White Paper on Next-Generation Fixed Network Access Technologies

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1 Fixed Network Construction is Associated with Technology Development

The development of broadband networks greatly encourages the users to use and share information, and has a positive impact on economic development and people's living standards. Many countries and organizations even measure national progress and competitiveness improvement on the basis of the broadband network development level, and have launched corresponding policies to stimulate the development so that they can take initiative in the future global competition and cooperation process. After years of development, broadband networks are evolving towards higher bandwidth, more flexibility, more intelligence, and more openness, and network integration is also a direction being continuously explored.

Network development and revenues depend on service applications and user acceptance. With emerging services and booming service applications in recent years, the types and quantities of services are increasing exponentially from pure narrowband voice services to multiple services distribution that includes voice, data, video, and image services, and network operation has changed from voice service dominance to data service dominance, and then to video service dominance. The video services have become the basic service of broadband networks, and account for 80% of the total broadband network traffic, where IPTV and OTT video play a significant role. With the application and popularization of 4K/8K/Cloud VR, video services are expected to develop rapidly in the next five years. The development of fragmented video, diverse video contents, as well as rising and rapid popularization of short videos attract mass users, especial young people. The high-interactive services become the development direction, which attracts users to proactively participate in it.

The service development of fixed network (FN) in the last two decades present obvious trumpet and superimposed effects. Traditional services are still used in the network, while the newly-built networks require compatibility with existing services, and the emerging new services require enhanced network support capabilities. On one hand, it means that the continuous support for existing services needs to be considered from the technical layer, network planning and construction, as well as maintenance layer. On the other hand, the requirements of new services such as video services for higher bandwidth, lower jitter/delay and less packet rate must be satisfied.

Service users are gradually differentiated. With the openness of people's minds and the services targeting for different users, the service applications suitable for different user groups are differentiated and diversified. And the service group attributes are becoming more obvious, which requires that services can be subdivided in accordance with different user intentions, user habits, and demands to match users' daily activities and behaviors, and to provide more precise services to different types of users. The users will shift from passively accepting services to proactively demanding and choosing services, and then to defining services. In this way, users will be authorized to a certain extent and truly become the definer, owner and controller of a service under the framework set by the operator, and the owner attribute of the service will be more obvious. In this process, users will have higher demands for service experience and perception, which will force networks and technologies to make corresponding changes to meet the needs of times.

From the development history of fixed networks in the past two decades, network bandwidth is increased tenfold every five years, and technology updates and iterations occur every five years. However, networks are upgraded or updated every ten years. The new technologies may be compatible with the services supported by existing technologies and be extended, but the implementation modes might vary. Some technologies such as analog voice, 2/4 line audio, and DDN have been replaced or discarded due to various reasons. During network development, the existing resources, such as optical fibers, twisted-pair cables, cabinets, ducts, are used as much as possible, which not only improves the utilization of existing resources, but also extends the device lifecycle, effectively reducing costs and operation pressure.

At the same time, the driving force of the fixed network development is also shifting from technology to service. In the traditional narrowband era and the initial stage of broadband development, network development was always subject to technology development, and technologies determined the network construction capabilities. As the video service gradually becomes the basic service of broadband networks, user perception and experience is enhancing, and higher network quality is required, but the corresponding tolerance is decreasing, which also makes service-driven network a reality.

Bandwidth acceleration is a basic demand of broadband network development and a frequently talked about topic that promotes continuous upgrade and evolution of technologies of different networks and transmission media. At present, the mobile networks have entered the 5G era, and the fixed networks should also have entered the new era. The fixed and mobile networks promote and stimulate each other and develop coordinately. The development of fixed networks facilitates bandwidth offering of mobile networks, and the development of mobile networks also forces fixed networks to make innovations and changes. They complement each other in service provision and scenario adaptation, so that service provisioning has more flexibility and margin, network capabilities are more robust, and competitions are easier to win.

2 Analysis of the Transmission Media Used in Fixed Network Construction

During the construction of a fixed network (FN), it is difficult to change the transmission medium in a long time after it is deployed on a large scale, and it may cause waste and loss if it is improperly selected. Therefore, the development trend, functions performance, technology maturity, and costs must be considered comprehensively in selecting different network transmission medium. Especially in recent years, many countries and operators have invested a lot in network infrastructure construction to achieve universal access and ubiquitous connections, in order to keep pace with the informatization revolution and improve the broadband network access capability of the people.

In fixed network constructions, various transmission media are usually adopted.

2.1 Optical Fiber

An optical fiber is an optical conduction tool that works on the principle of total internal reflection. Due to the strong availability, low cost, lightweightness, small loss, long transmission distance, and easy transportation and deployment, optical fibers have been rapidly developed since the 1980s. Especially with the accelerated process of “replacing copper with fiber” in this century, the POP points of the access network have gradually moved down to the user side, greatly stimulating the wide use of optical fibers in the telecommunication field. Optical fibers are gradually extended from cells, to buildings, offices and homes to desktops, making FTTH develop in full swing, and all-fiber home coverage a reality. With reduced CPE costs, the development and breakthrough of pre-terminated optical cable laying technologies, and the deployment of ODNs, FTTH end-to-end network construction costs are reduced greatly, which in turn promotes the development of FTTH.

In a broadband access network, the coverage distance of optical fibers can reach dozens of kilometers, single-mode optical fibers are generally used in the downlink to meet the coverage requirements of different distances. Single-mode or multi-mode optical fibers are selected in the uplink in accordance with upper-layer device connectors, and are adapted in accordance with different connectors.

When selecting optical cables, the operating wavelength, system capacity, and transmission distance should be considered comprehensively. In actual network deployment, the type, number of cores, and structure of optical cables should be considered in advance, such as the laying conditions, water resistance mode, and sheath.

With the technology development and the improvement of optical fiber techniques, optical fibers become easier to be deployed. The rubber insulated indoor optical cable makes it easier to access the users' premises, and the armored optical cable makes the feeder optical fiber more secure and easy to be protected during the laying and use. The new pre-termination technology can reduce the time required for optical fiber connection, and the air-blowing technology can speed up the deployment of optical fibers in pipes, thus promoting the worldwide application of optical fibers.

2.2 Twisted-Pair

A twisted-pair is a common transmission medium used in copper access, especially in voice networks. It consists of two insulated metal wires (such as copper wires) twisted together, and the two copper wires are insulated through protective sleeves to prevent external electromagnetic interference and improve the quality of transmission signals.

Twisted-pair cables can be divided into unshielded twisted-pair cables and shielded twisted-pair cables. The Unshielded Twisted-pair (UTP), which contains four pairs of wires in different colors, provides the features of light weight, low cost, and flexible deployment. Therefore, it is widely used in telephone and Ethernet cables. Shielded twisted-pair cables (STP) are shielded by a layer of metal between twisted-pair cables and the outer insulation sheath. The shielded layer can reduce the radiation and noise from external electromagnetic interference. Therefore, compared with the UTP, the STP is safer, provides higher transmission rate, but requires a higher cost.

Twisted-pair cables can be classified into CAT3 cables, CAT5 cables, CAT6 cables, and CAT7 cables based on cable diameter. The larger number indicates larger cable diameter, more advanced technology, and higher bandwidth it provides.

In actual deployment, multiple pairs of twisted-pair cables are wrapped in an insulated cable sleeve to form a twisted-pair cable. Twisted-pair cables are widely used in telephones, Ethernet cables, and other application scenarios. They are a basic communication infrastructure, especially for indoor cabling in homes or buildings.

2.3 Coaxial Cable

A coaxial cable is a cable that the signal transmission conductor and the shielding layer outside it use the same axis. The most common coaxial cable consists of insulated copper wire conductors, and is encapsulated by a sheath made of PVC or Teflon. A coaxial cable from the inside out is divided into four layers: central copper (single strand of solid or stranded strand), plastic insulator, mesh conductive layer, and wire sheath. Coaxial cables can be used to transmit analog and digital signals, and are applicable to cable TV transmission and long-distance telephone transmission. AC power rather than DC power is transmitted through coaxial cables.

Coaxial cables can be divided into baseband coaxial cables and broadband coaxial cables. Baseband coaxial cable shielding layer is usually made of copper mesh structure, its characteristic impedance for 50Ω. It is usually used to transmit digital signals. Broadband coaxial cable shielding layer is usually use aluminum stamping, and its characteristic impedance is 75Ω. It is usually used to transmit analog signals.

Coaxial cables have the advantages of supporting high-bandwidth communication over relatively long distances, and have the disadvantages of large size, large diameter, heavy weight, and high cost. Coaxial cables are mainly used for the transmission of cable TV signals. In recent years, due to its disadvantages in network transformation, bandwidth capability and Triple-play service provision, the application of coaxial cables has been gradually reduced.

Furthermore, in order to access the end users, electromagnetic wave is also used for convenient and rapid coverage. For example, by using Wi-Fi, a wireless access technology used in short distance coverage scenarios such as home, office and hot spot coverage. The factors that affect Wi-Fi signals include distance, house layout, location of Wi-Fi equipment, antenna gain, transmitting power and interference of peripheral signals. The strength and quality of signals directly affect the use and experience of users, such as slow network speed, video blurring and video stuttering.

3 Evolution of Next-Generation Fixed Network Access Technologies

3.1 Development of Next-Generation PON Technologies

3.1.1 Review and Prospect of PON Technologies

The PON technology is a P2MP broadband access technology based on the passive ODN network. It uses different wavelengths for uplink and downlink transmission, and uses Time Division Multiplexing (TDM). A PON network consists of an Optical Line Terminal (OLT), Optical Splitters (Splitter) and Optical Network Units (ONU). Located in the central/access equipment room, the OLT allocates and controls channel connections, and provides monitoring, management, and maintenance functions in real time. The ONUs are located at the user side. The OLT is connected to the ONUs via the ODN.

