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RESEARCH ARTICLE

China Telecom's Research and Applications of Business-Enterprise Full-Optical Networking

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ABSTRACT With the continuous development of optical fiber access and other network infrastructure, cloud conference, online education, online office, cloud virtual-reality (VR) and other innovative services requiring high bandwidth are widely developed, which puts forward higher requirements on network bandwidth, delay, jitter and stability. Upgrading the legacy optical fiber network, building a gigabit optical broadband network, and promoting the further extension of optical fiber network to the enterprises help to improve the operation efficiency of information infrastructure and solve the problem of network coverage. High-quality business and enterprise broadband services can be realized, which stimulate potential consumer demand, and lay a solid foundation for the sustainable development of internet services. The business-enterprise full-optical network technology and the applications are studied, the related industrial chain and standardization progress are introduced, and the application mode and development trend are analyzed in this paper.

INDEX TERMS Business-enterprise full-optical networking, main gateway, sub gateway, fiber-to-the-room.

I. INTRODUCTION

As a new technology for home networks, the topology and functionalities of fiber-to-the-room (FTTR) are different from the traditional optical network. The FTTR technology directly bring optical fiber access to different rooms, realizing over 1000M broadband access for each room.

Business-enterprise full-optical networking is a novel networking solution launched in the Gigabit broadband era by operators. The networking scheme is used to solve problems of poor internal networking experience, and difficult maintenance and upgrading of micro, small and medium enterprises (MSMEs). The wireline and wireless network speed of every place in the enterprises can reach to Gigabit level with Business-enterprise full-optical networking, which greatly improves the broadband internet experience of users. For the internal networking of enterprise scenario, the full-optical networking solution, which is specifically oriented to the operating requirements of large concurrency, high stability, and simple maintenance, introduces main and sub devices and simple photoelectric hybrid cable technology with higher performance, providing end-to-end networking solution for MSMEs.

For legacy enterprise internal wireline networks, the medium is formed by telephone lines, network cables and other traditional types of wires. The transmission performance and stability will be declined over time. The enterprise network wireline is commonly Category 5 (CAT5), which has a data rate of lower than 100 Mbps. Once the traditional Wireless Fidelity (Wi-Fi) networking has been deployed, the data rate of a single Wi-Fi access point (AP) would be limited [11], [14]. Multiple user access while working will compete for the network bandwidth, causing network lagging and dropping, which cannot achieve digitalized office, online meeting and other services [1], [2], [3], [4], [5].

As for network operation and maintenance (O&M), the information technology (IT) departments and technical personnel are not generally available for MSMEs. Instead, the network O&M is commonly entrusted to the third-party service integrator. When there is a sudden failure of the network, the third-party service integrator may have problems such as late response, inaccurate fault locating, and long-time repairing. and even the closing down of the third-party company

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TABLE 1. Typical scenarios and key requirements of business-enterprise full-optical networking.

Scenario	Key requirement	Detail
Wireless Officing	Wide coverage	Fully covered Wi-Fi signal in office area, no lagging or dropping for mobile office, no perception roaming while moving.
	High concurrency	Simultaneous access of different terminals (e.g. laptop, pad, phone) in public area, office area and meeting room. High stability and robustness of peak-time network services.
	Bandwidth guarantee	Simultaneous support of multiple business and enterprise services (e.g. clouding, High-definition (HD) online meeting), high bandwidth over 500M, high guaranteed actual bandwidth.
	Safety	User access security, firewall, security audit, anti-attack, anti-virus, low professional skill requirement, security supporting service.
	Smart O&M	Visualization model of business and enterprise services, smart operation and maintenance, application-based self-operation and self-management.
	Future upgrading	Scalable network infrastructure, long-term network evolution (500M, 1000M and higher bandwidth).
Wireline officing	Bandwidth guarantee	Support of multiple high-quality business and enterprise services (e.g. clouding, 4K/8K online meeting, VR, Augmented reality (AR), high bandwidth over 500M.
	High concurrency	A large number of wireline terminal access, local forwarding and north-south traffic.
	Stability and reliability	High stability and reliability for important business and enterprise services, network redundancy protection, low overall fault rate.
	Smooth evolution	Scalable network infrastructure, transmission medium for long-term network evolution (e.g. CAT5, optical fiber).
Multiple service convergence with hybrid wireline and wireless	Multiple service carrying	Increasing of emerging services such as HD online meeting, 4K/8K real-time video monitoring, man-machine interactive, streaming, clouding and remote officing, multiple service isolation, multiple service different support.

itself, which will seriously affect the business development of the enterprises.

In addition, wireline access, wireless access and telephone access need to be supported by enterprise-level switches, routers, Integrated Access Device for voice, wireless AP and other devices for enterprises in common. The construction and upgrading of the full set of IT systems require a high initial investment, increasing the operating costs of MSMEs. Moreover, there are compatibility problems between networking equipment from different vendors, as well as problems such as the expiration of wireline cable and re-wiring, which increase the network construction and operation costs additionally [12], [13].

The remainder of the paper is organized as follows. Section II provides an overview of the technical requirements of business-enterprise full-optical networking. In section III, the system and management architectures and networking scheme are presented. Then, the laboratory testing and corresponding results are given and analyzed in section IV. Finally, in section V, the conclusions of this paper and prospections for future development of Business-enterprise full-optical networking are presented.

