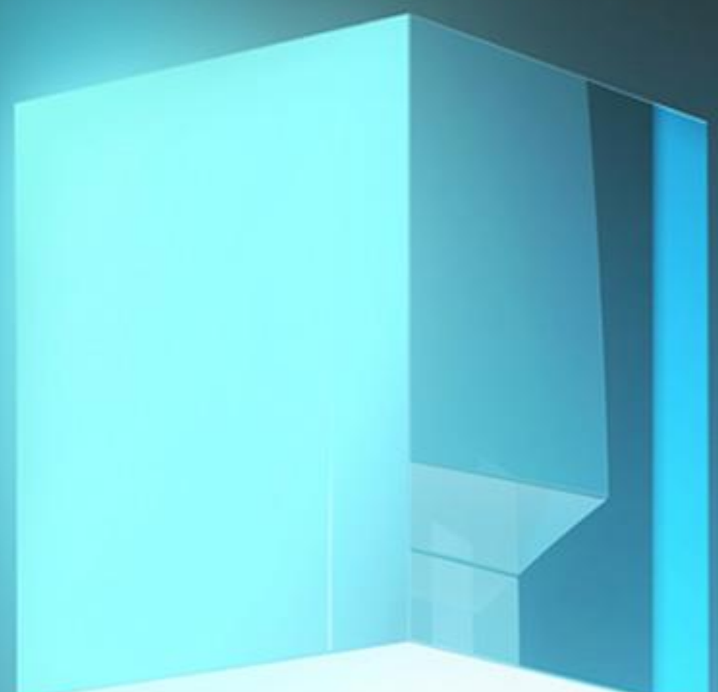
ZTE

White Paper on 50G-PON Technology



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1 PON Technology Review and 50G-PON Outlook

1.1 History of PON Development

Passive optical network (PON) technology is a passive broadband access technology that uplinks and downlinks data with different wavelengths, and uses time-division multiplexing technologies for data transmission. A passive optical network utilizes a point-to-multipoint (P2MP) topology, where a plurality of optical network units (ONUs) are connected to the same PON port to save central office resources. The ODN connecting the OLT and ONUs uses optical fibers and passive components to avoid electromagnetic interference and provide strong environment adaptability as well as easy expansion and upgrade. PON technology has been applied on a large scale due to its advantages of high bandwidth, high reliability, multi-service transmission, and low cost.

FSAN/ITU-T and IEEE have played a significant role in promoting the development of PON technologies. PON developed from the first ATM PON (APON) and then evolved in Broadband PON (BPON). The commercial PON technologies have experienced three generations of development, among which GPON and EPON have been commercially deployed on a large scale. At present, 10G-EPON and XG(S)-PON have already matured and enter the window period of large-scale commercial use.

Table 1-1 Evolution of PON Technologies

Generation of PON Technology	Downlink Rate	IEEE	ITU-T
GPON/EPON	2.5 Gbps/1.25 Gbps	EPON (IEEE 802.3ah)	GPON (ITU-T G.984)
10G PON	10 Gbps	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)

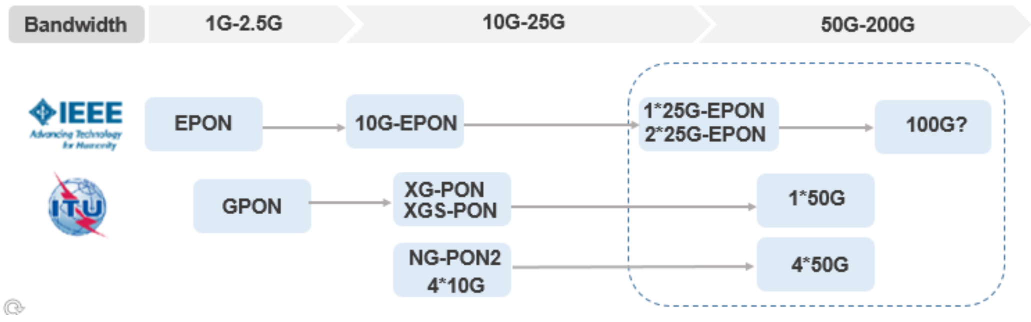
The first-generation GPON/EPON technology can provide 100 Mbps-capable bandwidth to users, and gradually replace the existing copper cable access technology. The second-generation 10G PON technology can provide 300 Mbps-1 Gbps bandwidth to users, which satisfies the large-scale application of 4K/8K video services and the introduction of VR/AR services in the early stage. The services requiring a bandwidth of more than 1G, such as extreme AR, government and enterprise access and 5G Fronthaul/Backhaul, propose higher requirements for the bandwidth and latency of PON technologies.