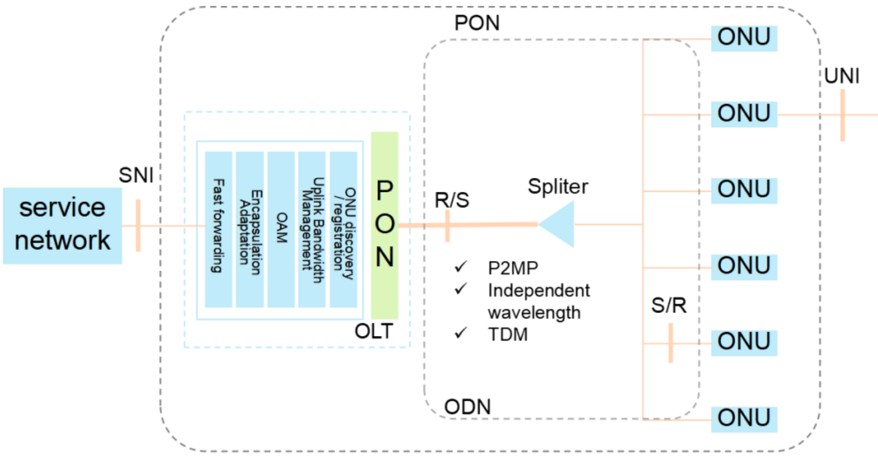
Compared with other access modes, the PON technology has the following advantages:

- High reliability: It uses pure optical medium to avoid electromagnetic interference and provides strong environmental adaptability. It requires low construction and maintenance costs, and is easy to expand and upgrade.
- Large bandwidth: Based on optical fiber technology communication, GPON/10 G-PON, which is widely used at present, it can provide a bandwidth of 2.5G/10G.
- Multi-service bearing: It provides flexible bandwidth allocation and guarantees service quality, and supports the access of multiple services such as voice, video

and data.

- Low cost: The PON network adopts the P2MP topology. One PON port can be connected with multiple ONUs, which greatly saves the central office resources. Meanwhile, the intermediate ODN network is passive, easy to build and expand, and the comprehensive cost is low.

Fig. 3-1 PON Network Architecture



In the development process of PON technologies, FSAN/ITU and IEEE have played a great role. GPON and EPON have been widely used. On this basis, 10G GPON and 10G-EPON, the next generation technologies of GPON and EPON, have also been applied on a large scale.

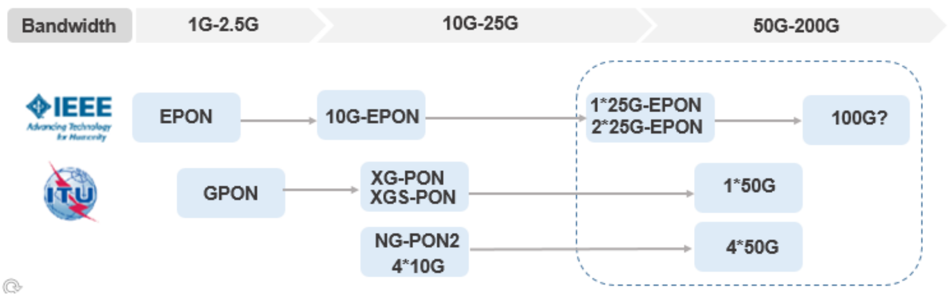
Table 3-1 Evolution of the Three Generations of PON Technologies

Item	Downstream	IEEE	ITU-T
GPON/EPON	2.5G/1.25Gbps	EPON (IEEE 802.3ah)	GPON (ITU-T G.984)
10G PON	10Gbps	10G-EPON (IEEE 802.3av)	XG-PON(ITU-T G.987) XGS-PON(ITU-T G.9807)
50G-PON	25G/50Gbps	25G/50G-EPON (IEEE 802.3ca)	50G-PON (ITU-T G.9804)

The first generation of GPON/EPON technology can provide users with 100M bandwidth access and gradually replace the original copper access technology. The second generation of 10G PON technology can provide the user with 300Mbps-1Gbps bandwidth, meeting the large-scale application of 4K/8K video services and the introduction of VR/AR services in the early stage. At the same time, the requirements of extreme AR services for 1G bandwidth, and the PON service transmission extending to 5G wireless transmission put forward higher requirements for the bandwidth and delay of the PON technologies. At present, the third-generation PON technologies are actively evolving.

From the perspective of technical routes, the next-generation PON evolves into single-wavelength speed-up and multi-wavelength overlapping. For the next-generation single-wavelength speed-up technology route, the unicast rate can be increased to 25Gbps or 50Gbps, and the requirement for higher bandwidth can be realized by multi-wavelength stack. The current IEEE and ITU-T are carrying out research based on this way of thinking.

Fig. 3-2 Evolution Trends of PON Technologies



IEEE was the first to start the formulation of the next-generation PON standard. A single optical fiber supports a downlink rate of 25Gbps, and upstream rates of 10Gbps or 25Gbps, and supports compatibility with 10G-EPON. For the bandwidth requirements of 50G, it uses the multi-wavelength overlapping technology and channel binding technology to provide two 25Gbps channels and achieve 50Gbps bandwidth.

ITU-T is considering the technical development after 10G PON (XG-PON and XGS-PON). Based on the technical research report of G.sup.HSP and considering the requirements of home users, enterprise users, mobile backhaul and fronthaul, the industrial chain including the operators and the equipment vendors gradually has the requirements for the next-generation PON. The 50G-PON standardization project was initiated in January 2018, as well as the NG-PON2 based on multi-wavelength overlapping, with a rate of 50Gbps per channel.

3.1.2 Progress of the Next-Generation PON Technical Standards

3.1.2.1 Progress of the IEEE 25G/50G-PON Standards

The IEEE's PON standards are divided into three generations:

- IEEE 802.3ah, the technical standard of the first generation EPON technology, was officially released in September 2004.
- IEEE 802.3av, the technical standard of the second generation 10G-EPON, was officially released in October 2009.
- IEEE 802.3ca, the technical standard of the third generation 25G/50G EPON, was officially released in July 2020.

IEEE is early to start the research on 25G/50G EPON IEEE 802.3ca as the next-generation PON technology. The specific process is as follows:

- In 2013, IEEE started the research of NG-EPON, and established IEEE ICCOM to analyze the market demands and technical solution of NG-EPON.
- In March 2015, IEEE released the NG-EPON technical white paper. In July 2015, IEEE initiated the 100G-EPON standardization IEEE 802.3ca.
- In July 2020, IEEE released the IEEE 802.3ca standard, deleted the 100G MAC layer rate configuration, and provided 25G over a single wavelength and 50G over dual wavelengths. Among which, 25G is divided into two modes: asymmetric 10G/25G and symmetric 25G/25G.

3.1.2.2 Progress of ITU's Next Generation 50G-PON Standard

After formulating the 10G PON standard XG(S)-PON, FSAN has also started the research of the next-generation PON. Firstly, it initiated the NG-PON2 standards research based on the 10G wavelength overlapping in 2011, and completed the standards formulation in 2015. It selects TWDM-PON as the main technical solution for NG-PON2, and adopts the 4/8 wavelength overlapping mode. Each wavelength adopts the 10G TDM mode, and uses the point-to-point WDM overlay technology for mobile backhaul and commercial customers. The key requirements of NG-PON2 are 40G downlink and 40G/10G uplink. However, due to the high cost of tunable optical components and system maturity, NG-PON2 commercial deployment progress is slow and future applications are doubtful or may be skipped.

ITU-T has also carried out research on the subsequent evolution technologies. On Q2/15 2018, ITU-T launched the white paper on the next-generation high-speed PON technology to investigate the possibility of various next-generation high-speed PON access technologies. The 50G-PON standard was initiated in ITU-T projects in January 2018, which will provide 1G-10G bandwidth to users in the future. It is estimated that the 50G-PON will be put into commercial use around 2025.

3.1.3 Key Technologies of Next-Generation PON

3.1.3.1 Wavelength Planning

Low cost and high performance have always been the basis of large-scale application of PON technologies. Wavelength selection is the key factor, and the following factors should be considered:

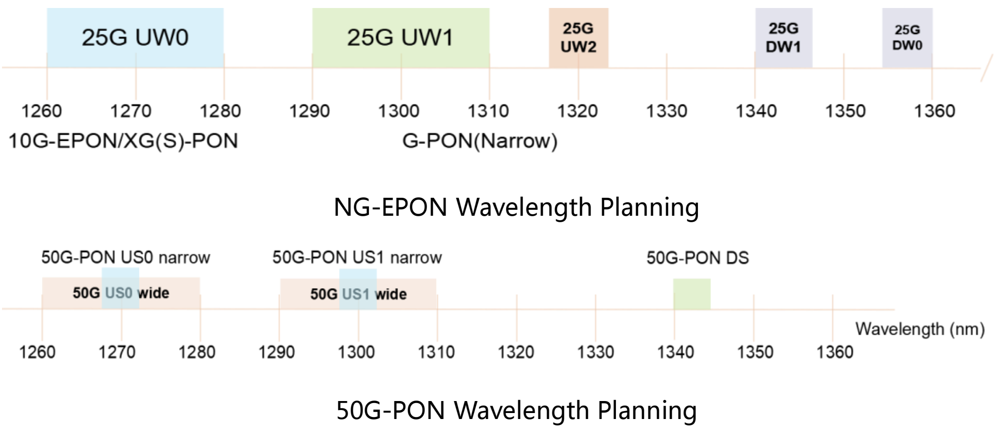
- Optical fiber dispersion and optical fiber loss of different wavelength.
- PON system compatibility.
- Optical component cost.
- Implementation complexity of line coding.