II. SYSTEM REQUIREMENTS OF BUSINESS-ENTERPRISE FULL-OPTICAL NETWORKING

Driven by innovative services and application requirements, the optical fiber network is further extending to terminals, realizing full-optical coverage. The business and enterprise services have the features of multiple types, customization, and wide demand in terms of different aspects such as application scenarios, service types and functional requirements [5], [6], [7], [8], [9], [10]. Therefore, the business-enterprise network needs high-quality networking solutions to provide services with high value and better experience to users. According to a practical survey results, the typical scenarios and key requirements of the business and enterprise are summarized in Table 1.

A. WIDE COVERAGE

The dense distribution of enterprises results in many office rooms with many users. The Wi-Fi signal needs to fully cover the office area, offering no lagging and dropping network for mobile officing, enabling seamless roaming when position change.

B. HIGH CONCURRENCY

The office sharing area, meeting rooms, public area and other places in the enterprise will maintain many concurrent user terminals (e.g. laptop, pad). Hence, a guaranteed network service with good performance of anti-interference is required especially for the working peak time.

C. HIGH GUARANTEED BANDWIDTH

Many users in enterprises require a high bandwidth channel (500M, even up to 1000M) to support multiple services such

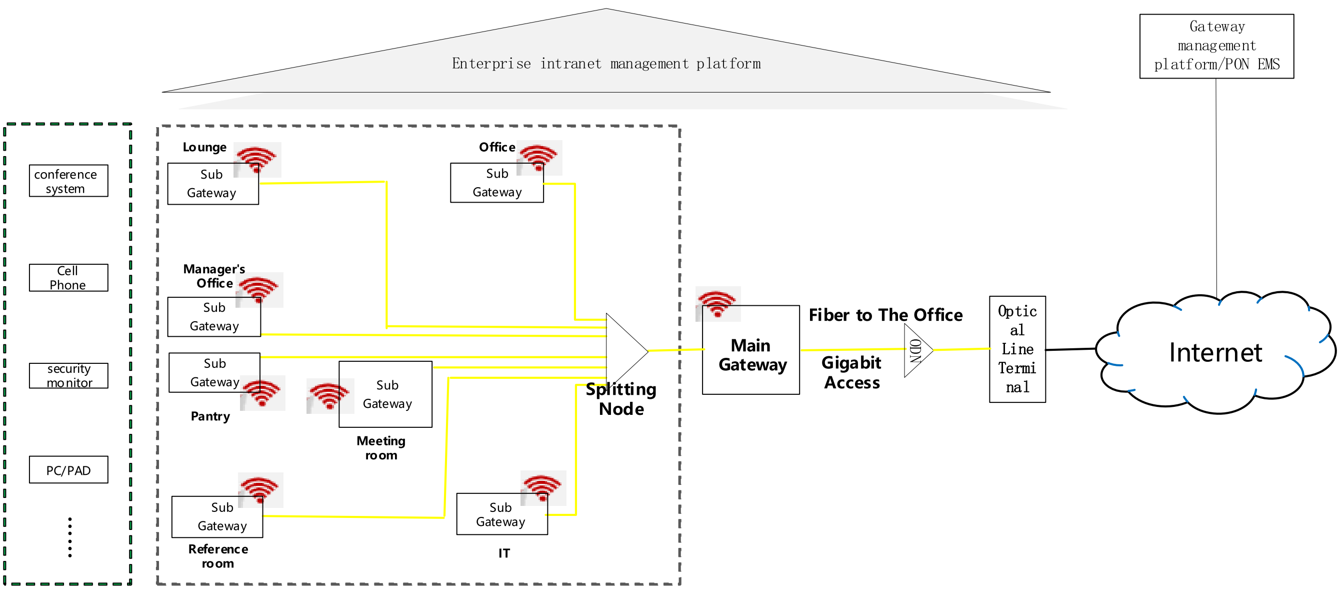

FIGURE 1. **The architecture of the business-enterprise full-optical networking.**

as internet access, cloud access, and HD online conference simultaneously. The actual bandwidth capability should meet the guaranteed data rate corresponding to the contract.

D. MULTIPLE SERVICE CONVERGENCE

Based on the traditional intranet mutual access, public network access and voice connection services, emerging type of services such as HD online meeting, man-machine interaction, live streaming, cloud services (video creation, cloud rendering, cloud design, and etc.), online officing anywhere are increasing, which require multi-service isolation, high quality and high-reliability network and guaranteed access methods such as high concurrency Wi-Fi 6 access, differentiated real-time stable service, upstream stable broadband and etc.

E. UPGRADING AND EVOLUTION

The continuous development of new services for indoor users is placing greater demands on the capabilities such as bandwidth and latency provided by FTTR networks. In addition, optical access networks are now employing 10G Passive Optical Network (PON) technology on a large scale, providing gigabit service access capabilities. As an indoor network, FTTR is seamlessly integrated with the upper layer of the optical access network, and its network capabilities should be upgraded and evolved in line with the development of the optical access network to meet the higher bandwidth requirements of new services and provide a better service experience.

