亿，千兆宽带用户数超7千万，FTTR部署超过80万套，FTTO/FTTM 进企业超过2万家，F5G的产业生态已经全面建立。

2. F5G Advanced产业演进四大驱动力

与前几代通信网络不同，F5G千兆光网被认为是新型信息基础设施的重要组成，构成了经济社会发展的信息大动脉，在赋能数字经济发展，助力千行百业数字化转型中具有重要支撑作用。欧盟提出2030数字罗盘（Digital Compass）计划，明确制定了千兆全光战略，中国也在千兆光网赋能行业应用方面启动“追光计划–工业领航行动”将 持续深化“千兆光网+行业融合应用”作为当前的重要目标。从产业演进的角度看，F5G需要应对如下挑战：

超高清沉浸式体验，需要更大带宽更低时延的网络：随着技术的发展演进，元宇宙应用的兴起，极大地促进了VR/AR/XR、光场显示等高清视频产业的发展。根据华为研究以及第三方咨询报告，2030年将有超10亿用户通过XR体验“身临其境”的全新虚拟世界，并实现和物理世界的交互。以远程办公为代表的多方视频通话、虚拟会议等将成为常态， 构建沉浸式体验的虚拟世界，实现自然的交互体验，需要1Gbps~10Gbps带宽、20ms~5ms的时延，同时为保障家庭、企业多用户并发体验，需要带宽10倍提升，对现有F5G千兆网络能力提出了新的挑战。

工业制造、能源、交通等行业数字化，需要网络进一步提升实时性和可靠性：F5G推动光网络进入工业领域，随着产业数字化、智能化升级加速，机器视觉等超高清视频回传、远程运动控 制等应用规模发展，需要20us时延、20ns抖动、零丢包和99.9999%高可靠联接。而当前的串行总线时延 >100us，且时延、抖动逐站累加，难以满足要求，需要新型现场 总线满足工业控制的苛刻要求。能源、交通生产网对网络的安全可靠、低时延有很高要求，随着高清视频回传等大带宽业务需求的发展，需要提供每个站点GE带宽、1ms低时延、99.999%高可靠的硬管道联接，承载并使能OT的自动化、智能化升级，加速 行业生产网络的数字化转型。

无处不在的光缆网，需要数字化管理和增加环境感知能力：随着F5G Fiber to Everywhere的深化部署，光纤进一步向末端延伸，连接数增加10倍，光纤部署里程数增加 20%。一方面，运营商拥有海量的光缆哑资源，管理维护变 得越来越复杂，需要通过数字化技术手段，实现光缆位置的 精准定位、光缆故障位置的准确识别等数字化、可视化管 理。另一方面，F5G在行业的规模部署，推动企业场景光缆 无处不在。光纤不仅可以满足企业通信的功能，还具有感知 振动、温度、应力等参数的特性，可以通过光纤对外部环境进行精准感知，在油气管线在线巡检等场景发挥巨大作用。

企业数字化、云化加速，需要网络架构极简、绿色低碳：随着企业云化和数字化转型加速，业务集中云端部署，流量主要是从终端汇聚到数据中心，同时8K/XR等大带 宽应用驱动未来10年网络的流量复合增长率26%以上，要求网络带宽10倍以上提升。而现有多级逐跳转发的网络架 构，在时延、功耗等方面均面临挑战，需要一跳直达、全光调度、极简扁平化架构的绿色全光网，实现网络能效10 倍提升，更好满足企业数字化发展的需要。

F5G Advanced产业目标与特征

F5G Advanced以光纤、OTN站点、Wi-Fi频谱为核心，与家庭、行业应用、光缆及管网感知深度融合，通过提升传送和接入的全光底座能力服务于万物互联。其目标是实现像水电一样的“无处不在的全光基础设施”，构建“Fiber to Everywhere、OTN to EverySite、通感一体及全光自智网络“的产业目标。

具体内涵包括：

接入侧带宽持续由1Gbps向10Gbps演进；通过Fiber to Everywhere推进光纤化部署，打造宽带数字化底座支撑业务从现实世界走向虚拟世界。

OTN向楼宇、小区、站点、DC延伸覆盖并能够一跳直达入云， 实现OTN to Every Site的覆盖，通过构建超低时延、绿色高能效品质承载网络实现各种场景的差异化承载，助力千行百业数字化，全面支撑向数字世界的演进。

对无处不在的光缆网，进行数字化管理和环境感知，实现通信与感知的融合，释放光纤无限潜能，助力各种管网资源的数字化，从人工巡检演进为无人巡检，实现社会资源与通信资源的综合治理。

全光自智网络助力网络从自动化向智能化演进，加速

图 | F5G Advanced 产业目标

差异化产品运营，通过L4自智网络网络的升级，实现传送和接入的全光底座的智能智慧化管理，实现家宽体验自优化，专线、品质算力极速联接提质。

围绕产业目标，F5G Advanced阶段与F5G最大的变化是在原有特征持续扩展的基础上新增了绿色敏捷全光网、面向工业制造的实时韧性联接、通感一体三大特征，具体表现为：

- 增强宽带（eFBB）：从千兆接入迈向万兆家庭/万兆园区/百T网络，实现1 Gbps->10 Gbps Everywhere（线路带宽翻番 200G/400G-->400G/800G）
- 绿色敏捷全光网（GAO）： OTN to Every Site，打造一跳直达、10倍能效提升的绿色敏捷的品质全光网
- 全光联接（FFC）：打造智慧家庭/企家协同/全光园区数字化底座，提升高品质联接数
- 低时延高可靠工业级联接（RRL）： 6个9超高可靠、μs级确定性低时延全光生产网，助力千行百业数智化升级.
- 体验可保障（GRE）：家宽从可视定位到体验自优化，专线/算网极速智能联接提质
- 通感一体化（OSV）： 从通信到感知，释放光纤网络无限潜能

图 | 从F5G演进到F5G Advanced，产业特征持续扩展

F5G Advanced应用场景探讨

1. 联家：打造智家DICT新生活

1.1 沉浸式XR+全屋智能，持续提升家庭生活品质

随着终端成熟度提升及千兆网络规模部署，家庭业务向多屏化、多元化和智能化演进，打造智慧新生活。一方面业务从4K->8K->XR沉浸式体验不断提升，根据第三方咨询报告，未来5年XR产业迎来高速发展，2030年将有超10亿用户通过XR体验“身临其境”的全新虚拟世界，并实现和物理世界的交互。如工作场景下人们戴上1个头盔设备，在家里即可以和客户、同事创建虚拟“面对面”的真实交互的工作体验。学习场景下将以一种全新的方式呈现，教育资源线上化可最大化资源共享，学生也可通过AR眼镜近距离观察化学反应变化等。生活场景下XR带来更加丰富多彩的生活体验，如人们可以随时随地和朋友举办虚拟派对，和远在他乡的亲人进行亲切交谈等。另一方面终端连接数量将10倍以上增长，智能家居从单终端走向全屋智能，各类终端互联互通并结合场景式交互，打造亲切自然的居家体验，构建懂你的空间。如疲劳一天回到家时，喜欢的灯光、音乐、香氛和电视节目自动开启；智能床、智能枕、卧室的照明、音效等系统的协同，为人体打造一个睡眠辅助系统，根据个体的生理健康特征和睡眠习惯，自动匹配床垫和枕头的软硬度；营造助眠的光环境，刺激褪黑素分泌等。通过3D光感知精准感知老人姿态等，并和摄像头等联动，既保护隐私，又无需佩戴可穿戴设备，科技赋能智慧养老。