The current all-O wavelength planning solution does not require complex dispersion compensation, and can use the simplest NRZ line coding technology. At the same time, the next-generation PON technologies adopt the two rate modes of 25G and 50G. As a result, the O-band can reuse the current 100GE Ethernet industry chain and the DML/EML laser. It is a preferred solution because of simple implementation of the physical layer. However, the dispersion of the C-band and L-band is large, and complex modulation and equalization technologies are required for dispersion compensation. The impact of their performance and costs needs to be further studied.

For the compatibility of the PON system, both IEEE and ITU-T consider the WDM coexistence of two PON generations. The third generation of PON does not coexist, but its wavelength can be released. Considering the physical layer convergence of IEEE and ITU, the wavelength planning of ITU is consistent with that of IEEE and coexists with GPON or XG(S)-PON. Therefore, IEEE 802.3ca has passed two downlink wavelength and two uplink wavelength solutions, meeting the requirements of different evolution scenarios. ITU plans one downlink wavelength and two uplink wavelengths, as shown in Fig. 3-3. ITU-T 50G-PON uplink wavelength has multiple options. Some scenarios are still under discussion. ITU-T also considers the compatibility between 10G-EPON and the next-generation 50G-PON. In this way, multiple evolution paths can be implemented as needed:

- 10G-EPON/XG-PON+2*25G-PON
- GPON+25G EPON
- 10G-EPON+ 50G-PON
- 10G-EPON/XG-PON+50G-PON
- GPON+50G-PON

Fig. 3-3 NG-EPON (a) and 50G-PON Wavelength Planning Options

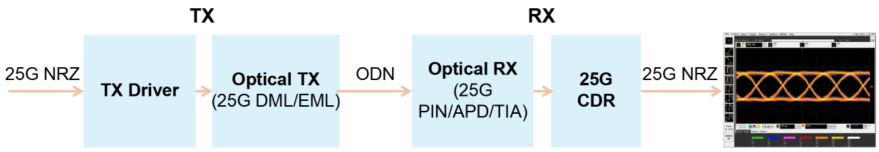


3.1.3.2 Line Coding Modulation Technology

The rates of the next-generation PON include 25Gbps and 50Gbps. In order to achieve high performance and low cost of the entire PON system and the power budget within a specified range, the line coding modulation technology is very important. At present, the optional implementation solutions are as follows:

- NRZ

Fig. 3-4 NRZ Modulation Architecture and Signal Eye Diagram



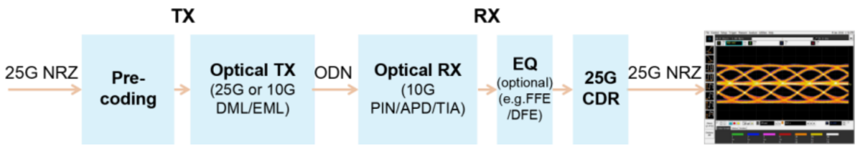
The advantage of NRZ modulation is simple implementation. The key optical components can reuse the mature industry chain of 100G Ethernet and 10G PON. There are two specific implementation modes, both of which use OOK modulation:

– Without balance NRZ: Both the transmitting and receiving ends use 25G optical components. This solution can only reach the 25Gbps rate.

– With balanced NRZ: The transmitting end and receiving end use 25G optical components, and use the balancing compensation algorithm to improve sensitivity and realize a transmission rate of 50Gbps.

- Duobinary

Fig. 3-5 Duobinary Modulation Architecture and Signal Eye Diagram



Duobinary system is a binary data coding mode. It converts the logical signal "0" in binary system into the logical signals "+1" and "-1," so that the spectrum bandwidth of the signal is reduced by half. In optical fiber communication, duobinary has two application forms.

– Electrical duobinary

One is three-level amplitude modulation. This type of duobinary modulation requires dual-binary decoding circuits for the receiver. Compared with the traditional IM-DD system, the three-level decision will cause the deterioration of the receiver sensitivity.

The advantage of the three-level amplitude modulation solution is that the system implementation is simple and the signal bandwidth of the electrical and optical domains can be reduced by half compared with the NRZ system. Compared with the NRZ system, the optical power budget of the system is reduced.

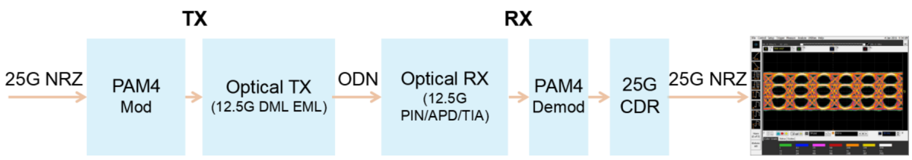
– Optical duobinary

Another duobinary implementation mode is optical duobinary. It uses the M-Z modulator and combines amplitude modulation and phase modulation (AM-PSK). This solution features that the receiving end can be compatible with the receiver of the traditional binary IM-DD system, without causing sensitivity deterioration.

The advantage of optical duobinary is that the receiving end does not need to determine the received phase, but only needs to take out its amplitude. Therefore, the receiving end only needs to use the traditional component for direct detection, and the difficulty is the large size and high cost of the M-Z modulator.

- PAM-4

Fig. 3-6 PAM-4 Modulation Architecture and Signal Eye Diagram



Pulse amplitude modulation ((PAM)) is a kind of high-order modulation technology. Its principle is to map two or more bit information to different transmission pulse amplitude (voltage) to increase the bit transmission rate of each symbol. The main purpose of using PAM modulation is to reduce or maintain the bandwidth of transmitted signals when the transmission rate is increased, so as to reduce or maintain the transmission and receiver costs. PAM-4 has 4 amplitude levels, and each level encodes 2 bits. The dispersion tolerance of PAM-4 modulation can be quadrupled compared with NRZ. The PAM-4 modulation uses 12.5G bandwidth optical components to transmit 25G signals, but the cost is to use high-speed AD and DA technologies at the transmitting and receiving ends for encoding and decoding, the receiving end needs to use relatively complicated algorithms for bandwidth compensation.

Taking 25G-PON as the objective, the coding modulation solutions of various lines are compared based on various factors. Refer to Table 3-2:

- In terms of performance, NRZ and ODB have the best performance while EDB and PAM-4 have the worst performance.
- In terms of components, NRZ and ODB require 25G components, while EDB and PAM-4 can be reconstructed by using 10G components.
- In terms of implementation, NRZ and EDB are the simplest, but PAM-4 is much complicated.

Table 3-2 Line Coding Modulation Technologies

Line coding		NRZ	NRZ (balance)	Optical duobinary ODB	Electrical duobinary EDB	PAM-4
Optical component	Laser	25GHz EML	10 GHz EML	10 GHz MZM	10 GHz EML	10 GHz EML
	Modem	IM-DD	IM-DD	AM-PSK	IM-DD (3 level)	IM-DD (4 level)
	Receiver	25GHz APD	25GHz APD	25GHz APD	25GHz APD	25GHz APD
	Receiver sensitivity	Medium	High	Medium	Medium	Low
	Dispersion compensation	Required	Required	None	Required	Required
Electrical modulation parameter	Baud rate	25G	25G	25G	25G	25G
	Number of electrical level	2	2	2	3	4
	Phase	0	0	2	0	0
	Pre-equalization of the transmitter end	None	Required	None	None	Required
	Equalization of the receive end	None	Required	Required	Required	Required
	Component linearity	None	None	None	Relatively high	Very high
	SNR	Medium	Low	Low	Medium	High
System	Co-existence	O	C/L	C/L	C/L	C/L
	Cost	Low	Medium	High	Medium	High

Based on the above analysis, the single-wavelength 25G-PON implementation needs to consider the two factors: optical component bandwidth and the implementation complexity of the electrical layer, and select a proper implementation scheme with a proper price/performance ratio. Due to its simple architecture and high maturity of components, 25G-PON based on NRZ coding has recently become a major focus of standard formulation and industry research. After the 25G transmission rate is achieved over a single wavelength, the 50G-PON (2 wavelengths) can be achieved by combining the wavelengths and channel binding technology. At the same time, the 25G NRZ technology can transmit and receive the equalization algorithm through lines, and is expected to reach a rate of 50Gbps.

3.1.3.3 Burst Clock Restoration Technology

Burst clock data recovery (BCDR) is the key technology of the PON system. The BCDR industry chain with the upstream rate of 10G is already mature, and the related technology in PON system is commercial ready. The standard of the single-channel 25Gbps-rate PON network is being formulated, the current 25Gbps-rate BCDR technology is still in the research stage, and few chip manufacturers can provide commercial 25G BCDR chips. The BCDR technology used in the PON system is mainly from two implementation solutions: the feedback Alexander phase detector technology and the forward-feed phase oversampling technology.

Alexander detector is also called bang-bang phase detector. In a UI cycle, the upper and lower clocks collect signals twice. By comparing the XOR results of signals collected for four consecutive times, you can determine whether the clock and data are ahead, delayed, or synchronized.

The Alexander technology is the most common means adopted by the PON system to implement the BCDR function in a simple and cost effective manner. However, the Alexander-based BCDR is based on the feedback system, so it takes a relatively long time to recover the data lock. Therefore, to improve the recovery time of BCDR, the oversampling technology can achieve better performance based on three times of oversampling phase.

3.1.3.4 Enhanced FEC Technology

The forward error correction of the next-generation PON technologies focuses on the

LDPC coding technology. In the PON system, the upstream channel works in the burst mode. Due to the transient switch effect of the burst mode transmitter (Slow Transients), the transient effect of the optical amplifier (e.g., the Er-doped optical fiber amplifier with stable gain) and the transient effect in the burst mode receiver of the ONU, a series of memory and uneven distribution continuous errors will be introduced at the front end of the burst. However, most error correction codes (such as LDPC) do not perform well in correcting continuous errors. Due to the unique code construction characteristics, the confidence coefficient of LDPC codes in some specific bit is low, which needs to be further optimized.