The next-generation PON (NG-PON) following 10G PON has two development directions. The first direction is to improve the single-wavelength rate and the second direction is to increase the total rate through multi-wavelength multiplexing. It is widely recognized in the industry that the capacity of the next-generation optical access network will be increased to 50 Gbps. Therefore, how to upgrade the system capacity in a simple and efficient manner becomes a research hotspot in the PON field. Based on this idea, IEEE and ITU-T are studying and actively promoting the follow-up evolution of PON technologies.

IEEE was the first to start the formulation of the NG-PON standard, which supports a downstream rate of 25 Gbps over a single optical fiber, an upstream rate of 10 Gbps or 25 Gbps rate, and compatibility with 10G-EPON. To address the 50 Gbps bandwidth requirements, it employs the multi-wavelength multiplexing technology and channel binding technology to provide two 25 Gbps channels to achieve a transmission rate of 50 Gbps.

Based on the technical research report of the G.Sup64 PON transmission technologies above 10 Gb/s per wavelength, ITU-T takes into account the requirements of home users, enterprise users, mobile backhaul and fronthaul, and gradually sets requirements for NG-PON, focusing on the 50G-PON technology with a single channel rate of 50 Gbps.

Fig. 1-1 PON Technology Evolution Diagram

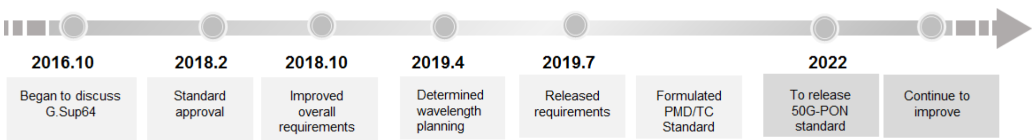


1.2 50G-PON Standards Development

After completing the formulation of the 10G-GPON standard, specified as the XG-PON standard, FSAN started the technical research of NG-PON, which initially has multiple wavelengths, each operating at 10 Gbps. The NG-PON2 standard research was initiated in 2011, and was formulated in 2015. Restricted by the high cost of tunable optical components and system maturity, NG-PON2 has seen slow commercial deployment, and its future applications are doubtful, therefore it may be skipped.

At the same time, ITU-T has carried out research on the subsequent evolution of PON technologies, and initiated the white paper of the next-generation high-speed PON technology to investigate its various technical possibilities. Compared with the multi-wavelength multiplexing solution, the single-wavelength 50G-PON has the potential to become the mainstream industrial standard of the next-generation optical access network after 10G PON. In 2018, FSAN/ITU-T started the formulation of the 50G-PON standard *G.HSP: G. Higher Speed PON*, which is expected to be released in 2022 and be gradually put into commercial use by 2025. Before it, 10G PON will remain the mainstream technology in the industry and will be put into large-scale commercial deployment.

Fig. 1-2 50G-PON Standards Development



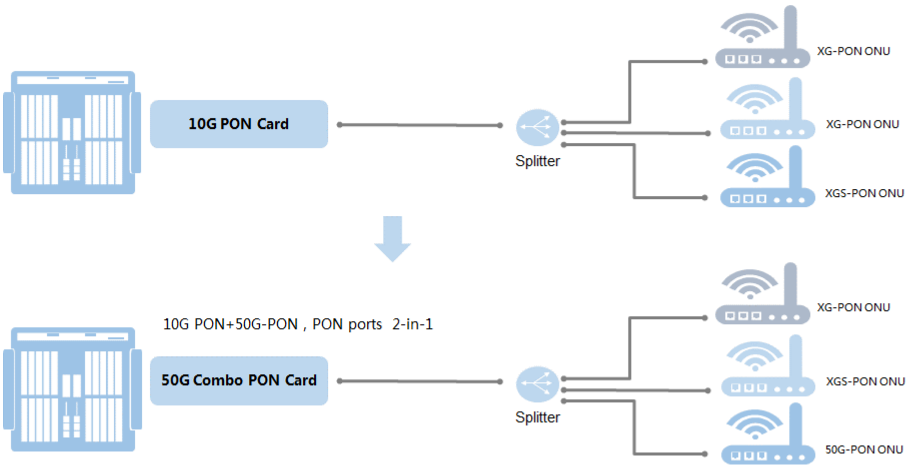
The research on single-wavelength 50G-PON has also been carried out. Both the upstream and downstream of the 50G-PON operate in the O band and 50G-PON does not support coexistence with GPON and XG(S)-PON. The FEC adopts the LDPC error correction algorithm. In order to better support low latency, 50G-PON introduces the dedicated activation wavelengths (DAW) and CoDBA. With the DAW technology, ONUs are registered and activated on dedicated wavelengths, and service wavelengths are not allocated with a quiet window, reducing the transmission delay caused by registration window opening. CoDBA means that the OLT allocates authorization bandwidth to the ONU through the coordination with the base station when carrying wireless services. The time when the mobile terminal data reaches the ONU is the DBA authorization time of the PON system. The data can be forwarded without waiting, thus reducing the delay caused by bandwidth scheduling.