沉浸式XR和全屋智能等业务发展对网络带宽、时延等提出更高要求，F5G Advanced阶段通过50GPON和FTTR Wi-Fi 7等新能力实现1~10Gbps全屋无缝覆盖、ms级时延和无缝漫游等运营级的Wi-Fi体验保障等，提供随时随地工作学习、无眩晕感的身临其境交互、隐私无忧的健康看护和亲切自然的居家体验等智慧新生活品质，打造家庭DICT新服务和新业态，开启万亿新空间。

1.2 家庭从娱乐中心到多元生活中心，提供企家协同差异化服务

社会发展和疫情等多种因素影响，家庭从娱乐中心向多元化生活中心演进，远程教育、远程办公、全民直播等成为家庭场景下的重要组成。如在疫情期间居家办公成为一种新模式，办公场景边界模糊，远程办公要能达到企业办公室体验诉求，包括超高清视频会议不卡顿，文件传输和远程访问毫秒级无感知，物理层安全权限隔离控制和数据不出园区等。

家庭多元化生活中心的发展对网络提出带宽时延可保障、加密隔离等类专线的品质要求，F5G Advanced阶段通过E2E差异化承载管道、高价值业务一跳入云、OTN政企专网隔离等新能力，使能家宽从传统的互联网尽力服务向SLA品质可保障的家宽类专线演进，提供企家协同、直播宽带等差异化服务，2H流量变2B流量，进一步释放宽带网络价值。

1.3 品质宽带自智网络，使能业务从带宽经营向体验经营转型

伴随千兆光宽的高速发展和用户规模增长，家庭业务的多样化和个性化诉求激增，对光纤宽带网络的服务运营能力提出更高要求，宽带网络引入 AI、大数据等技术，使能运营商从带宽经营向体验经营转型，提升用户粘性和发展个性化新业务。TM Forum的《自智网络白皮书》定义了L0-L5自智网络分级标准，近期多个运营商发布白皮书将2025年达成自智网络L4等级作为数字化转型目标， 实现感知、分析、决策、执行的高度自动化，实现开通Zero Wait、维护Zero Touch、业务Zero Trouble的高品质个性化服务。

F5G Advanced阶段通过引入大数据和人工智能等新技术构建家宽业务E2E数字化运营运维能力，实现宽带体验从感知、分析、决策、执行的全生命周期高度自动化&智能化分级经营。一方面实现质差实时可视和故障自愈，推进家宽从投诉驱动的被动式排障运维演进到体验驱动的主动式调优保障，从线下传统营销到线上精准营销。另一方面针对高价值业务体验自动优化，通过提供不同保障等级的金银铜管道业务和动态分流入云，实现终端业务体验自优化，助力家宽不断提升体验和服务品质，持续提升用户满意度并加速新业务发展。

2. 联企：推动IT和OT融合，FTTO/FTTM赋能企业数智化

2.1 沉浸式XR应用：带来办公、学习和远程医疗全新体验

企业数字化加速发展，在办公、学校、医院等场景下XR广泛应用、数据上云和跨地域智能协作等逐步成主流。如医院医疗场景，疫情常态化、人口老龄化、公平医疗、分级诊疗，驱动医院广泛应用体征检测等智能终端，3D CT等医疗检查数据实时上云，医生通过360 度高清视频远程观察患者相关部位；XR广泛应用在智慧教室，实现智慧教学、远程课堂、电子书包等多场景沉浸式教学场景；在企业办公场景，数字化办公一直追求的是用户存在感和空间感，让互动方式更自然、沟通效率更高效，沉浸式XR办公可帮助人们体验到共处一室的空间感。开会时还可以“面对面”互动，能从不同角度观察聊天对象并进行肢体或眼神交流，打破屏幕阻隔感。

企业8K直播、XR办公和XR智慧教室等业务对网络提出更高的要求。F5G Advanced阶段通过50GPON和FTTR Wi-Fi 7等新能力实现1~10Gbps全屋无缝覆盖、ms级确定性时延等，带来100G设计文件分钟级上传下载，三维CT影像浏览秒级可视，给企业和行业客户带来极致的网络体验。

2.2 工业光网：打造工业互联网光底座

随着社会经济的快速发展，行业数字化转型进一步加速。工业制造逐步向数字化、智能化、无人化和柔性化方向发展，3D机器视觉质检、云化PLC以及集中控制类应用在未来的工业制造中逐步成为主流。伴随着3D质检、云化PLC及远程操控等应用在工业互联网行业的应用，对网络可靠性、带宽及时延提出了更高的要求，1~10Gbps的上行能力，6个9的可靠性要求，μs级的确定性时延及产线分钟级灵活扩展能力，匹配智能应用对网络的需求。

F5G Advanced演进阶段工业光网一方面发挥光纤绿色节能、稳定抗干扰、大带宽、灵活柔性扩容、长距覆盖等特点，另一方面增强确定性μs级时延和抖动，E2E硬管道隔离等新能力实现工业级品质网络保障，促进港口无人化、工厂柔性智能产线及3D AI质检等业务发展，打造工业互联网光底座，进一步释放千行百业生产力。

2.3 行业数智化转型：向绿色、高可靠和确定性演进

随着行业数智化转型的逐步深入，传统的能源交通行业向着云化、视频化、物联化方向发展。以电力为例，清洁低碳是全球的趋势，光伏/风电等绿色新能源、数字化变电站的物联应用等新场景，电力公司需要一张面向新型电力系统网络，包括三方面能力：一、配网侧各种新能源设备的并网，包括屋顶光伏，充电桩，会导致配网的调控复杂度提高，需要更精准的采集和调控通信能力，电力配网需从二遥向三遥升级，以进一步缩短年均停电时长。二、数字化变电站加速建设，一个变电站布放几百个各类的传感器，一个数字换流站会布放几千个各类传感器，各传感器授时尤其是雷击要求达到μs量级。三、分布式光伏并网+配网终端激增，智能终端和视频接入不影响生产区业务稳定性，需确定性低时延<5ms和硬隔离能力。

因此未来电力通信网络相较传统网络需要更多的连接数，更可靠的通信质量，更低的确定性ms级时延，确保采集与调控业务的100%安全可靠，才能满足新型电力系统“削峰填谷”的需求。F5G Advanced阶段，基于硬切片的OSU技术应运而生，不光具备OTN大带宽优势，同时承载小带宽业务，带宽0浪费，时延有保障，是传统

网络升级演进的最佳技术路径，实现E2E硬管道为终端设备提供“微专线”的通信质量保障。

其它行业如煤矿、公路、铁路等长距传输网络场景，通过光纤将各个孤立的信息点位数据串接在一起，实现数据的汇集与共享，催进行业数字化应用发展。

2.4 通感一体：释放光纤网络无限潜能

随着海量的光纤资源部署，光纤作为哑资源，不能准确收集光缆网资源信息光路故障难以定障和定界等问题成为世界难题。F5G Advanced阶段引入光路智能数字化技术，实现ODN拓扑和光功率全程可视和米级精准诊断，为运营商打造一张实时可视、精准感知、高效运维的数字化光缆网极大提升运维效率。