The stable operation of business and enterprise services is based on scalable network infrastructure. Once deployment for long-term upgrading and evolution (bandwidth of 500M/1G and above) is the basic guarantee of the business and enterprise services.

From the perspective of application scenarios and requirement analysis, the main requirements of business and enterprise services include high bandwidth, low transmission delay, high concurrent user terminal access and several sessions. As for service experience, real-time stable operation, smooth, no lagging, and seamless roaming of services are the main expectations of the network from the business and enterprise scenarios and users. Therefore, the novel networking solutions supporting high bandwidth, wide coverage, seamless roaming, different service isolation and differentiated service guarantee meet the requirements of business and enterprise network development.

III. BUSINESS-ENTERPRISE FULL-OPTICAL NETWORKING

A. SYSTEM AND MANAGEMENT ARCHITECTURES

The system architecture of business-enterprise full-optical networking is illustrated in Figure 1. The business-enterprise full-optical network consists of three parts: the main gateway, the sub gateway, and the enterprise internal Optical distribution Network (ODN) [1], [2], [3].

The networking is based on optical fiber. The main gateway is deployed at the access point of the enterprise information network as a center to further build the full-optical network. The main gateway connects to the Optical Line Terminal (OLT) PON port and several sub gateways through the optical interface of the full-optical gateway. The sub gateways can extend to the areas where the user required according to the internal structure of the enterprise, providing fully covered wired and wireless connection and realizing a true high-bandwidth network. The original enterprise private PON line can be further extended to the enterprise internal network, providing enterprise internal full-optical networking services.

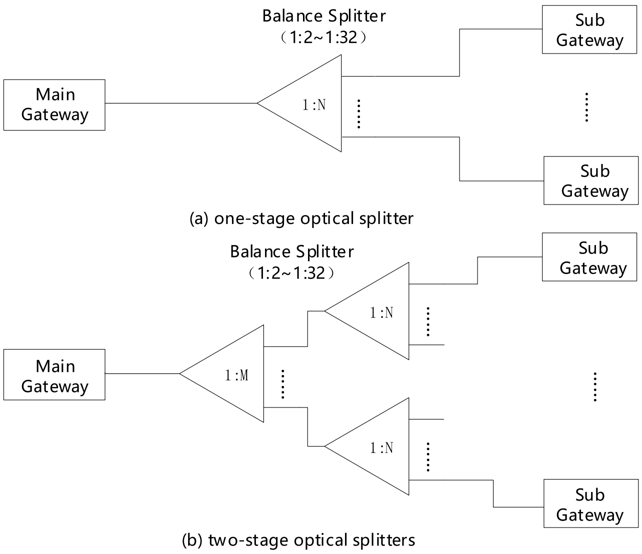

FIGURE 2. **The illustration of the balanced optical splitting mode.**

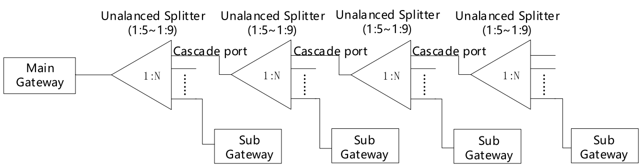

FIGURE 3. **The illustration of the unbalanced optical splitting mode.**

The main gateway is the core interconnection device of the enterprise network and operator network, working as an interconnection center for the enterprise internal network. It can forward, control, and manage the enterprise network data and applications, and realize service functions such as firewall, wireless AP, Virtual Private Network (VPN) interconnection and etc. Various user terminals within the enterprise network communicate with the main gateway through sub gateways. User terminals can also directly communicate with the main gateway based on the actual deployment location of the main gateway.

In the scheme of the networking, as the core node within the enterprise, the main gateway cooperates with the sub gateways to complete the enterprise's internal networking and process services.

The enterprise internal network management platform is an integrated platform for internal network management, control, and analysis. The main gateway manages and controls all connecting devices including sub gateways and other connecting devices and reports the collected enterprise internal network information to the management platform, realizing the visible, manageable, and controllable of the internal network, such as network topology, device information and service traffic. The network management platform includes a cloud management platform and a user-side application, which both types provide remote management and O&M functions, guarantee the service experience, and improve the O&M efficiency of the full-optical network. The main functions are listed in the following:

1) VISIBLE, MANAGEABLE AND CONTROLLABLE

Visible network topology, equipment information, network data rate and equipment access data rate; fault identification and analysis; O&M efficiency improvement.

2) AUTOMATIC Wi-Fi TUNNING

Wi-Fi coverage and roaming experience quality evaluation, Wi-Fi experience enhancement by automatic channel tunning.

3) USER EXPERIENCE ENHANCEMENT

Poor quality identification such as low data rate and frequent dropping; service experience-based differential quality analysis and network fault locating to solve differential quality problems actively and quickly.

The existing management way can be reused for a business-enterprise full-optical gateway to cooperate with the enterprise's internal network management platform. The internal networking management platform realizes the unified O&M of networking. In the future, this internal platform can be integrated into the operator's management platform to achieve centralized management and control.