In addition, the polar codec used by the 5G network is likely to become a short code solution to replace the Reed-Solomon codec in the next-generation PON, which is also the direction of follow-up research in the industry.

3.1.3.5 Channel Binding Technology

To achieve a higher transmission rate, the ONU supports multiple optical modules. The ONU can transmit and receive data on multiple wavelength channels at the same time, which is called the channel binding technology. The peak rate of the ONU supporting one channel is 25Gbps, and the peak rate of the ONU supporting two channels is 50Gbps. In the channel binding technology, if an ONU supports one channel, when the OLT sends data, the OLT maps the data of the corresponding ONU MAC to the channel supported by the ONU for transmission. If an ONU supports two channels, when the OLT sends data, the OLT maps the data of the corresponding ONU MAC to the channel supported by the two ONUs for transmission.

Take IEEE802.3ca 25G/50G EPON as an example:

Step 1: The OLT divides the data sent to ONU1 into n * EQs, each with a length of 8 bytes.

Step 2: The OLT determines the start time of the data transmitted on each channel and the total size of the data transmitted on each channel in accordance with the bandwidth allocated to the ONU on all the supported channels.

Step 3: The OLT places the data into one buffer according to the bandwidth allocation in step 2. The buffer has four queues representing four channels, and the buffer has 32 lines. The OLT first transmits data on the first available channel. When multiple channels are available at the same time, the OLT places the data in the first EQ according to the channel sequence, transmits the second EQ on the second available channel, the third EQ on the third available channel, the fourth EQ on the fourth available channel, the fifth EQ on the first available channel, and so on.

Step 4: The OLT allocates the data in buffer to each corresponding channel for transmission. The OLT adds a frame header at the front of a group of data transmitted on each channel, called ESH. The whole segment of data is called an Envelope.

Step 5: According to the ESH header of the data received by each channel, the ONU can automatically adapt to the difference between different channels, and restores the out-of-order data fragment to the original data packet.

3.1.3.6 Low Latency Technology

In the traditional PON system, it is difficult to reach a latency of within 200us without special processing. The major reasons are as follows:

- Quiet window

  The quiet window is used by the OLT to discover and measure the distance of ONUs. To implement fast ONU registration, the OLT needs to open the quiet window periodically to discover ONUs. If you want ONUs to register in seconds, the cycle should be seconds. In the current standard, when OLT measures the distance to ONU, the quiet window should also be opened. At a normal distance of 20 km, the quiet window should be 250us each time. Therefore, the delay caused by the quiet window will be greater.

- Traditional DBA

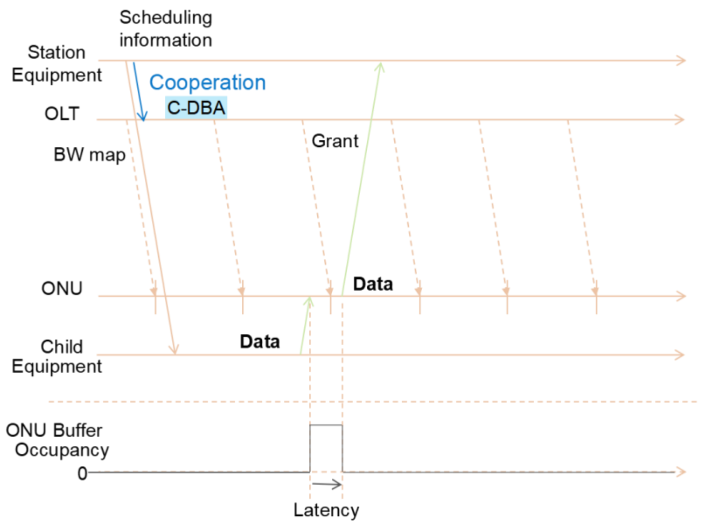
  The traditional DBA algorithm is based on the ONU bandwidth request or traffic monitoring, that is, dynamic bandwidth allocation DBA. The dynamic bandwidth allocation method can achieve high bandwidth utilization, but the bandwidth is delayed to a certain extent, which brings great cache delay to the uplink transmission of the ONU.

In order to meet the interactive VR and 5G services, the next-generation PON technologies pay much attention to the breakthroughs of the low-latency technology compared with the previous PON technology. The specific solutions are as follows:

- CO-DBA(Cooperative DBA)

When the Station Equipment controls the uplink transmission of a Child Equipment, the Station Equipment knows the arrival time and size of the uplink transmission of the Child Equipment. The Station Equipment works with the OLT to exchange the uplink transmission time and size of the Child Equipment, and the OLT allocates bandwidth to the Child Equipment so that the uplink transmission data of the Child Equipment can be cached in the ONU for the minimum time. See Fig. 3-7.

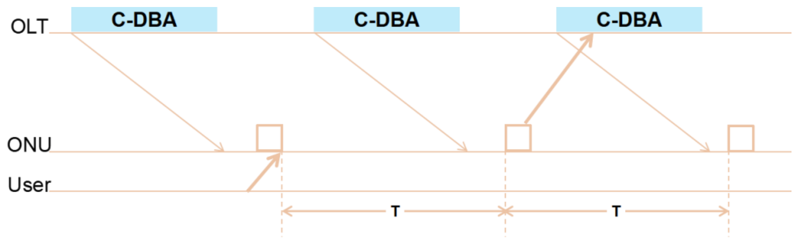
Fig. 3-7　CO-DBA Sample

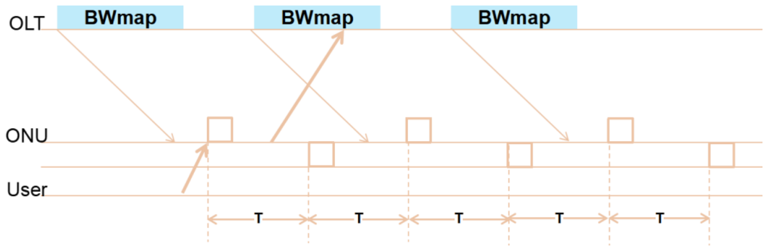


- Small-granularity bandwidth

By cutting the bandwidth, the bandwidth allocation is smaller and denser, and the time interval between adjacent bandwidth allocations is smaller, thus reducing the waiting bandwidth time and the maximum delay, see Fig. 3-8.

Fig. 3-8　Small-granularity Bandwidth Sample

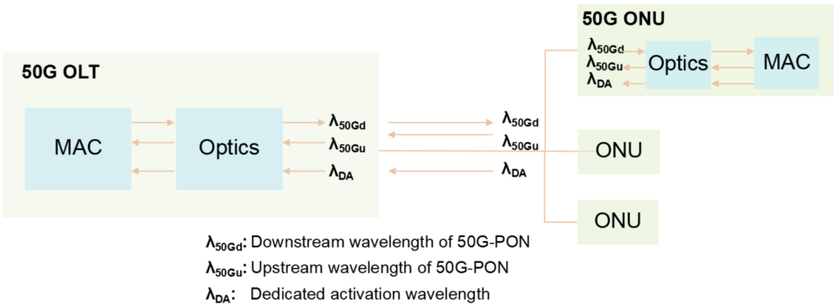




- Dedicated active wavelength (DAW)

The quiet window is opened on DAW(λ DA), and the quiet window is no longer opened on the working channel (such as λ 50Gu)). Therefore, there is no more quiet windows on the working channel, eliminating the delay caused by the quiet window. See Fig. 3-9.

Fig. 3-9 DAW Sample



CO-DBA needs accurate coordination of PON and service, which is difficult to implement and is still in the research stage. The dedicated active wavelength (DAW) solution has mature and reliable technology, good compatibility of existing standards, and low implementation cost. Combined with the small-particle bandwidth technology, it has great advantages over the CO-DBA solution.

3.1.4 Next-Generation PON Technologies of IEEE/ITU-T

3.1.4.1 Next-Generation 25G/50G-PON Technologies of IEEE

Fig. 3-10 100G-EPON Network Architecture

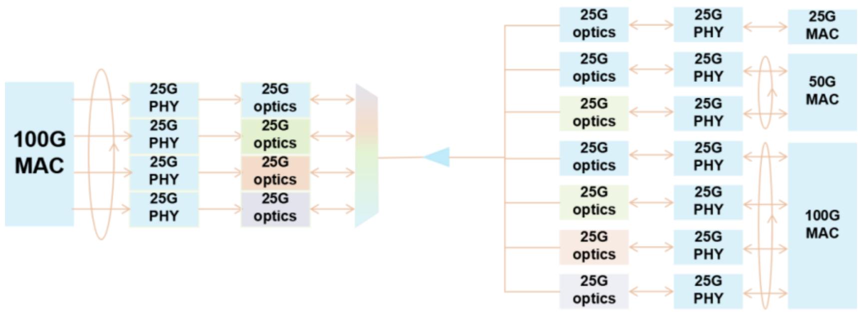


Fig. 3-10 sows the 100G-EPON system architecture discussed in the current IEEE 802.3ca standard, which supports 25G/50G/100G MAC rates. To support the deployment of different generations of OLTs, you can deploy the single-wavelength 25G OLTs/ONUs first, then the 50G and 100G OLTs/ONUs. Due to the performance problems and commercial difficulties of the tunable lasers and filters, the 100G-EPON adopts the fixed wavelength, and coexists with the deployed 10G-EPON system in the same ODN through wavelength division. At the OLT side, the 100G-PON is combined into one PON OLT port via wavelength division multiplexer. Each wavelength supports an optical layer rate of 25Gbps and a PHY layer rate. The MAC layer supports multiple rates of 25G/50G/100G. Through the channel bonding technology, multiple 25G PHY layers and the optical layer are bound to support higher MAC rates.