同时，光纤不仅可以进行信号传递，同时具备良好的温度、振动、应力等感知功能，各行各业逐步认识到光学传感绿色、高效、本质安全等独特优势，主动将光传感技术应用于生产活动中。如传统的油气和轨道交通等领域需靠人工进行长距离的巡查存在耗时耗力，而且巡查的效果和实时性不佳的情况，油气管道巡线费用高达2万￥/km/年。F5G Advanced阶段将光纤感知功能应用于油气等管道检测、机场等周界安防等领域，并结合智能算法可极大改善传统人工巡检等模式效率达到99%准确率和米级精度等商业级应用水准，真正实现全时段无人化巡检，入侵事件提前检测预警，有效减少管道事故，大幅提升行业效率。

面向未来光谱检测技术还能实现微元素、气体浓度的测量。如将光谱气体感知功能应用于城市地下管廊可燃易爆气体检测、炼化厂有害气体泄露检测，不仅能提前预警，还能够实时掌握有毒有害气体空间场分布状态，秒级确定泄漏源，辅助救援人员制定救援措施；依托第四代原子光谱LIBS，可替代传统X射线荧光和伽马射线法，使能冶金和矿业实现实时、无辐射、高准确率的元素含量检测。

3. 联算：大带宽、确定性、可调度运力，实现品质入算

3.1 从算间互联到用户入算，需要大带宽、确定性、可调度、快速灵活接入的品质运力保障

算力枢纽互联需要大带宽：受新基建、数字化转型等国家政策促进及企业降本增效需求的驱动，我国数据中心近年来发展迅速，截至2021年底，全国在用数据中心机架总规模超过520万，近五年年均复合增速超过30%。其中，大型以上数据中心机架规模增长更为迅速，占比达到80%。根据部分省市发布的枢纽集群建设规划， 10大集群节点规模共计超500万机架，其中西部枢纽以服务全国算力需求为主，出省带宽预计超80%，东部省份出省带宽预计35%。东数西算将带来骨干网带宽大幅增长，当完成规划的机架数时，预计骨干带宽将增加3000T以上，对算力互联的大带宽提出更高挑战。

算间互联延需要确定性低时延：东数西算和数据中心间多级协同开展业务是趋势，数据中心直连网络需要稳定与可靠的低时延，如时延要求较高的数据中心双活业务要求时延在1-2ms以内。发改委牵头的《 全国一体化大数据中心协同创新体系算力枢纽实施方案 》中明确，为保障冷温热业务的合理调配，枢纽之间数据中心端到端单向网络时延原则上在 20 毫秒范围内。

云边协同需要全光运力网络具备灵活调度能力：根据Gartner预测，到2025 年，约75%企业生成的数据将在数据中心之外创建和处理。边缘计算在智慧交通、安防监控、工业互联网等场景中的应用越来越广泛，通过边缘计算承担了许多实时性、需要快速数据处理的任务，但仍有大量经过处理的数据需要从边缘节点汇集到中心云做进一步的大数据分析挖掘、数据共享，进行算法模型的训练，并将升级后的算法推送到前端，使前端设备及时更新和升级。同时，边缘节点存储的大量数据，也需要备份到云端，防止边缘节点故障导致的数据丢失，所以，需要云与云、云与边、边与边高效协同，而全光运力网络作为连接的纽带和桥梁，就需要具备高度灵活的调度能力，以匹配云边协同的业务需求。

用户入算需要便捷接入、灵活敏捷、安全可靠的运力网络：政府、金融、教育等企业机构在城市内广泛分布在不同的地理位置，当他们需要算力服务时，要求可以快速接入全光运力网络；一些企业核心业务需要高安全、低时延，亟需全光运力网络提供保障；新的业务动态性的特点，要求全光运力网络具备灵活敏捷的调整能力，快速响应客户需求的变化，及时匹配资源、并且也及时释放资源。

在F5G Advanced阶段，大带宽、确定性低时延、可调度能力以及快速灵活敏捷的接入的运力网络是品质入算的保障。

3.2 品质入算的自智网络

算力的全国一体化调度，需要全国范围的端到端资源调度能力：算力网络时代，算力可在全国范围内实现跨区域大范围协同，要求全国资源一盘棋，提出一张网调度，带来了大网管控能力的诉求，目前按照分省、分市分级管理的方式面临挑战。具不完全统计和估算，各运营商在大规模省份平均约1.5~2万台OTN设备，中等规模省份平均约7千台，小规模省份平均约3千台，结合未来5年发展各运营商全国规模可达到30~50万台OTN设备，这就需要管控系统要具备大规模网络的管控能力，并实现端到端的运力调度，同时还要很好地解决网络规模变大后带来的更为复杂的告警管理分析、定界定位、隐患分析等网络运维挑战。

随着枢纽算力、省级算力、地市边缘算力的分级部署，用户的算力需求可由不同的算力资源进行响应，算网大脑需要综合考虑时延、带宽的运力能力和算力因素做出判断和选择。这就需要全光运力网络的管控系统与算网大脑能够有效协同，统筹进行资源选择和网络连接的建立。

在F5G Advanced初期，通过提供全网运力可视，支撑网络资源的灵活调度，提升网络资源调配效率。在F5G Advanced成长阶段，提供网络资源的灵活调度能力和高可靠的业务服务能力，如支持秒级智能调度能力，支撑5个9的高可用率等，从而支撑可保障带宽、可保障时延。在F5G Advanced成熟阶段，通过支持百万级超大网管控，将实现全国一张网的灵活调度，使能东数西算为代表的全国算力资源灵活调度。

4. 绿色全光底座：助力承载网络能效10倍提升

面对海量的数据传输和“碳中和”的要求，网络对高效节能的技术方案提出了更高的诉求，在承载网中，光纤传输技术能耗最低，是达成目标的方案首选。在2C场景，把光纤传输延深到基站站点，完全满足5G和未来6G的接入带宽和时延诉求；在2H场景，用光纤传输替换铜线、电缆传输，降低75%能耗，满足用户未来数字家庭的体验；在2B场景，延伸到办公室、厂房的光纤连接大幅减少信号的网络路径功耗，大带宽低时延提升用户的线路品质体验。

网络演进到F5G Advanced阶段，光网络需从四个维度实现绿色低碳：第一、光谱从C波段到L波段，大幅提升光纤单纤容量，降低每bit功耗；第二、提升设备硬件能效技术降低设备本身耗能、如引入液冷、智能调温控温、洋流算法等优化能耗；第三、实现DC化设备改造进一步提升站点能效；第四，传统光层架构采用FOADM方式部署，网络资源利用率低、业务穿通需要大量人工操作，占用较大机房空间和更高的能耗。通过OXC解决方案简化核心及汇聚光层部署；利用城域池化波分使能单个汇聚站点通过一块池化单板接入多个接入环，实现多环共享方式，提升波长资源利用率，降低光层复杂度，实现波长自动规划；结合二者构建端到端全光极简目标网架构，使能一跳入云、多业务统一承载，从而在网络架构上实现能耗的优化，整网的能效提升10倍以上。

在绿色运营上进行多种节能创新：通过设置单板绿色休眠工作模式，降低非业务模式下的能耗；全网实现多级动态节能，实现设备槽位、单板、端口、接口等多级能耗动态管理使光传输设备能耗能效实时最优；强化业务快速接入，敏捷建立连接，实现光层分钟级、电层秒级的建联以及M~T级带宽ms级无损调整整体提升运营效率实现精准控制。