B. NETWORKING SCHEMES

1) NETWORKING NODE

The typical user requirements for business-enterprise full-optical networking mainly include small overall coverage which the typical radius distance is generally between 500 m and 1 km. The user terminals are relatively centrally deployed in areas, floors, and rooms. There may be dispersion between areas. The user terminal devices mainly access through wireless Wi-Fi. During operating, small range movement within or between regions is required. The total number of user terminals is about 50 to 300, which requires full-optical networking to satisfy the multi-service concurrent of terminals and support reliable applications. Considering the frequent change of the MSMEs room topology, the full-optical networking ODN needs to have better flexibility and scalability. In addition, in some scenarios, when it is difficult for the sub gateways to obtain local power supply due to device type or deployed location reasons, a remote power supply through ODN may be needed.

In response to the above requirements, the networking should deploy enough networking sub-node devices to satisfy the wired and wireless fully covered access of all user terminals. Generally, for a single sub gateway, guaranteed high-speed experience and reliability can be realized when the total number of concurrent users for dual-band Wi-Fi is less than 20. Considering the performance of networking node devices, redundant coverage, roaming experience, unbalanced distribution of users and other factors, the total number of 16 to 32 sub gateways can generally meet the use requirements.

2) OPTICAL SPLITTING MODE

When the coverage is realized through point-to-multiple-points (P2MP) PON technology by the main gateway,

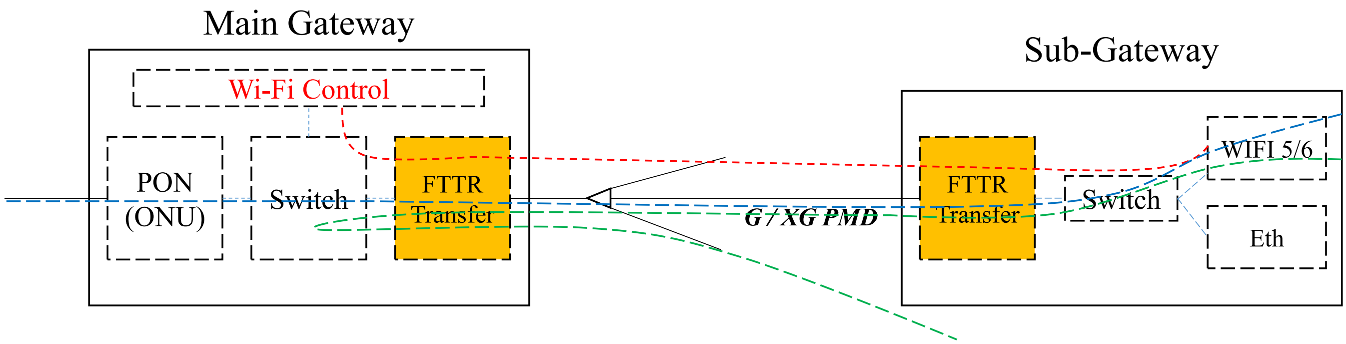

FIGURE 4. The illustration of layer 3 router forwarding in FTTR.

as the requiring number of the sub gateways, also considering the network site topology, optical power budget, eco-friendly and other factors, balanced and unbalanced optical splitting modes can be adopted by the ODN network [1], [2], [3], [4], [5].

The balanced optical splitting mode has a tree configuration, which is widely used by operators at present. The 1:N networking is generally achieved through a one- or two-level balanced optical splitter. As the topology is consistent and balanced, the received optical power at each end of the branches is similar, which is suitable for scenarios with lots of user information points and high density. Among them, the two-stage optical splitter has better networking flexibility but requires a relatively higher optical power budget.

For balanced splitting, fault locating is relatively simper, however, due to the uniform beam splitting, when the optical splitting ratio reaches 1:8 for a single stage, the power budget generally cannot support more splitting levels. The optical splitters need to be deployed directly, which limits the flexibility and expansibility of the networking.

For balanced optical splitting mode, the major impact factor to the optical link budget is the sub gateway at the final stage. The maximum loss at the output of the final-stage splitter can be calculated as:

$$L_{MAX} = \left(\sum_{1}^{M} SL\right) + D \times FL + N \times JL + MA \quad (1)$$

where SL represents the splitter loss, M represents the splitting levels, D represents the distance in km, JL represents the joint loss, with value as 0.3dB per joint in average to simplify the calculation, and N is the number of joints. The maintenance allowance MA is 1dB in 1-2 km.

Unbalanced optical splitting mode has a chain configuration. The 1:N networking is achieved through multi-stage optical splitting. The optical power output allocation ratio can be flexibly controlled by the cascade output and branch output of the optical splitter to meet the optical link budget of sub node devices at each stage. The Unbalanced optical splitting mode is generally suitable for scenarios where the number of user information points at each node is small, the density is low, and a narrow area is covered.

This mode can satisfy different requirements when topology changes in different periods by gradually extending the cascaded optical splitter, which has high flexibility. Besides, it is relatively more difficult for fault locating after multi-stage cascade optical link.

For unbalanced optical splitting mode, the major impact factor to the optical link budget are the first-stage and final-stage sub gateways. The maximum loss at the output of the final-stage splitter can be calculated as:

$$L_{MAX} = (M-1) \times SL_C + SL_B + D \times FL + N \times JL + MA \quad (2)$$

where SL_C represents the splitter loss of the cascaded port output, SL_B represents the splitter loss of the branched port output, other parameters are same as notations in (1). Note that the insertion loss of unbalanced optical splitter may be different based on the splitter ratio and the distribution of optical power.