In 2019, IEEE revised 802.3ca and deleted the 100G MAC rate. Currently, the next generation of IEEE EPON is 25G/50G EPON.

IEEE 802.3ca adopts all-O band solution, NRZ coding, and LDPC forward error correction.

Single-wavelength 25G defines two modes: Asymmetric mode: Uplink 10Gbps, downlink 25Gbps, symmetric mode: Uplink 25Gbps and downlink 25Gbps.

Two power budget levels are defined at the same time: 1) PR20<=24 dB, corresponding to 1:16 and 20 km or 1:32, 10 km; 2) PR30<=29 dB, corresponding to

1:32 and 20 km.

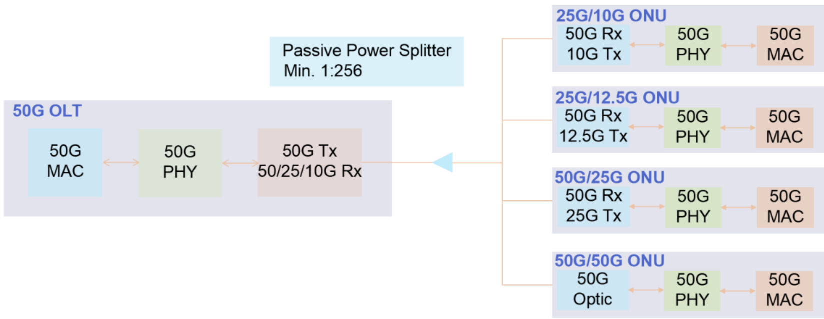
Two types of power budgets are defined: 1) PR-S corresponds to 25G or 50G symmetric PON; 2) PR-A corresponds to 25G or 50G asymmetric PON.

It is divided into PR-S20, PR-S30, PR-A20 and PR-A30 according to level and type.

3.1.4.2 Next-Generation 50G-PON Technologies of ITU-T

The ITU-T 50G-PON project was initiated in January 2018, and the standard is still under discussion. The line coding NRZ and wavelength solidification have been determined, and other technologies are still under discussion.

Fig. 3-11 50G-PON Network Architecture



As shown in Fig. 3-11, 50G-PON employs a single wavelength to implement a transmission rate of 50Gbps. The 50G-PON standard defines a downlink rate of 49.7664Gbps, and the uplink rates of 9.95328Gbps, 12.4416Gbps, 24.8832Gbps and 49.7664Gbps, and the line coding uses NRZ. The O band is used for the wavelength, see Fig. 3-12. The downlink wavelength is 1342nm+/-2nm, and the uplink wavelength is still being discussed. Different options such as coexistence with GPON/10G PON are available, see Table 3-3. The optical power budget mainly concerns two power levels: 29dB and 32dB. In order to improve the receiver sensitivity, the 10^{-2} FEC adopts the low-density parity check (LDPC) error correction algorithm. The low latency and slicing features are still under research.

Fig. 3-12 PON Wavelength Planning

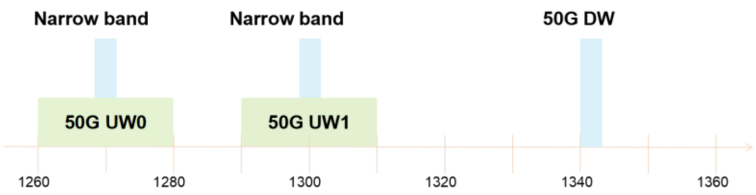


Table 3-3 50G-PON Wavelength Planning

Uplink wavelength	US0-wide	US1-wide	US0-narrow	US1-narrow
	1260-1280 nm	1290-1310 nm	1268-1272 nm	1298-1302 nm
10G uplink	Determined	Determined	Under discussion	Under discussion
25G uplink	Determined	Determined	Under discussion	Determined
50G uplink	Not discussed	Not discussed	Under discussion	Under discussion

3.1.5 Discussion on Next-Generation PON Applications

Application Trends of the next-generation PON Technologies

- Cable operators' 10G-EPON evolution

Most of the traditional cable operators adopt the EPON technology, and are upgrading it to the 10G-EPON technology. In the future, they will use the 25G/50G EPON technology as the next step of evolution, which faces the home broadband market and meets the future interactive VR/AR bandwidth requirements.

- Operators' smooth evolution

At present, mainstream operators adopt the ITU-T GPON technical route, GPON is widely used, and XG(S)-PON is being introduced step by step. The Chinese market has entered the stage of large-scale deployment of 10G PON. There are two technical paths for its future evolution:

  – XG(S)-PON evolves to 50G-PON

    After XG(S)-PON replaces GPON, the XG(S)-PON needs to provide 1Gbps-10Gbps to meet the future interactive VR/AR bandwidth requirements. Later, 50G-PON will be introduced and coexist with XG(S)-PON.

  – GPON evolves to NG-PON2

Due to the immature technology and high cost of the tunable optical components of NG-PON2 ONUs, the large-scale commercial use prospect is not yet seen.

Some incumbent operators will migrate 10G-EPON to 50G-PON and coexist with 10G-EPON

- Expansion of new services such as 5G transmission

The high bandwidth and low delay features of 50G-PON meet the application of 5G transmission and dedicated enterprise lines in the future. The PON technologies will move from the traditional home broadband field to the wireless field. In this way, the widely-deployed FTTH ODN networks can be reused to achieve the goal of comprehensive access of all services, greatly reducing the operators' network construction and O&M costs.

3.1.6 ZTE's Research Progress on Next-Generation PON

ZTE has carried out research on the next-generation PON technologies very early, and established the next-generation technology platform based on 25Gbps. Through high-speed bit error tester, high-speed random waveform generator (AWG) and high-speed sampling oscilloscope, ZTE tested the key components (such as 25G EML/DML/APD/TIA and burst CDR) of 25G, and was able to perform simulation test on various debugging formats (NRZ, Duo-binay, PAM-4, DMT) and DSP algorithms.

In 2017, ZTE successfully demoed the prototype of 100G-EPON at MWC Barcelona. In the first half of 2017, ZTE successfully verified the symmetric 100G-PON prototype and the symmetric single-wavelength 25G and 4-wavelength 100G-PON system in the joint demo network of the "Special Optical Fiber and Optical Access Network" in the key lab of the Ministry of Education at Shanghai University.

ZTE was one of the first initiators of the IEEE802.3ca 25G/50G EPON standard. Many key technical indicators of ZTE were adopted as standards, and ZTE is also the initiator, editor and main contributor of the white paper on the next generation high-speed PON technologies at ITU-T Q2/15.

Except for a few cable operators, most operators adopt the ITU-T next-generation PON technologies at present. Therefore, ZTE will focus on breakthroughs in the key technologies of 50G-PON, and actively promote the research and commercial process of 50G-PON.

3.2 Analysis of the Development of Next-Generation Copper Access

3.2.1 DSL Technology

3.2.1.1 Evolving Copper Wire Access Technology

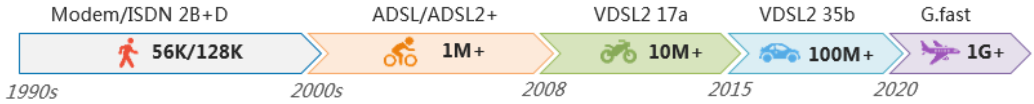
With the gradual popularization of the Internet in the 1990s, requirements for information data services began to rise. The dial-up modem and ISDN services for homes and small enterprises have emerged, and copper networks have begun to expand from voice transmission to the data field.

In the early of this century, the copper-based DSL technology gradually matured, including HDSL, ADSL, ADSL2 and ADSL2+. ADSL2+ stands out with its high transmission bandwidth and price-performance ratio. Its theoretical downlink rate reaches 24 Mbps, and has been deployed widely around the world.

HD video has gradually become a common requirement, yet the ADSL2 + technology cannot meet the bandwidth requirement. The VDSL2 technology extends the broadband spectrum to 17 MHz or even 35 MHz and the bandwidth to 100M. The emergence of the Vectoring technology solves the long-term problem that troubles the copper cable quality - crosstalk. Without sacrificing performance, Vectoring uses algorithms to cancel the crosstalk, so that VDSL2 technology can realize 100M and multiple 100M access.

The G.fast technology makes it possible to provide gigabit over copper.

Fig. 3-13 Copper Access Technology Evolution Route



3.2.1.2 G.fast Leads the Copper Cable into the Gigabit Era

G. Fast is an access technology that achieves ultra-high rate over copper cable within a short distance. Compared with VDSL2, G.fast has achieved a leap from 100 Mbps to 1Gbps or even 2Gbps, improving the copper access capability to a new level. As an effective supplement to FTTH, G.fast can solve the problems of optical fiber access failure and access difficulties in specific scenarios, and achieve fast deployment and performance improvement of the operator's network.

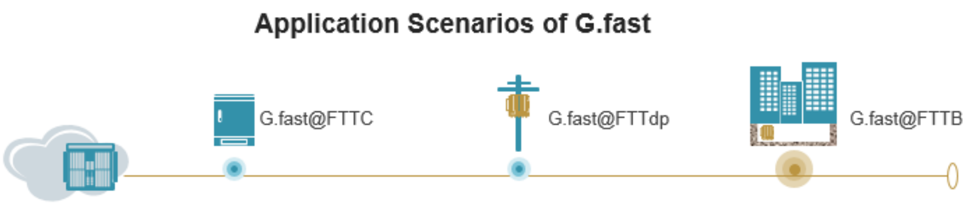
The application scenarios of G.fast are FTTB, FTTdp and some FTTC scenarios.