F5G Advanced演进路径

1. 联家：向FTTX演进，打造全屋智慧家庭

全球运营商整体上通过3个阶段发展FTTH网络，不断深化服务边界和提升业务品质。

第一阶段，全光网络具有绿色低碳、高带宽、高稳定性和低延迟等特点，并为用户提供先进的服务和应用，正成为各国绿色和数字化转型的关键战略。各国政府和运营商通过光纤政策牵引、综合光缆网规划、利旧现网基站和回传光纤等各种资源、引入数字化预链接ODN等技术，持续降低FTTH建设TCO等措施，全面加速FTTH建设。

第二阶段，随着业务和宽带套餐发展升级到500~10000M，发展4K/8K/VR、在线办公/教育、直播等价值业务，通过构建规建验维能力推进光纤延伸到房间，通过10GPON+FTTR构建千兆带宽，满足用户真千兆、超低时延、全屋覆盖、无感漫游的千兆体验的家庭网络第三阶段，随着XR、8k超高清、云游戏，家庭多终端的接入，标志着真千兆家庭演进到了智慧家庭阶段，在这个阶段，各种家庭终端都通过全光底座Wi-Fi 7实现互联，为了承载VR，8K等低时延敏感业务，家庭底座需要具有确定性低时延能力，0干扰能力，多宽谱的Wi-Fi 7，这个阶段的典型特征为：网络带宽升级为50GPON、Wi-Fi 7实现宽谱接入。升级支持L4自智网络：网络体验支持秒级体验可视、分钟级主动定位、线上精准营销，从而实现业务体验自优可保障、网络级故障自愈。

2. 联企：企业广域网、内网数字化升级，实现通感一体

随着行业数智化、视频入云、无人值守远程遥控等应用的普及和发展，对行业广域网提出了大带宽，高可靠、小颗粒硬管道的诉求，以SDH技术为核心的行业广域网将升级到新一代OTN网络。利用OTN OSU技术所具备的10M时隙粒度及完全固定时隙复接方式，同时支持4K连接/100G的能力，支撑关键业务数据一跳如云，实现高安全，高可靠、低时延传输。

企业内网，承载着企业的办公，视频，监控，采集，及生产系统互联的需求，进一步推进光纤到桌面、光纤到机器形成企业内的无缝光网覆盖，升级现有10GPON网络到50GPON和FTTR Wi-Fi 7等新能力，引入网络硬切片功能，以及确定性承载技术建设一张统一的光网，企业内网将具备末端接入高达10G带宽，ms级低时延以及0干扰的网络能力。

面向通感一体，在F5G Advanced阶段，升级设备端口、板卡及管控等功能，将光纤感知功能应用于油气等管道检测、机场等周界安防等领域，使得感知定位精度达到99%准确率和米级精度等商业级应用水准，通感一体帮助构建行业的内生感知能力并进一步延伸出更深的应用。

3. 联算：品质专线向品质入算升级

在品质专线阶段，核心理念是实现业务的品质承载，为专线客户提供5个9网络高可用性、低时延、低抖动及可视化能力并能够进行分钟级业务发放，品质专线的用户从党政军高端客户逐步向大中，中小企业扩展，品质专线的典型特征是OTN端到端组网，从覆盖上向最终用户500m-1km范围内延伸，实现快速接入；同时骨干部署400G，城域广泛部署100G+网络，OXC在骨干核心层全面部署增强专线网络的低时延能力。构建城市内1ms、城域到区域集群算力5ms、枢纽间20ms的1-5-20ms三级时延圈。

第二阶段：品质入算，本阶段是算力网络的起步阶段，其核心理念是"协同"。光网作为品质算力的承载底座，尽管和算网依然是两个独立的个体，各自编排调度，但光算网开始向布局协同、运营协同发展，通过协同算网服务入口，实现资源互调，满足用户一站开通需求。按需进行算力网络编程，灵活调度泛在的算力资源，降低应用响应时延，提升系统处理效率，实现算网发展互促互进，共生共赢。典型特征为：OTN从品质专线阶段的按需覆盖完成普遍CO侧覆盖，实现业务到OTN站点<300m快速接入，构建算力枢纽间、枢纽内以及用户入算的1-5-20ms低时延圈，引入算力感知功能，能够快速识别算力目的地通过运力网络一跳入云直接接入算力端；对骨干侧速率提速，通过骨干网升级到400G、800G大容量满足算力集中带来的大容量传送要求；管控侧升级支持L4自智网络：全网运力可视，资源池化，秒级自动开通，百万级超大网管控，全面使能可保障带宽、可保障时延的品质运力网络。

4. 绿色全光底座：老旧设备升级改造、以光换电优化架构、波分向城域、接入延伸构建全光底座

向F5G Advanced演进，绿色光传送底座需要从如下几个维度进行升级：

行业数字化转型加速带来大量老旧业务和设备面临收编和退网；全球约有200多万套老旧SDH设备在现网运行，随着2G和小颗粒专线业务的逐步迁移，大量SDH占据的机房资源需要清理改造。MS-OTN、OSU小颗粒等技术的成熟使得OTN已经成为替代SDH的必然趋势。参照中国区某市的案例，20+万条SDH业务被OTN替代实现全面割接后，每年节省了166万度电，相当于每年种70000多棵树，节省电费近百万，O改S实现了机房资源90%+的节省。

为了应对流量快速增长带来的能耗大幅增加，承载网络一方面通过不断提升单Bit能效，实现总网络能耗不增加，同时通过建设全光目标网，优化架构设计降低整网能耗成为发展的方向：引入OXC以光换电，从电层调度向光层调度演进使得网络具备立体化、Mesh化的全光连接架构；分离式的ROADM向OXC统一平台演进，实现32~64维、C120到C120+L120的400G+大带宽的全光调度，可大幅降低骨干流量在电层转发的能耗。

OTN从城域核心向城域汇聚、CO机房逐步延伸，通过光电融合的组网架构，进一步减少城域的逐级电层调度层级。同时在XR、8K、云计算/云存储等业务驱动下，OTN光传送阶段进一步延伸到业务接入站点，部署到机房、室外柜、杆站等多种位置，距离用户仅<300m，实现品质业务的全光就近接入。整体上形成业务从接入到核心/DC之间光层调度一跳直达；骨干、城域到接入一张端到端的全光大网，光电资源统一调配，资源池化按需取用，整个网络的能效得到的10X提升，促使全网向更加绿色节能的方向持续发展。

F5G Advanced十大关键技术

Top1. 400Gbps和800Gbps+超宽技术

随着中国“东数西算”工程正式全面启动，优化东西部间互联网络和枢纽节点间直连网络，成为一项重要的任务，海外围绕DC数据中心建网也成为趋势。数据中心DCI互连和干线光网络流量持续提升，需要传送网的传输端口速率持续翻番，并能在距离不变的情况下单纤容量倍增，实现骨干网络大容量传输。

400G城域标准也已发布，定义了200G@C80和400G@C40；400G长距标准在2021年底完成立项，预计2024年发布；800G标准当前主要是几个标准组织在讨论客户侧模块，线路侧及系统标准后续会跟随产业发展逐步提上日程。