Considering the practical application deployment scenarios and to maximize the benefit of product design, the maximum splitting ratio of the business-enterprise full-optical networking is designed as 1:32. Due to the large gaps between different actual sites of the business and enterprise scenarios, the complexity of the situation, the number and location of the information points, the layout of deployment sites, flexible networking and scalability and other factors, both the balanced splitting and unbalanced splitting can be considered while deploying.

3) PROTOCOL LAYER FUNCTIONS

The different functions of the networking protocol layer are mainly used to support the adaptation and transmission of data in the PON link.

For business and enterprise scenarios that require a certain degree of security, problems such as phishing and unauthorized access are the main security threats. In the protocol layer, the security of these scenarios will be reliably guaranteed with optional authentication and identification mechanisms. For example, identifying the sub gateway serial number and/or registration identity during sub gateway registration, or mutual authentication between main gateway

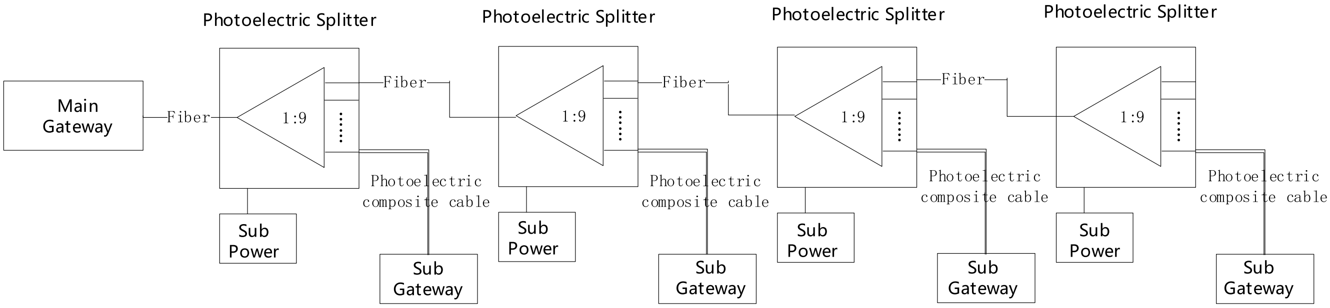

FIGURE 5. The illustration of remote power supply by photoelectric devices.

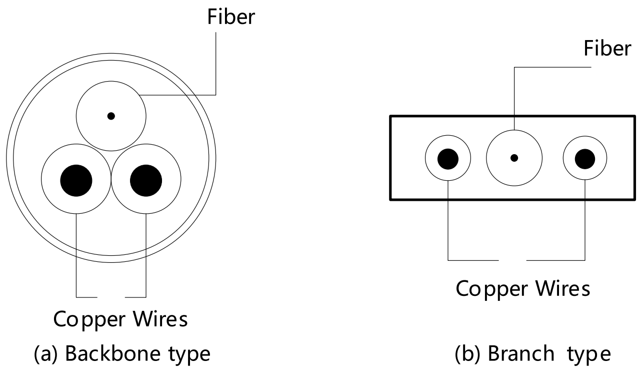

FIGURE 6. The structure illustration of the photoelectric hybrid cable.

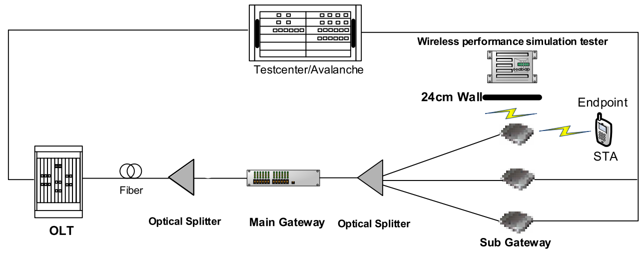

FIGURE 7. The illustration of laboratory test networking.

TABLE 2. Test results for enterprise-business full-optical networking system forwarding capability.

PON Uplink	Package Length (Byte)	Uplink Rate (Mbps)	Downlink Rate (Mbps)
XG-PON	82	2524.8	4553.6
	128	2483.2	6491.2
	256	2387.5	6509.4
	512	2337.4	6519.6
	1024	2313.8	6508.7
	1280	2309.9	6500.0
	1518	2299.6	6494.9

and sub gateway. For business and enterprise internal data that require higher security, main gateway can prevent unauthorized sub gateway data interception by encrypting downstream unicast data.

Considering the functional area division in the overall layout of the business and enterprise networking, different terminal numbers require different bandwidth allocations. Generally, the mechanism of the bandwidth allocation reuses the dynamic bandwidth allocation (DBA) to realize the real-time dynamic adjustment of user bandwidth, to improve the overall bandwidth utilization. Fixed bandwidth allocation can also be adopted. According to the terminal deployment situation, the pre-organized fixed bandwidth can be allocated to each functional area to provide a more stable network.

Considering the support for low latency services, the networking can support an on-off bidirectional forward error correction (FEC) function as required, to improve the link's overall reliability by sacrificing a certain bandwidth efficiency. Generally, the FEC is on in the downward direction and can be controlled by sub gateway.