In the FTTB scenario, the optical fiber arrives at the basement or corridor of the apartment and provides G.fast access via multi-port DPU equipment. The existing twisted-pair resources of the buildings are reused. The distance between the optical fiber and the user is usually about 100m, and the longest distance is 200m.

In the FTTdp scenario, the optical fiber reaches the last distribution node of the copper cable, reuse the last segment of twisted-pair cable. In most cases, the distance from a user is not greater than 200m.

In the FTTC scenario, the user distance is about 300m. By using the long-distance G.fast technology (Such as G.fast profile 106b), the transmission distance of G.fast can be extended to approximately 300m.

Fig. 3-14 G.fast Application Scenario



Compared with VDSL2, G.fast has the following improvements:

- G.fast uses extended spectrum planning to reach 2Gbps.

  The G.fast technology extends spectrum resources on the basis of the original VDSL2. The typical operating frequency of VDSL2 is 17 MHz or 35 MHz, while the spectrum of G.fast is expanded to 106 MHz or 212 MHz. The higher the frequency, the higher the bandwidth available. However, the higher the signal frequency, the shorter the transmission distance. The best application distance of G.fast is within 250m (at a diameter of 0.5 mm).

- Employs TDD duplex mode for flexible uplink and downlink rates and different service adaptation.

  Different from FDD duplex mode used by ADSL and VDSL, G.fast adopts TDD duplex mode, that is, it distinguishes uplink and downlink traffic by allocating different timeslots. It is easy to implement, and the ratio of uplink and downlink rate can be flexibly defined to adapt to different services and users.

- More stable links, fast reconfiguration.

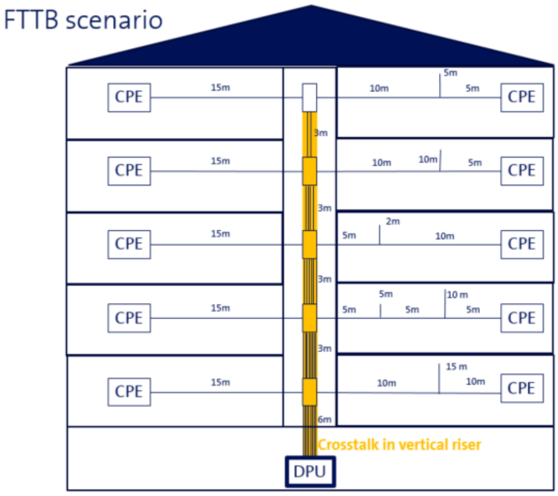
  Link stability is an important indicator for user experience. If the link environment deteriorates and link disconnection frequently occur, user experience is reduced. Therefore, G.fast introduces online reconfiguration (OLR) to address this situation. The parameters can be adjusted online, including modulation parameters, transmission parameters, frame structure parameters and management channel parameters, to adapt to the changes in the line environment and prevent link disconnection.

3.2.1.3 The Next Generation G.fast Technology G.mgfast

The G.mgfast standard was officially initiated at the plenary session of ITU-T in June 2017. G.mgfast uses part of the G.fast standard, and adds the new definition of profiles above 212 MHz and full duplex operations. The target access rate of G.mgfast is 5Gbps or even 10Gbps, and the transmission distance should be within 100m. The main application scenarios of G.mgfast are FTTB and FTTD.

In Fiber to the Building (FTTB) application scenarios, multi-port DPU is usually installed in the basement or corridor of a building. The pair of cables connected to each subscriber pass through a shared cable pipe. Each DPU port is connected one to one with the CPE in each subscriber unit. It is recommended that the maximum distance between the DPU and the CPE should not exceed 100m.

Fig. 3-15 G.mgfast Application Scenario



The FTTD (Fiber to the door) scenario is usually aimed at house users. The optical fiber has been extended to the home entrance. The single-port DPU equipment is usually installed next to the copper cable junction box on the external wall. The line length is usually less than 30m.

Compared with G.fast, G.mgfast has the following improvements:

- The spectrum is further expanded to increase the rate to 10Gbps.

  The working frequency of G.fast is 106 MHz and 212 MHz, while the spectrum of G.mgfast will be extended to 424 MHz or even 848 MHz. In the initial phase of high frequency band, G.mgfast will use 424 MHz and increase the rate to 5Gbps. In the future, it will extend to 848 MHz and increase the rate to 10Gbps. The higher the frequency, the higher the bandwidth available to G.mgfast. However, the higher the signal frequency, the shorter the transmission distance, the higher the cost and power consumption. Therefore, it is necessary to balance performance, cost and feasibility.

- Adds the full duplex FDX technology.

  Compared with G.fast TDD duplex, G.mgfast has added full duplex mode (FDX). That is, the G.mgfast supports either TDD or FDX mode, or both. In TDD mode, uplink and downlink traffic is distinguished through different time windows. FDX receives and sends uplink and downlink traffic simultaneously in the same time window, that is, signals are sent and received at the same frequency band.

Theoretically, the spectrum efficiency can be doubled, and the end-to-end latency and signaling overhead can be reduced.

- Multi-delay channel technology

  To meet the transport requirements of different types of services, G.mgfast supports 2-4 delay types with different delay_max values to match different delay requirements. The G.mgfast physical layer receives packets of different types of services from the upper layer, it marks the delay type in the DTU (e.g., DTU header or DTU frame header).

  Whether G.mgfast is mature is yet to be tested, especially to be promoted by the industry chain. For example, whether the operator's deployment demand is large or not, whether the chip supplier can provide mature and reliable chip solutions, and whether the equipment vendor can launch low-cost mature products. Each factor is very important and is linked together.

3.2.2 DOCSIS Technology

DOCSIS is a standards system defined by CableLabs for transporting data services on the cable network. It is mainly used to transform the broadcast mode of HFC network into the duplex bidirectional transmission mode. DOCSIS defines the CMTS and CM, and the interfaces between them and the back-end OSS system. It ensures interoperability among the DOCSIS-based equipment from different vendors, thus achieving automatic provisioning of data services.

In the early stage, a large number of HFC networks were built by MSOs. However, the HFC networks were originally designed for broadcasting, which determined that the network architecture, frequency band division, and number of node users could not meet the development requirements of the high-bandwidth Internet era. Especially, video has become the basic service of broadband networks. For some video services such as 4k/8K/Cloud VR, the HFC network cannot meet the diversified and flexible user requirements. A large number of analog active components also cause high OpEx in the HFC network. In addition, the coaxial cable at the end usually adopts a chain network, and users share the spectrum/bandwidth under the optical node. With the development of services, the demands for bandwidth, and the intensification of competition (not only between MSOs but also between MSOs and telecommunications operators and OTT systems), spectrum resource sharing, insufficient uplink bandwidth resources, and the O&M and management of active devices are urgently needed.

The DOCSIS technology based on coaxial cable has evolved from DOCSIS 1.0, DOCSIS 2.0, DOCSIS 3.0 to DOCSIS 3.1. DOCSIS 1.0 solves the problem of bidirectional data transmission, that is, whether there is any problem with data service. DOCSIS 2.0 focuses on the increase of bit/Hz rate. DOCSIS 3.0 increase the bandwidth through channel bonding.

DOCSIS 1.0, DOCSIS 2.0, and DOCSIS 3.0 have been deployed and applied on a large scale in the network. At present, the cable network is mainly upgrading and evolving to DOCSIS 3.1, in the technical research stages of DOCSIS 4.0.

Compared with DOCSIS 3.0, the DOCSIS 3.1 technology has the biggest improvement on the PHY layer. It adopts the OFDM modulation mode, each channel width changes to 192 MHz, and extends spectrum planning and bandwidth capability to meet the bandwidth capability of uplink 1-2Gbps and downlink 10Gbps. At the same time, it adopts the new FEC algorithm (LDPC) and higher modulation efficiency (QAM4096), and introduces OFDM to re-plan the spectrum, thus effectively improving the spectrum usage.

Driving force for the MSOs to upgrade to DOCSIS 3.1:

- The fiber-based technology can provide 1000M to the home. The cable operators need to provide a similar bandwidth to maintain its bandwidth competitiveness and balanced competition against PON-based FTTH.
- Emerging services like big video require higher uplink and downlink rates and better user experience. The cable network needs to greatly improve bandwidth to support new user experience and future applications, such as 4K/8K/VR, enterprise broadband access and smart home. These new applications will bring exponential traffic growth and further raise higher network requirements.
- The development of 5G will affect the wired network to adapt to the development needs of the new situation, and raise higher requirements for bandwidth, connection, delay and transport capability of basic transmission media.

From the global perspective, DOCSIS 3.1 is now in the introduction phase, and has been tested and deployed by some MSOs. For the MSOs that have a large number of coaxial cable resources, upgrading to DOCSIS 3.1 is attractive, and the existing network does not need much change. At the same time, the existing network can effectively protect the existing investments.

The DOCSIS 4.0 technology is a continuous evolution based on DOCSIS 3.1. It focuses on formulating a unified standard combining full duplex FDX and spectrum extension and low delay, so as to enable the uplink and downlink traffic to run on the same spectrum and provide low delay. It can achieve a downlink rate of up to 10Gbps and an uplink rate of 6Gbps.

The DOCSIS 4.0 standard was released in March 2020. However, it is estimated that it will take some time before it is deployed on the market. Some mainstream DOCSIS vendors in the early stage tend to reduce the investment and focus on DOCSIS 4.0, and need to further discuss and improve the technical development and selection. The global popularization of FTTH impacts the cable network. Some operators have started to transform from the cable network to FTTH, bringing uncertainty to the future development of the DOCSIS technology.