为了适配这一需求，光电产业需要在光模块、光谱、光纤以及相应的系统调测领域做关键技术准备：

- 光模块端口速率需要由当前的200G提升到400G和800G，同时要能保持相同或近似的传输能力，这就需要在高性能编解码算法、FEC算法以及非线性补偿算法方面进行研究。
- 光放在400G阶段将从原来的C波段扩展到C+L波段，实现频谱翻倍，从而可以在谱效率基本不变的情况下，实现容量翻倍。在频谱效率面临瓶颈的情况下，800G代际可继续探索更宽频谱的技术演进路线。
- 新型光纤的研究和探索，包括大有效面积、低非线性的G.654E， 多芯少模光纤，空芯光纤等。

Top2. 端到端波长交换OXC

目前，全球范围内骨干层面均已经部署大规模的ROADM/OXC网络，光层调度逐步向城域汇聚及接入层延伸。相对于传统的老光层平面，全光网实现业务波长级一跳直达，减少复杂电光转化，建立类似“高铁”大站直达，无阻塞，超低时延、全光调度式“高速立交”，高效疏导业务流量，极大提升带宽调度效率。面向未来业务发展，全光网络调度和全光交叉单元也面临了一系列挑战。骨干传输向高端口、更快调度、更宽频谱演进；城域网络要求更加灵活的部署、更低成本和极简运维成为城域光层动态化发展新常态。针对OXC一系列的技术挑战，需要在包括低成本少端口、64D及以上多端口、C+L一体化WSS等进行研究。

Top3. 敏捷发放业务协议

敏捷业务发放协议：面向全光业务入云和入算提供极简、高效控制协议

- 业务协议：业务路由控制，控制和转发分离
- 连接协议：控制信令随数据通道转发，转发性能同管

道数量解耦，海量连接快速建立性能保证

2B/2H入云业务场景中，用户需要一点/多点接入并连接到多云，OTN边缘节点需要通过感知业务报文的目的地址/VLAN，自动映射到对应的OSU/ODUk管道中。同时OTN边缘节点感知业务应用类型和流量，并根据应用流量模型计算所需带宽，自动触发对应OSU管道带宽调整。OTN边缘节点通过业务协议实现企业端私网地址的转发，同时通过控制器转发可以大幅降低对网络内中间经过网元的操作复杂性。

面向OSU小颗粒度业务，断纤影响的业务量会到千级甚至万级以上，恢复性能会受到影响。智能路径计算单元预先计算恢复路径并将预置资源配置到恢复路径每个节点，当断纤故障时，连接协议随数据通道转发，快速激活带宽，实现十毫秒级恢复性能。

Top4. 光业务单元OSU

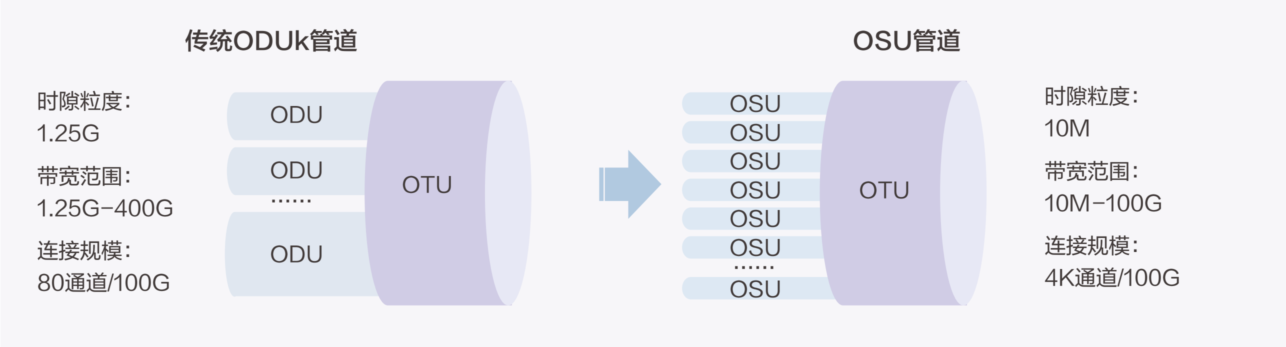
光业务单元（OSU）是OTN网络面向城域网大规模小颗粒专线承载场景演进的网络技术，采用更小的时隙粒度（Mbit/s级），支持海量的弹性硬管道连接，提供可承诺的确定性低时延，完善的端到端OAM功能，满足城域网专线承载场景的高品质需求。

国内和国际标准组织分别积极开展OSU标准的研究与制定，国内CCSA已经完成了OSU标准立项及技术方案定义，当前技术方案定义已经稳定；国际ITU-T 已经完成了G.OSU标准的立项、场景需求以及技术方向的讨论，在2022年9月ITU-T SG15全会上达成众多的技术方向共识，为OSU标准制定奠定了基础。

OSU关键技术特点:

- 海量连接：单100G 支持10K级别的连接，实现单个城域网络内十万级的连接数
- 带宽弹性可调：支持按业务需求，实现管道带宽的无损调整
- 时钟透传：支持CBR业务的透明传输，满足客户业务的时钟性能要求
- 业务感知和映射：支持业务感知，实现业务流到OSU管道的封装映射
- 稳定低时延：大颗粒业务电层穿通处理时延达到10μs以内，时延维持稳定

图 | OSU管道



Top5. 50G PON

2021年9月ITU-T批准发布了50G PON标准，业界普遍认可50G PON是下一代PON的主流技术。ITU-T标准定义的50G PON系统采用点到多点架构和时分复用技术，第一版本支持下行50 Gb/s和上行12.5 Gb/s或25 Gb/s，未来增强版将支持对称50 Gb/s。50G PON引入DSP（digital signal processor）弥补器件性能损伤，使能接入带宽相比10G PON提升5倍。50G PON的业务支持能力也得到增强，单帧多burst、注册窗口消除、Co-DBA(协作DBA)等技术降低了传输的时延和抖动，PON切片技术提升了确定性业务质量保障的能力。

标准发布推动了业界50G PON技术和产业成熟，预计2025年左右开始商用部署。网络代际升级，平滑演进历来是关注重点。网络演进是逐步推进的过程，因此需要提供50G PON系统和现网PON系统同ODN共存的技术方案，局端单PON口MPM（multi-PON module）多模方案是重点研究方向。为了提升50G PON的部署效率，局端设备需要支持现网同等光功率预算和端口密度。当前实现>29dBm光功率预算、高密PON线卡仍面临技术挑战，研究方向包括新型大功率激光器及高灵敏度接收芯片、低复杂度DSP算法。

Top6. Wi-Fi 7

Wi-Fi 7 (IEEE 802.11be) 是Wi-Fi 6以及Wi-Fi 6E的升级。 2022年Wi-Fi 7 Draft2.0定稿，预计2024年底完成标准发布，Wi-Fi 7可以提供超过 30Gbps的标称峰值数据速率，比Wi-Fi 6快约三倍，同时Wi-Fi 7仍可向后兼容前代Wi-Fi设备。