Considering the network using frequencies are different between functional areas, the networking can support an optional line rate switching according to the functional area working behavior, providing different degrees of energy conservation without affecting normal work.

4) TRAFFIC MANAGEMENT AND CONTROL

The business-enterprise full-optical networking scenario includes the main gateway and multiple sub gateways. Besides, the main gateway is the core node for the entire data forwarding of all sub gateways.

In the corresponding scenarios, according to different applications in the industry, the large size data/file transmission between enterprise internal information access points exists. In this case, the bandwidth and service processing resources of the main gateway are occupied by a large amount of data transmission between sub gateways, causing insufficient overall bandwidth or congestion, transmission delay and jitter, which affect the normal operation of user services. Thus, the main gateway needs to manage and control the traffic of its connecting sub gateways.

First, due to the service requirements of business-enterprise broadband and private lines, and the importance of northbound-southbound data interaction and instructions in business and enterprise scenarios, the basic principle of the networking is to give the highest priority to the northbound and southbound traffic.

Secondly, the enterprise average traffic of the northbound and southbound services can be considered, to fully utilize

TABLE 3. Test results for enterprise-business full-optical networking system VxLAN forwarding capability.

PON Uplink	Package Length (Byte)	Uplink Rate (Mbps)	Downlink Rate (Mbps)
XG-PON	82	2103.4	4119.7
	128	2470.4	6491.2
	256	2386.5	6491.7
	512	2335.4	6487.8
	1024	2312.8	6492.5
	1280	2304.9	6487.0
	1518	2299.6	6494.3

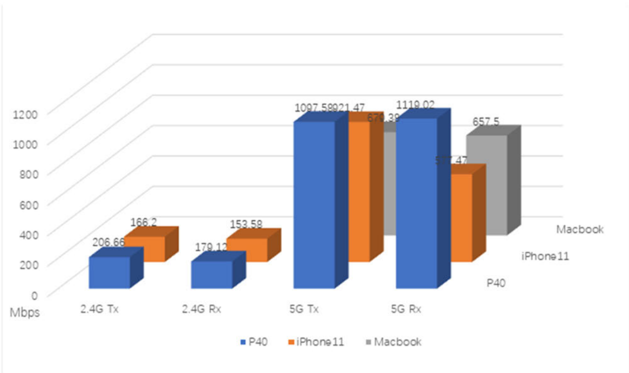

FIGURE 8. The analysis figure of Wi-Fi forwarding capability.

TABLE 4. Test results for enterprise-business full-optical networking system WLAN coverage capability.

Frequency Band	Distance (M)	Receiver Sensitivity (dBm)	Tx (Mbps)	Rx (Mbps)
5G	1	-39	695.9	383.4
	4	-46	619.8	334.4
	30 per wall	-54	431.3	235.7
2.4G	1	-40	146.8	76.8
	4	-44	145.3	75.1
	30 per wall	-55	120.9	54.8

the remaining bandwidth while ensuring the northbound and southbound service priority. For example, if the bandwidth for enterprise A is 500M, and the enterprise average northbound and southbound traffic is 100M, then the maximum bandwidth that can be occupied between the sub gateways will be 400M, which is configured by the main gateway. The enterprises can also adjust the configuration according to the actual situation such as the company scale and the number of access terminals.

The real-time northbound-southbound and eastbound-westbound traffic adjustment can also be achieved by the optimized scheduling algorithm or intelligent application, to realize the internal traffic management and control of the enterprise and maximize the utilization of bandwidth resources.

5) Wi-Fi CONTROL AND MANAGEMENT

In business-enterprise FTTR network, the flow directions are different between services (e.g., optical access network,

TABLE 5. Test results for enterprise-business full-optical networking system multi-user concurrency performance.

STA Number	Frequency Band (MHz)	Total Downlink Traffic (Mbps)	Downlink Average Traffic (Mbps)	Total Downlink Traffic (Mbps)	Uplink Average Traffic (Mbps)
32	80	537	16.78	569	17.78
32	160	540	16.88	571	17.85
64	80	400	6.25	493	7.71
64	160	403	6.29	502	7.84

TABLE 6. Test results for enterprise-business full-optical networking system multi-user concurrency delay.

Frequency Band (MHz)	User Number	Average Delay (ms)	Maximum Delay (ms)
80	32	6	17
	64	20	130
160	32	6	13
	64	21	178

cloud, internet access for northbound-southbound, and internal server access, document sharing and monitoring for eastboundwestbound).

In business and enterprise scenarios, user terminals are mostly connected via wireless Wi-Fi access. To guarantee the user experience, the requirements such as large bandwidth and seamless roaming are required to be supported. Therefore, Wi-Fi control and management are two important aspects for Business-enterprise full-optical networking. As can be seen in Figure 4, with the original user traffic, two additional flow directions are introduced. One is to support the Wi-Fi management and control, the other is to support the internal traffic forwarding between sub gateways. These different flows bring forward the forwarding capabilities certainly for the switch in the main gateway.

6) ELECTRONIC DEVICES

In order to balance the Wi-Fi coverage and decoration requirements, the sub gateways in some scenarios may be deployed at places where there is a lack of local power supply.