3.3 Optical Fiber Access Will Become the Mainstream Development Direction

With the further decrease of FTTx costs and the accelerated process of “fiber-in and copper-out”, continuous bandwidth acceleration will become a trend in the fixed broadband field in the coming 5 to 10 years. After years of development, the future evolution direction of the DSL technology based on twisted pairs and the DOCSIS technology based on coaxial cables is uncertain. The G.mgfast technology is still in the process of standards discussion and formulation. The DOCSIS 4.0 needs to be further improved in its technical implementation.

At the same time, the copper cable network has been built on a large scale since the 1980s, and has a service life of nearly 40 years up to now. However, affected by multiple factors such as oxidation, the transmission capability and quality of copper wire will gradually decline, and the service life is usually 50 years, which means that after 10 years, the life cycle of copper media will reach the end, and network transformation planning needs to be considered in advance. The service life and quality of copper cables will become a key factor that restricts its development. As a strategic resource, the copper price has been hovering at a high level in recent years, which will lead to more investments in new copper-based networks.

Optical fibers have the following advantages over copper cables:

- Low cost, high availability, light weight and easy deployment.
- Invulnerable to external interference, such as electromagnetic radiation and oxidation, and the loss is even lower at the same transmission distance.
- The life cycle much longer than that of copper cables.
- Higher bandwidth bearing, and the amount of transmitted information is much larger than that of copper cables.

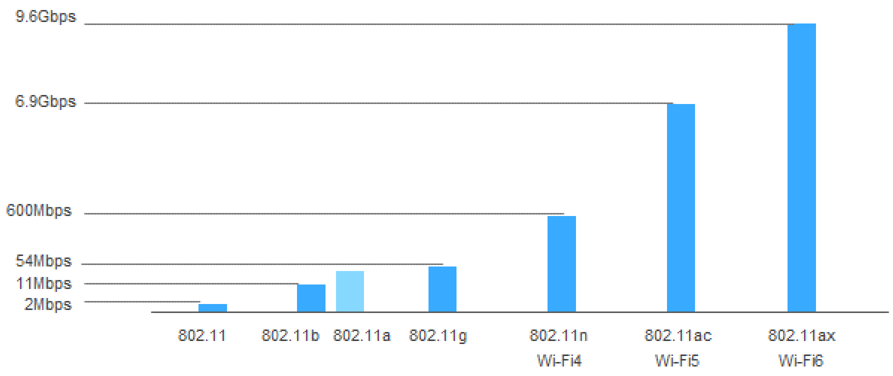
In addition, the PON technology has a clear evolution direction. The industry has reached a consensus on the PON evolution from GPON to 10G PON and then to 50G-PON. The 10G PON technology, the peer of G.mgfast and DOCSIS 4.0, has been commercialized on a large scale, and its deployment process is far ahead. This means that at the same time, the bandwidth provided by the copper technology lags far behind that provided by the PON technology, increasing the pressure of network operation and market competition.

3.4 Next-Generation Wi-Fi Technology

3.4.1 Evolving Wi-Fi Technology

The Wi-Fi technology is a wireless access technology that converts wired signals into wireless signals for short distances based on the IEEE 802.11 series protocols. Nowadays, Wi-Fi has become the preferred way for users to surf the Internet at home or at work. According to the forecast of Wi-Fi alliance, there will be approximately 40 billion Wi-Fi equipment that provides services to the whole world in 2022, with Wi-Fi carrying more than half of the global data traffic. Such achievements cannot be achieved without continuous evolution of the Wi-Fi technology.

Fig. 3-16 Wi-Fi Standards Evolution



IEEE 802.11b was the first widely accepted Wi-Fi standard, followed by 802.11a, 802.11 g, 802.11n and 802.11ac. The Wi-Fi standard has experienced five generations. During this period, the Wi-Fi technology mainly focuses on how to further improve the theoretical rate, that is, to increase the throughput in the high SNR environment to meet the growing bandwidth demands.

However, with the rise of new services such as smart home, video conferencing and AR/VR, the Wi-Fi network becomes congested due to the access of more and more smart devices, which makes the 802.11ax (Wi-Fi 6) not only focus on the increase of the theoretical rate, but also the increase of spectrum efficiency, and the improvement of the multi-terminal access capability. Compared with the previous generation of the Wi-Fi technology, 802.11ax improves the peak rate by 37%, increases the access efficiency four times in high-density scenarios, and reduces the CPE power consumption by more than 30%.

3.4.2 Key Technologies of Wi-Fi 6

Compared with Wi-Fi 5, Wi-Fi 6 is more applicable to the scenarios that require high rate, high density and low latency. The high-rate and low-latency scenarios include videoconferencing, electronic classrooms and AR/VR. The high-density scenarios are mainly applicable to smart homes, airports, and large venues.

Table 3-4 Wi-Fi6 Application Scenario

High bandwidth	Wi-Fi 6 can reach 500Mbps+ in the 5GHz band, twice the bandwidth required by VR.

Low latency	Based on VR service identification, ensures that the traffic of dedicated channels is less than 50% of the peak traffic, and ensures the average latency of Wi-Fi 6 is less than 5ms.
High density	Concurrent access of 128 CPEs meets the home IoT service development requirements.

In order to meet the service requirements of the high bandwidth and high density scenarios, Wi-Fi 6 mainly introduces the following key technologies to improve spectrum efficiency and throughput, and enhance network performance and user experience in dense application scenarios:

- 1024QAM: It is increased from 256QAM of Wi-Fi 5 to 1024QAM, from 8 bits per symbol to 10 bits, and the theoretical data throughput is increased by 25%.
- 4 times sub-carrier: The sub-carrier gap can be reduced from 312.5 kHz to 78.125 kHz, and the corresponding symbol duration will be increased fourfold. This technology can effectively reduce the packet loss rate and retransmission rate. Especially in the case of medium-distance and long-distance transmission or multi-obstacle transmission, the multipath effect is obvious. This technology can reduce inter-carrier interference and improve the signal coverage distance.
- UL/DL MU-MIMO: It supports simultaneous upload and download of multiple users. The Wi-Fi 6 protocol supports a maximum of eight terminals to share the uplink and downlink bandwidths. It is suitable for parallel transmission of large data packets, and exponentially improves the utilization efficiency of spatial stream and the theoretical rate.
- OFDM MA: Divides a wireless channel into several sub-channels, and subscriber data can be carried on different frequency resource modules. This avoids the disadvantage that a single packet size will occupy the entire channel in Wi-Fi 5, reducing network congestion and delay and greatly improving data transmission efficiency.
- BBS coloring technology: It distinguishes the information that belongs to the terminal through the 6 bits label in the header of the packet, without the need for complete decoding verification, thus reducing the possibility of co-channel interference, improving the transmission efficiency and saving the terminal power.

- TWT technology: The AP negotiates with each terminal to set a "wake-up protocol" so as to negotiate the time interval of the awakened data or the receiving data. It is expected that 30% or above power for the IoT equipment can be reduced.
- 6 GHz frequency band: The 6 GHz frequency band is open for unauthorized use and seven additional 160 MHz channels are added so that the users can easily have their own 160 MHz channels, which doubles (compared with 80 MHz) the throughput and greatly reduces the possibility of spectrum sharing with another device.

*The 6 GHz support certification specifications of WFA are still being formulated.

3.4.3 Next-Generation Technology of Wi-Fi 6

With the release of the EasyMesh™ standard and the rapid increase of multi-AP requirements and applications, the next-generation Wi-Fi technology focuses on multi-AP coordination and network performance optimization. In contrast, Wi-Fi 6 begins to consider network performance in dense scenarios for the first time. At the same time, with the introduction of 6 GHz, large-scale commercial use of fixed network terminals supporting tri-band will be expected in the near future. Therefore, the topic of how to make full use of multi-link advantages is becoming more attractive.

The next-generation Wi-Fi technology is still in the formulation phase, and its functions and technologies are still being further discussed and improved. Based on the information disclosed by the IEEE 802.11 working group, the possible technical improvement directions in the future can be summarized:

- Single-channel operation optimization: Continues the support of Wi-Fi 6E for 6 GHz, 320 MHz channel and 16 spatial streams.
- Multi-link operation mechanism: The CPE is allowed to use two or more links (for example, two channels of 5 GHz and 6 GHz) at the same time for upload and download, so as to improve the throughput, bring the advantage of low latency and support load balancing.
- Multi-AP coordination mechanism: Realizes distributed MIMO between multiple APs, and reuses idle spatial streams to improve network performance in the multi-AP scenarios, especially in the Mesh networking scenario with increasing

demands.

- Low-latency operation mechanism: By combining the latency measurement and multi-link technology, provides low-latency operation mode, enhances the QoS mechanism for low-latency services, and supports 4k/8k video, VR/AR video, gaming, remote office, cloud computing, and other high-throughput and low-latency service applications.
- Link self-adaptive mechanism: For example, uses the Hybrid automatic repeat request (HARQ) technology to decode the transmitted error packets and the retransmitted error packets, thus improving the decoding success rate.

3.5 5G FWA

3.5.1 5G FWA Becomes the Focus of Operators

With the advent of the 5G era, Fixed Wireless Access (hereinafter referred to as FWA) has become a topic concerned by more and more operators. The 5G access technology supports an access peak rate of 10Gbps, an average access rate of 1Gbps, and 1ms air interface delay. Compared with 4G, the 5G access technology significantly improves the rate, delay and spectrum efficiency.

Compared with FTTx, 5G FWA has shorter TTM and lower TCO. From the perspective of the market, the current market unserved by home broadband is a huge potential market for FWA. Considering that FWA can reduce the deployment cost of the last mile and provide broadband services at a relatively low price, especially in areas where wired broadband is unavailable, these unserved markets will be the potential markets for FWA.

At present, many operators have determined their 5G processes, and the market share of 5G FWA will grow rapidly in the future. FWA has been deployed in nearly 120 countries. 5G FWA can directly compete with DSL, Cable Modem and the access technologies other than FTTx. Except for FTTx, the fixed broadband with more than 500 million connections is a potential opportunity for 5G FWA.