针对未来新兴应用的需要，Wi-Fi 7相较于Wi-Fi 6引入了多项增强技术，除了更高的接入吞吐率，还可以提供更低的接入时延。 针对接入速率提升， Wi-Fi 7可以利用2.4GHz、5GHz和6GHz的频谱资源，引入320MHz频宽、4K正交振幅调变技术（QAM）等多种技术。 针对降低时延， Wi-Fi 7采纳了Multi-Link Operations、Multi-RU（Multi-User Resource Unit）等技术，并探索了多AP间的协同调度机制。要充分发挥Wi-Fi 7的能力，仍有不少研究工作要做。Wi-Fi 7 320MHz超高频宽借助于6GHz无线频段，但该频段在一些国家或地区可获取性是问题，此情况下毫米波段是可能的选择。由于6GHz或以上频段以及更高复杂度新机制的使用，高集成、小型化、低功耗的射频器件、天线以及配套算法是重点研究方向。

Top7. 集中管控FTTR组网

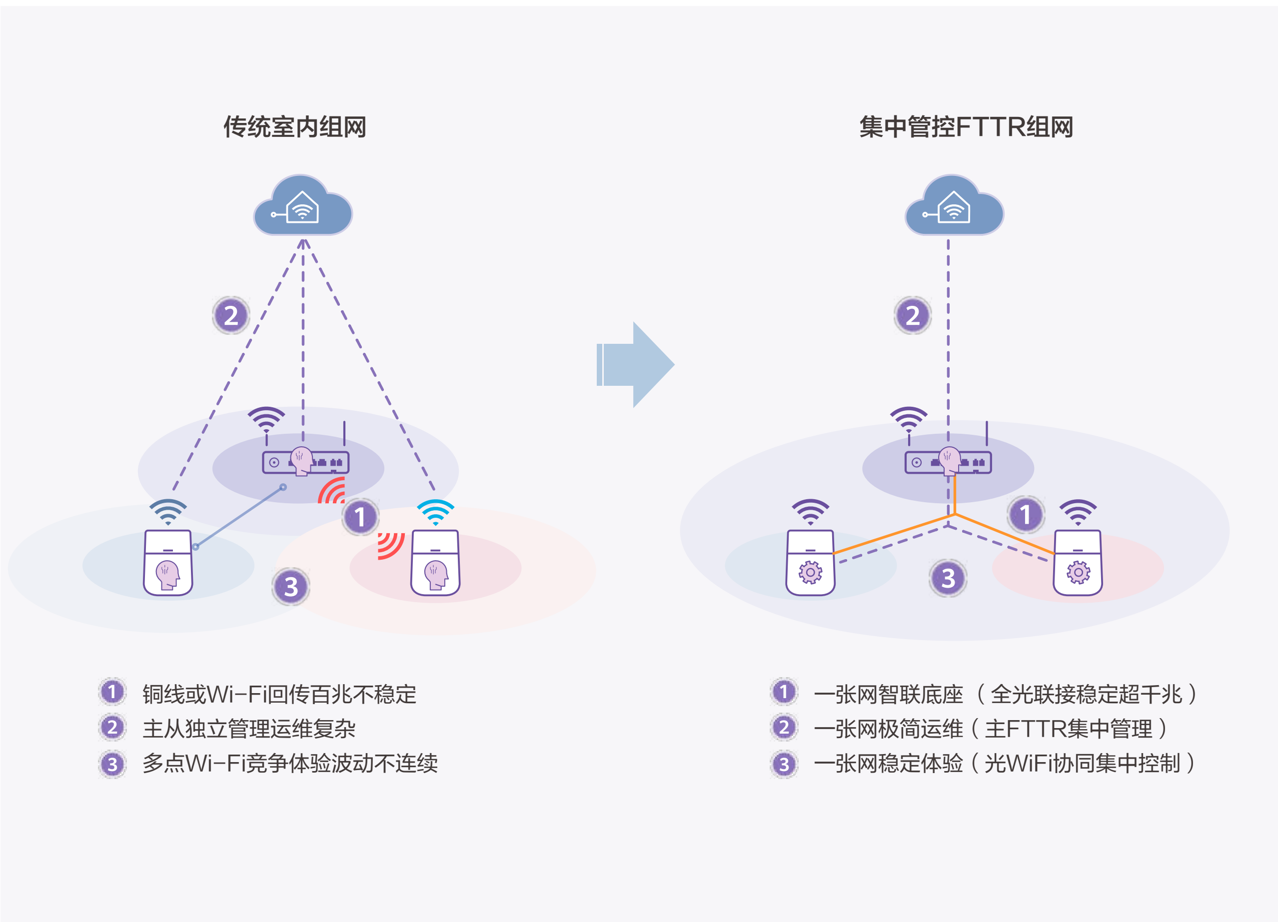
FTTR是将光纤进一步延伸至家庭/小微企业内部的每一个房间，通过光纤构建信息基础设施，围绕业务体验保障为室内每个区域提供高质量网络。FTTR由主设备、从设备和室内光纤分布式网络三部分组成。在家庭/小微企业接入点位置部署主设备并以其为中心，通过室内光纤分布式网络连接多个从设备，从设备基于需求和规划部署，为每个区域提供超千兆的有线、无线一体的网络覆盖。

室内光纤分布式网络是FTTR的关键特征。光纤组网具有超大带宽、稳定抗干扰、绿色节能的优点， 1次部署，长期演进，是室内组网发展的必然选择。为适应多样化的部署场景，提升部署和维护效率，美观抗拉的新材质光纤、光纤/光电复合缆组件及现场成端等技术创新活跃。

全屋一张网稳定高品质体验是FTTR的关键目标。针对传统室内Wi-Fi网络不可控、不稳定等关键问题，FTTR通过中心化的一张网管控架构，依托业务与连接协同、光+Wi-Fi协同、Wi-Fi集中控制等多层次技术增强，使能整网的Wi-Fi AP在频域、时域、空域等多维度精准协同，从而提供整网一致稳定的联接体验以及零丢包无感的漫游体验。权衡业务体验需求以及设备资源限制，获取最优的光与Wi-Fi协同机制、Wi-Fi集中管控算法需要持续的探索研究。

全屋一张网极简运维是FTTR的发展基础。一张FTTR网简化为一个管理点，支持一键式 业务发放及智能运维。FTTR一张网运维框架和管理模型有待业界共同研究和定义。一方面，FTTR高品质连接是家庭及小微企业智慧应用的基石；另一方面，广泛分布的光纤和设备本身也具备感知和计算能力，成为产生数据的源头和数据处理的资源，FTTR未来有巨大的潜力提供智慧服务从而增加网络价值。

图 | 集中管控FTTR组网



Top8. PON多维切片

从Wi-Fi空口、ONU以太网口，到OLT网络侧出口，实现E2E切片保障SLA体验。并通过应用SLA要求的精准感知，实现切片动态创建和资源按需调度等，实现SLA可承诺可视可管，支撑单纤端到端综合业务承载。同时通过家庭/企业内Wi-Fi网络优化、光接入网络时频分等技术匹配毫秒级及更低的微秒级确定性低时延需求。