Therefore, by using special photoelectric devices in ODN, the optical signal transmission and centralized/distributed remote power supply can be supported simultaneously, which also reduce the complexity of wiring and save the cables.

The photoelectric devices for remote power supply mainly include photoelectric splitter, photoelectric composite cable, and photoelectric connector.

The photoelectric splitter is to provide adapted output of optical power distribution and power supply distribution at the same time.

Taking the distributed remote power supply of the unbalanced splitting scenario as an example, as shown in Figure 5, the unified power supply of all belonging sub gateways of each stage is provided by the photoelectric splitter

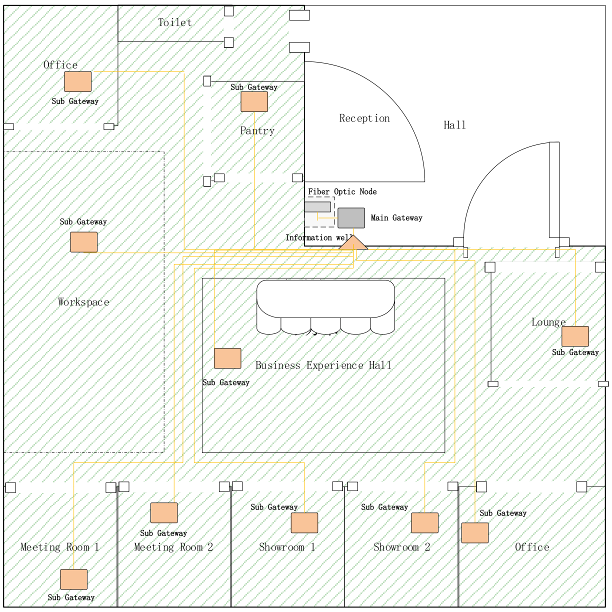

FIGURE 9. **The architecture of MSME business building.**

side of the corresponding stage respectively. The power of the photoelectric splitter can be supplied through the local sub power. The power and optical signal are recombined inside the optical splitter, then provide the results to the sub gateway through the end of the branch. This way has relatively low requirements for sub-power supply, and more portable photoelectric composite cables can be used.

Photoelectric composite cable can support optical fiber transmission and electric power supply at the same time. For business-enterprise full-optical networking, the total weight and the cost of the cables can be reduced, and the implementation can be simplified. According to the application environment, the photoelectric composite cable can be divided into outdoor and indoor two types. According to the deployed location and current bearing capacity, the photoelectric composite cable can be divided into backbone type and branch type, as shown in Figure 6.

The use of photoelectric composite cable still brings challenges to the deployment and O&M. At present, the interface of the photoelectric composite cable has not been standardized, therefore, it is necessary to use a pre-terminated cable, which makes it difficult to control the cable length. In addition, for maintenance and testing, the instrument photoelectric port, instrument interface or network have not been standardized as well. The industrial chain remains to be refined.

Photoelectric connectors include finished-head, on-site quick connectors, and other components, which can directly provide the connection of optical fiber and copper cable, forming a low-loss integrated plug-in component, meeting the requirements of the optical signal transmission and power supply. At present, the standard of photoelectric connectors is under development. The relevant connector form, structure and parameter values are for future study.

IV. ANALYSIS OF LABORATORY TEST RESULTS

In the laboratory evaluation and verification system, the main gateway is connected to the 10-Gigabit-capable PON (XG-PON) OLT interface through an uplink optical splitter, and the Gigabit-capable PON (GPON) port is connected to each sub gateway through a downlink optical splitter. The test networking diagram is shown in Figure 7.

The networking performance indicators can be verified through the data network analyzer and the service simulation networking test system including PON OLT, the main gateway and sub gateways. For Wi-Fi performance, the Wi-Fi processing capability and latency indicators are tested under different number of accessed user terminals while with the sub gateway Wi-Fi access enabled.

The basic functions and networking operation performances of main gateway and sub gateways are verified through the laboratory evaluation and verification, the detailed results and analysis are listed below.

A. SYSTEM ROUTER FORWARDING CAPABILITY

The layer 3 router forwarding capability was tested. The full-optical system under test (SUT) was built by a main gateway connecting with four sub gateways. The network analyzer was used to simulate service traffic, the typical packet lengths of 82 bytes, 128 bytes, 256 bytes, 512 bytes, 1024 bytes, 1280 bytes and 1518 bytes were tested in both directions respectively at once. The test results are shown in Table 2.

Then, the layer 3 Virtual Extensible Local Access Network (VxLAN) tunnel of router mode in main gateway was applied to verify the forwarding capability of VxLAN carrying service. The test results are shown in Table 3.

According to the test results, the overall forwarding and VxLAN service carrying capabilities can completely satisfy the 1000 M access requirement.

B. FORWARDING CAPABILITY OF Wi-Fi IN FTTR

The Wi-Fi forwarding capability was verified. The SUT was built by the main gateway connecting with one sub gateway. The Wi-Fi of the main gateway was on, testing the Wi-Fi forwarding capabilities of IEEE 802.11n and 802.11ac modes respectively. The test results are shown in Figure 8.