3.5.2 Main Deployment Scenarios of 5G FWA

The deployment scenarios of 5G FWA mainly include four parts:

- To improve the coverage: 5G FWA can be deployed in areas where FTTx is unavailable.
- To provide high-rate services: To mainly increase capacity and QoE for the areas accessed by twisted pairs.
- To improve efficiency: 5G FWA is deployed on the existing mobile network to improve spectrum utilization.
- For hotspot coverage: 5G FWA is deployed in hotspot areas to share the traffic pressure of MBB and FBB.

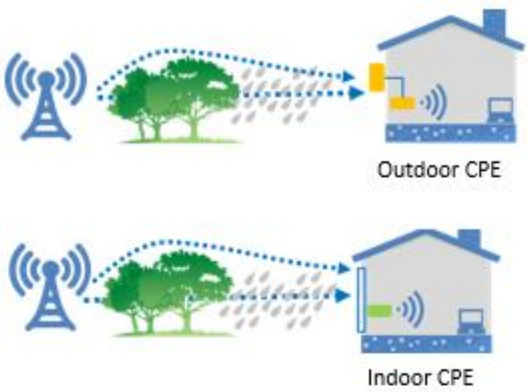
5G FWA brings the following benefits to operators:

- For traditional fixed network operators, the first benefit of 5G FWA is coverage improvement. It can be deployed in places that are not covered. The second benefit of 5G FWA is providing high-speed services, especially improving QoE for the areas accessed by twisted pairs.
- For mobile operators, 5G FWA can expand the new market, provide multiple services to meet the user requirements and prevent the users from shifting to other operators.

3.5.3 5G FWA Deployment Restrictions

Although 5G FWA has some advantages, it has some restrictions in actual use because it uses the air interface for transmission. To explore the impact of the external environment on performance, an environment is built for simulation tests.

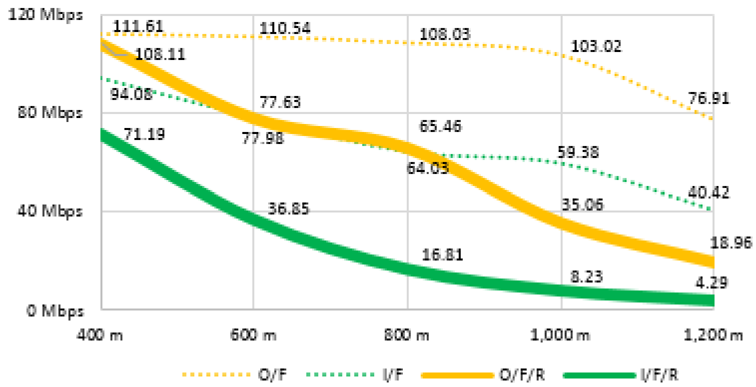
Fig. 3-17 Test Environment Simulation



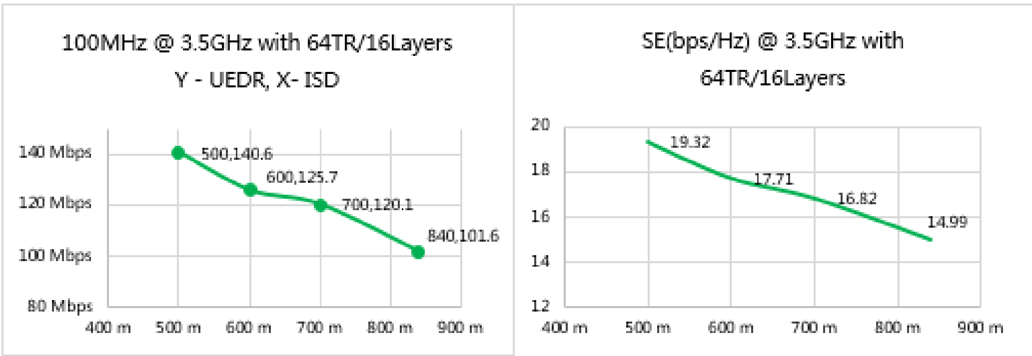
The test shows that the installation position of the CPE, rainfall, and vegetation all affect the final performance.

Fig. 3-18 Simulation Results

28G comprehensive performance (attenuation)



3.5G comprehensive performance



The following conclusions can be drawn through data comparison:

- When the edge data rates are the same, the radius of the outdoor CPE is more than four times that of the indoor CPE.
- Under the same coverage conditions, the outdoor CPE has a rate gain of over 25% compared with the indoor CPE.
- In the case of 50 mm rainfall, the outdoor rate can reach 100Mbps @1100m or the rate of CPE at the cell edge can be reduced to 89Mbps.
- In the case of rain of 50 mm, the indoor rate can reach 100Mbps @680 m or the rate of CPE at the cell edge can be reduced to 26Mbps.
- The vegetation has the penetration loss and diffraction effect in the NLOS

scenario. The vegetation will cause -0.54 dB/m loss at the frequency of 3.5 GHz, and -4.05 dB/m loss at the frequency of 26 GHz.

- In sunny days, only outdoor CPE can reach the rate of 100Mbps at a distance of more than 100m. In the case of other vegetation losses, a low GBR and short-distance coverage should be maintained.

Table 3-5 Analysis of the Relationship between Coverage and Frequency

Distance	3.5G (100M)	28G (400M/800M)
50m-400m	User>100 Mbps, the throughput of the cell is small, unable to provide high-speed services to more users.	User>100 Mbps, the throughput of the cell is two to three times that of 3.5G, deliver fiber-like services to more users.
400m-1000m	User>50 Mbps, higher download speed	User download speed decline sharply, the performance is far lower than that of 3.5G.
Capacity	2.7G (the simulation result is approx. 900M/Cell)	6G (based on 2G/Cell)
Scenario	Mobile user group + 5G FWA hybrid service	Suitable for high-density user areas.
	Suitable for medium rate FAW users (20-50M)	Suitable for fiber-like FWA users (200M-1G)

It can be seen that pure 5G FWA access requires a high position for 5G CPE deployment and relatively harsh environments such as weather.

3.5.4 5G+FTTx Solution

From the above conclusion, the FWA is convenient, but its reliability is far from FTTx. In the future application deployment, 5G FWA+FTTx combined solution can be launched, which is applicable to three scenarios.

- 5G+PON: It adopts the integrated gateway and supports dual uplink modes of 5G and PON for mutual backup.
- 5G+DSL: Uses the integrated gateway and supports both 5G and DSL uplink modes. The two modes take effect at the same time. The 5G mode makes up

for the shortage of the DSL access rate, effectively shares the FBB traffic, and guarantees high rate access, thus bringing premium user experience.

- FTTH+5G AP: Uses the existing FTTH access network, and carry 5G AP under ONT to supplement the 5G coverage. 5G can be used as the backup link, which greatly shortens the time for communication recovery after disaster and ensures the communication requirements of users under extreme conditions. In addition, 5G can be deployed in areas where the ODN construction is not completed to shorten the TTM, such as using 5G signals to cover blind spots in the areas like indoor and densely populated stadiums that the base stations cannot fully cover, thus ensuring network access of users.

The 5G frequency band determines that the penetration rate is not as good as that of the 4G network, and attenuation will occur due to the influence of weather. FTTH+5G AP networking can be supplemented by the high-speed access of existing PON. Create a dedicated channel on the ONT and connect a 5G AP under it to supplement 5G signals in indoor and densely populated stadiums where base stations cannot fully cover, thus ensuring access of users.

Generally speaking, 5G FWA can improve user experience to a certain extent, but pure 5G FWA access for home broadband service is still inadequate. Its performance is sensitive to deployment location, obstacles and weather conditions. While the 5G FWA+FTTx solution complements the disadvantages of 5G FWA and FTTx respectively to ensure the robustness of the user’s network and improve the access bandwidth, thus enhancing user experience of high-speed networks.

4 Summary

The access network is nearest to users, its development is closely related to the experience and perception of end users. The access network has the features of wide coverage, complex scenario, and high cost sensitivity. Whether an access technology can be recognized and widely used depends on its standards, industrial chain, costs, application scenarios, user groups, and other factors. In particular, fixed access networks involve a large amount of infrastructure construction and investment, and once they are deployed, their changes need to be considered in a unified manner.

At present, optical fibers have been widely used in networks at the core layer, distribution layer and access layer to support long-distance coverage, large-traffic data transmission and light network deployment. With the decrease of costs and the development of supportive technologies for optical fiber deployment, it is expected that optical fiber access will be further developed in the coming 5 to 10 years. Due to its clear evolution direction, wide coverage, and theoretically infinite bandwidth, the PON technologies based on optical fiber media have obvious advantages over copper cable access in terms of deployment. It is undoubtedly the mainstream technology for FN development in the future.

There is a huge amount of copper-based DSL and DOCSIS access, and some operators continue to upgrade and evolve their networks based on existing technical routes. However, due to the uncertainty of future technical development and the consideration of copper cable quality, under the prerequisite of the input-output ratio, gradual transition to optical fiber is the future development direction. At present, some traditional fixed network operators and cable operators are already transforming to PON-based FTTH networks. It is expected that this trend will become more apparent over time.

The home network will be the key direction of the future fixed network development. Based on the convenience of use, and the demands for small impact on the existing environment, seamless access and roaming, FTTH will be promoted to further solve fiber coverage in the last meter, or use the new Wi-Fi access technology to realize high-speed access without changing the existing layout of the user home, laying a solid foundation for smart home development.

The introduction and gradual deployment of 5G will inevitably affect the existing wireline broadband network and force it to make changes. In addition, the development of the fixed network will further promote the development of 5G. They will promote each other and jointly promote the development of the broadband field.