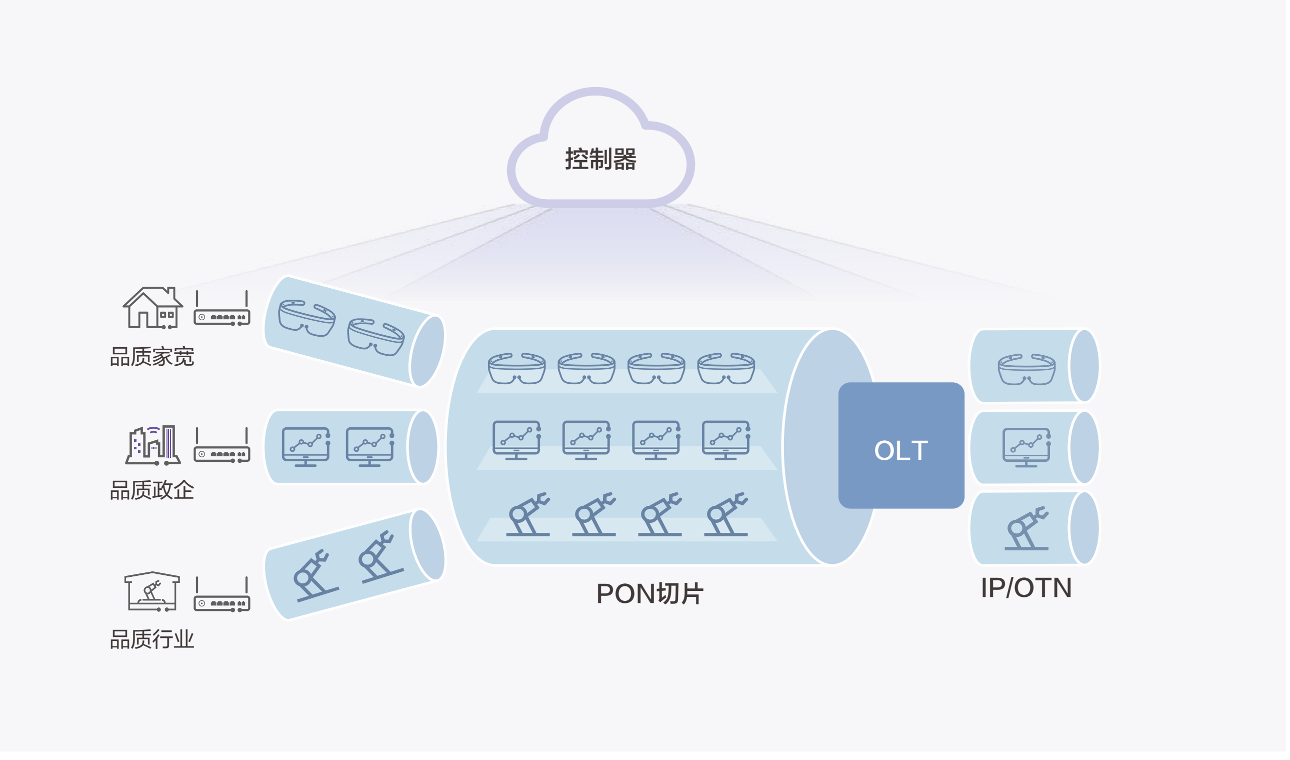
端到端的切片涉及到从接入侧的ONU、OLT网络侧出口，通过合理的组合网络中各个设备的切片，并实现切片动态创建和资源按需调度等，构成端到端的行业专网切片实现一网多用为不同的行业用户提供差异化承载服务。

PON接入网络切片包括三个功能： 管理切片，主要用于对管理资源进行切片以进行准入控制。在多租户场景中，每个租户可以根据业务需求定制视图，只有自己的网络资源才可视可管理。资源切片是接入网切片的基础，ONU、以太网络侧端口应支持独立划分到一个专网Dedicated-Network，每个D-NET应该拥有独立的转发域。流量切片主要用于对应用进行分类实现确定性差异化的SLA。

家庭/园区办公场景内Wi-Fi接口时延和抖动是关键瓶颈。Wi-Fi 7通过OFDMA技术、多用户资源分配和多链路协同算法，实现空口时频分综合切片，有效降低Wi-Fi空口冲突，降低业务转发时延和抖动，实现确定性ms级低时延，匹配XR Pro等业务需要。

光接入网络通过引入双平面转发架构，增加TDM转发平面；配合抖动补偿机制，引入单帧多突发技术、独立注册通道技术、协同DBA技术等，实现业务转发层面微秒级低时延转发、微秒级业务抖动，匹配工业远程控制及精密制造等行业数智化诉求。

图 | PON多维切片



Top9. 智能原生，自智网络

电信管理论坛（Telecom Management Forum，TM Forum）的自智网络项目（Autonomous networks (AN) Project）制定针对自智网络的总体框架和分级标准做了定义。另外，欧洲电信标准协会（European Telecommunication Standards Institute，ETSI）则从面向资源的业务（Resource Facing Service，RFS）的角度，研究和标准化如何实现端到端网络和业务的自动化管理，以及人工智能在自智网络中的应用。目前，TM Forum、ETSI、CCSA的各相关项目和工作组，以及其他相关标准组织，已经成立了跨标准组协同组织，共同研究和标准化自智网络，推动自智网络技术在光网络等不同领域的标准落地。