The performance requirements at bandwidths of 20 MHz, 40 MHz, and 80 MHz for 802.11n and 802.11ac modes are met. The broadband access rate of 1000 Mbps in the 5G frequency band can be even reached.

C. Wi-Fi COVERAGE PERFORMANCE

The capability of Wi-Fi coverage was verified. The system under test was built by the main gateway connecting with one sub gateway. An omnidirectional antenna was applied for gateways. According to test distance and test obstacle

(24 cm thick load-bearing wall), four levels of test points were set respectively. The test results are shown in Table 4.

During the test, the Wi-Fi connection was normal without interruption. As can be observed from the test results, the Wi-Fi performance decreases with the increase of distance and additional obstacles. However, the performance indicators still meet the wireless coverage requirement.

D. MULTI-USER CONCURRENCY PERFORMANCE

The multi-user concurrency performance was verified. The SUT was built by the main gateway connecting with one sub gateway. A simulated service traffic flow was sent to the station (STA) by the test center. The multi-user concurrency performance was verified by increasing the number of STA, and the average bandwidth of each STA was verified at the same time. The test results are shown in Table 5.

Besides, 7.5 Mbps Real-time Transport Protocol (RTP) service traffic flow was sent to 32 STA respectively to verify the average delay and maximum delay the of multi-user access scenario. The verification was repeated with increasing number of STA. See Table 6 for the test results.

According to the test results, when 64 terminals access and carry services simultaneously, the traffic bandwidth of 7.8 Mbps still can be realized. Besides, the average delay is only 6 ms under 32 users' access, and only about 20 ms under 64 users' access.

In summary, according to the laboratory results, the overall forwarding and VxLAN service carrying, and wireless forwarding capabilities can meet the requirement of 1000 Mbps broadband and private line bandwidth for a practical network. The performance indicators of Wi-Fi coverage can meet the requirements of wireless coverage under the strict test environment in the laboratory. In practical use, the sub gateways can be deployed next to each access point requiring network services according to the actual application scenario. Therefore, the wireless coverage performance in practice will be much better than in the laboratory test. For concurrency performance, the concurrent access of 64 terminals can be realized, which meets the requirement as well.

Thus, the business-enterprise full-optical networking technology is an ideal solution to realize the applications and service requirements of high bandwidth, low latency, and multi-user access in corresponding scenarios.

V. PRACTICAL FIELD DEPLOYMENT

In 2022, a field test of the business-enterprise full-optical networking was carried out in a design company. The company has about 60 employees and around 500 m^2 office size. For this scenario, wired and wireless networks are required to provide wide coverage, good signal quality, fast speed, and wireless networks with seamless switching capability. The concurrent access number is about 200, without lag on services.

The test scenario belongs to the typical MSME business building [3], [6]. The scheme architecture is shown in Figure 9.

As shown in the figure, the floor access node is connected to the main gateway. The main gateway is connected to multiple sub gateways inside enterprises through an optical splitter. The traditional network cables are fully replaced by optical fiber to realize the lossless extension of gigabit bandwidth to all access points of the enterprise.

In this scenario, an information room or well is designed for each floor where the optical splitter is deployed. With the optical splitter, the output fibers can therefore extend to the corresponding floor and room. The power supply is pre-deployed in the information room or well to support active devices.

This test reflects main functional highlights such as gigabit bandwidth extension, no perception roaming switching, fast deployment and installation, and simple and more efficient O&M. The auxiliary O&M application tool provided for customers enables the front office to quickly realize basic operations. Non-professional IT personnel can also realize real-time monitoring of the topology and quality of the network through this tool. Moreover, one-click detection of the network's overall operation situation, segmented speed measuring, and remote Wi-Fi tunning can be achieved, which improve the O&M efficiency.

Compared with the traditional networking mode, with the implementation of this pilot project, the bandwidth had been increased to 1000M level, and the latency had been greatly reduced, the Wi-Fi coverage also reached 100% in the office area. The customer requirements such as internal and external network isolation, visitor and employee network isolation, no lag in a dense area, no perception roaming, and application-based self O&M can be satisfied.

Besides, business agencies, hospital offices, university dormitories and other scenarios have also been tested and achieved good service and O&M experience results.

VI. CONCLUSION

With the rapid promotion and implementation of gigabit optical network construction, as the main access method for MSMEs, the coverage of optical broadband networks will be further improved. The operators have gradually realized large-scale deployment of 10G PON at present, which can provide gigabit access for more home, business, and enterprise broadband users. As an enterprise internal gigabit solution, business-enterprise full-optical networking technology can provide high-quality Wi-Fi signal with wide coverage, and extend the gigabit access to every terminal device, ensuring a real gigabit experience for users.

As a solution with obvious advantages in the development of business and enterprise services, the networking should plan and design the evolution and development of the entire industrial chain from the perspective of long-term development in the future. Now, the construction of industrial ecosystem of the networking is in its infancy, and the establishment of a win-win business model is the basis for the aggregation of industrial ecosystem. At this stage, we should accelerate the development of industrial partners, guide industrial cognition, build industrial standards and related technical specifications, promote the standardization and implementation deployment of the networking, and help the digital upgrading of enterprises, to better support the high-quality development of digital economy in the future.

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