目前TMF已经发布了自智网络白皮书，定义了自智网络的系统框架如下图。

支撑光网络自智网络的关键技术主要覆盖如下5个技术方向：

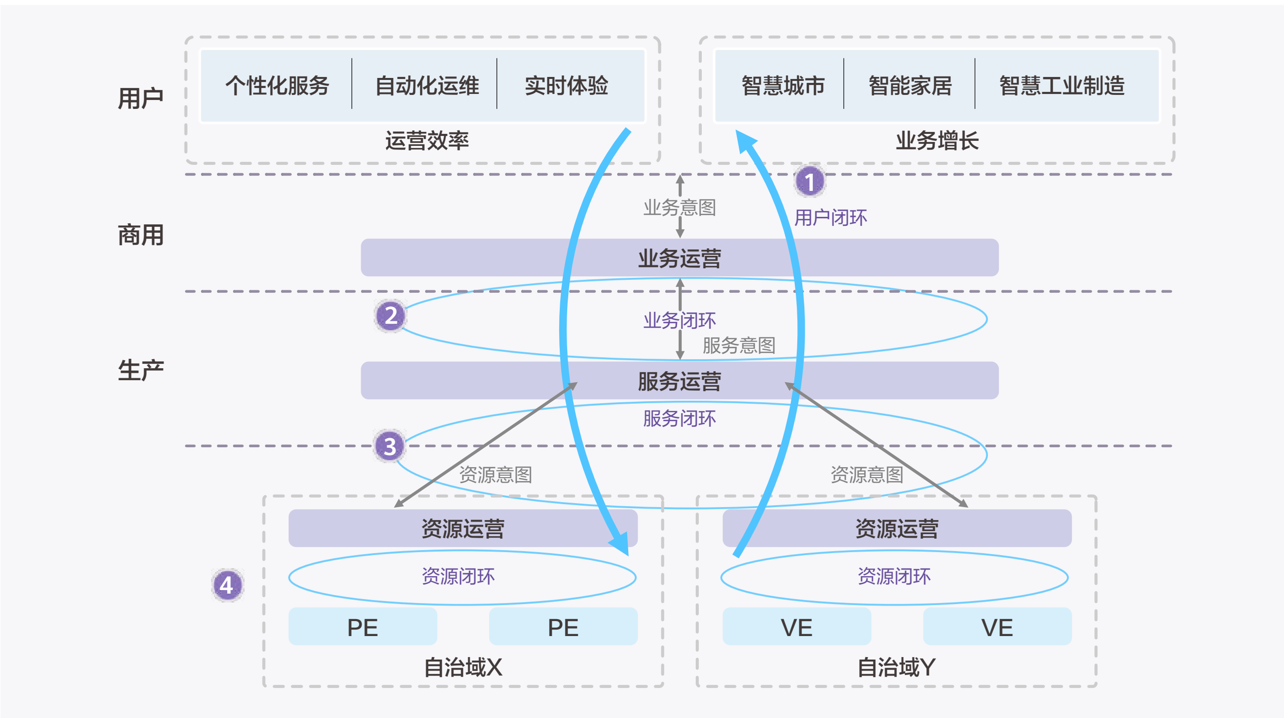
1）运力可视

通过实时感知算网状态，对网络利用率、时延等多因子进行综合权值分配，计算出满足不同业务SLA需求，同时均衡利用网络资源的路径。面向算网业务的动态化趋势，可引入AI技术自学习算网业务分布特征、时长模式、和增长趋势等，优化多因子算路能力。面向算网一体化调配，并发计算用户到所有可选算力节点的路由，使上层系统可以根据网络运力度量数据智能决策算网方案。

2）秒级自动开通

通过打通BSS/OSS各子系统间自动接口，整合设备厂商网络管控系统的光业务自动发放能力，可支持应用驱动的秒级自动开通。系统自动设定业务源/宿地址、用户设备端口类型、带宽和保护、时延等级要求，自动计算满足时延和保护要求的路径和分配资源，创建业务对应的服务层路径或重用现有的服务层路径，并端到端创建连接，实现从天级/周级人工开通到秒级自动发放的提升。

图 | 自智网络架构



3）超大网管控

部署Super控制器+域控制器两级架构，Domain控制器负责单域业务调度，Super控制器完成跨域业务调度，两级控制器协同实现百万级大网灵活调度。

4）个性化服务

OLT具备智能化能力，在线智能识别质差、体验状态、家庭组网、质差瓶颈4类70多个O域标签，从而支撑B域系统面向千兆/FTTR网络，从周级潜客识别到实时推荐的转变，更精准的实现个性化服务。

5）体验实时保障：

为VIP用户提供专属的端到端拓扑动态可视、故障诊断、体验优化等保障能力，从投诉响应、投诉定位到例行保障，对可能发生的卡、断、慢问题提供准确的感知&定位能力，从而实现体验可保障。

Top10. 通感一体化

- **光缆数字化关键技术**

光通信系统中的设备网元一般难以有效监控光缆网等无源基础设施哑资源的健康度和运营状态，运营商对机房光纤配线架（ODF）和室外光交箱的端口占用状态和跳纤连接关系长期缺乏行之有效的数字化管理手段。随着传感器、人工智能和大数据等先进技术的蓬勃发展，基于各类手持终端设备开发的数字化信息采集和处理工具，及具备光纤质量监控和光缆态势感知能力的智能化设备板卡，结合先进高效的计算视觉和机器视觉算法，将为运营商及其他光缆网业主提供实时、精确的无源设施点、光纤、光缆等海量哑资源的数字化录入、稽核和同步功能。同时，针对光缆线路总里程占比最高的运营商本地网主干和配线光缆段，基于底层光电器件和基础材料的创新突破，已有设备厂商实现了对千兆光网“端到端”光路资源的可视、可管，并逐步成为未来光缆网接入段运维管理的发展方向。

- **光纤传感关键技术**

光纤传感利用光在经过光纤时的物理性质来检测振动、温度、应变和其他参数的变化。光纤传感利用光纤作为传感器，在光纤沿线创建数千个连续的传感器点。这称为分布式光纤传感。基本原理是使用标准或特定光纤，通过拉曼、瑞利和布里渊分布式光纤传感器技术实现测量。

与传统的机电和电子传感器相比，光纤传感有着一系列的优点，该技术以抗电磁干扰、耐腐蚀、易集成、本质安全、距离远、精度高等特点，在大型工程项目中应用优势明显，已被人们广泛关注，并在各个行业涌现出大量成熟应用案例，如油气管道入侵监测、大型园区及轨道交通周界安全、桥梁大坝等大型土木工程结构安全检测，隧道等轨道安全监测等。

随着窄线宽光源性能持续提升，多载波技术，脉冲编码，特种感应光纤等新技术的成熟应用，叠加人工智能处理光纤传感产生的大数据实现事件自动识别，使光纤传感适应于更多场景，并持续提升光纤传感覆盖距离，感知精度，事件识别准确率等关键性能指标。

- **Wi-Fi传感关键技术**

弥散在空中的无线电波，是最佳的传感器。基于Wi-Fi 7的感知功能，有着低成本、不间断、不侵犯用户隐私的优势，可以支持室内定位、运动检测、呼吸频率检测等价值应用。Wi-Fi感知技术通常利用信号到达时间（例如IEEE 802.11az）、信号传播路径的信道状态信息（例如IEEE 802.11bf）变化模式来实现感知覆盖范围内人或物体的存在或运动信息。

受到使用环境的影响，Wi-Fi信号在传输过程中存在干扰、衰落、多径等效应，从而限制了Wi-Fi传感识别的精度和准确率。基于Wi-Fi信号传播的特点，持续提升Wi-Fi感知的精度和准确率是业界研究的热点。为了提升Wi-Fi感知的精度，可以通过匹配人体精细化特征的信号波形和序列设计使得信号能反应人体特征的细微变化，也可以使用多MIMO天线技术获取更多维的无线信道信息，采用更短波长的毫米波也是有潜力的方向。为了提升Wi-Fi感知准确率，可以增强环境抗干扰技术以避免统计特征被干扰淹没，或者探索多AP节点间同步与协调技术以获取整网更准确和丰富的信息。

总结与展望

光通信始终处于不断革新和发展的状态。在F5G的第一阶段标准已开始商用的今天，F5G技术还在不断向前发展，ETSI在9月16日会议上正式将F5G演进的名称确定为F5G Advanced，为F5G后续发展定义新的目标和新的能力。随着F5G在千行百业的广泛应用，家庭、企业和工业产生了新的机会和业务诉求，需要持续演进到F5G Advanced，丰富应用、促进创新，打造可持续发展的固网产业。 让我们携手，共同迈向F5G Advanced，开启光联万物新时代！

缩略语

AI	人工智能
Burst	突发
DCI	数据中心互联
ETSI	欧洲电信标准协会
F5G	第五代固定网络
FlexO	灵活光传送网
FTTH	光纤到户场景
FTTR	光纤到房间
FTTO	光纤到桌面
GPON	千兆无源光网络
MPM PON	多模PON模块
$NEE_{Network}$	网络能效指数
HPC	高性能计算
ICT	信息和通信技术
oDSP	光数字信号处理
OT	操作技术
OLT	光线路终端
ODN	光纤分配网络
ONU	光网络单元
ONT	光网络终端
OSU	光业务单元
OSUflex	灵活光业务单元
ROADM	光分插复用器
OXC	光交叉连接
OSS	运营支撑系统
PLC	生产线控制
SLA	业务等级协议
TM Forum	电信管理论坛
VR	虚拟现实
WI	子工作组
Zero Wait	零等待
Zero Touch	零接触
Zero Trouble	零故障
Autonomous networks (AN)	自智网络