1.3 Migration to 50G-PON

At present, 10G PON has entered the batch deployment phase. With the rapidly growing demands for home broadband access and government & enterprise access in the future, 50G-PON will be the next deployment trend of wireline broadband access. In order to implement smooth migration from 10G PON to 50G-PON and meet the networking requirements of different services, 10G PON and 50G-PON will coexist for a long time. To save the deployment space of the equipment room, reduce energy consumption of optical access equipment, effectively use the ODN resources of the existing network, and reduce the operators' network construction costs, the multi-mode optical transceiver module, such as Combo PON optical module in support for the coexistence of GPON and 10G PON, has been proved to be the most effective means so far.

According to the requirements for smooth network evolution, equipment room deployment space saving and efficient utilization of ODN resources, it is necessary to verify and test the coexistence of 50G-PON and 10G PON services.

Fig. 1-3 Smooth Migration and Evolution to 50G-PON



2 50G-PON Requirement Analysis

The increasing demand for access bandwidth requires continuous improvement of the access network capacity. The development goal of the optical access network in 5-10 years is to increase the access rate per subscriber to 1-10 Gbps. In addition, with the full deployment of 5G, new scenarios such as small 5G small cells emerge. Compared with the direct optical fiber connection solution, PON-based 5G Fronthaul can greatly save feeder optical fibers. Therefore, both the fixed networks and 5G mobile access networks have potential requirements for implementing the ultra-10G optical access technology. 10G PON has been deployed on a large scale, and the market needs to focus on and deploy next-generation technologies to meet network evolution requirements. The follow-up evolution of 10G PON requires more than a four-fold increase in bandwidth, smooth evolution, and compatibility with the existing ODN.

50G-PON is the next-generation PON standard formulated by ITU-T after 10G PON. It supports 50 Gbps uplink and downlink over a single wavelength, and provides a bandwidth five times faster than 10G PON. It still uses the TDM PON mechanism, and supports the coexistence with 10G PON and the deployed ODN infrastructure. In addition, in view of the features of intelligent new services, it improves low latency, slicing, energy saving, and reliability to meet the subsequent smooth evolution of 10G PON and meet the comprehensive access requirements of multiple scenarios while considering costs.

The general requirements of 50G-PON have been released, and are specified in terms of transmission capability, coexistence, service support, protection and security.

2.1 Bearer Capability Requirements

Requirements for all the 50G-PON systems intended to run on a PON infrastructure based on optical splitters:

- In the downlink and uplink directions, the nominal symmetrical rate of each wavelength channel is 50 Gbps to support a maximum service rate of at least 40 Gbps.
- The asymmetric nominal rate of each wavelength channel is 50 Gbps uplink and 25 Gbps downlink.
- Supports ONUs with different upstream nominal rate on the same wavelength channel through TDMA.
- Supports the optical fiber types described in ITU-T G.652 and ITU-T G.657.
- Operates on the ODN composed of optical fibers, connectors, splitters and wavelength selectable equipment.
- The TDMA-based system should support:
  - A maximum optical fiber coverage distance of 60 km.
  - A maximum differential fiber length of 40 km.
  - A minimum optical splitting ratio of 1:256.

2.2 PON Coexistence Requirements

The coexistence requirements for the 50G-PON technology are as follows:

- Supports coexistence of traditional PON and 50G-PON technologies over the same optical fiber.
- Avoids or minimizes the interruption of ONU services that not upgraded.
- Supports compatibility with traditional PON services.

Two steps can be considered in the migration from the existing network to 50G-PON:

from GPON to XG(S)-PON, and from XG(S)-PON to 50G-PON. This requires to migrate GPON under the PON port to XG(S)-PON before upgrading it to 50G-PON. The GPON wavelength window is reused so that 50G-PON and XG(S)-PON can coexist and implement full migration in two steps. In this case, the two types of PON technologies coexist at any time.

In order to enable simultaneous operation of XG(S)-PON and 50G-PON, the network should have the WDM functionality, provided by either independent CEx or 50G-PON Combo PON optical modules, see Fig. 2-1 and Fig. 2-2.

Fig. 2-1 Coexistence of XG(S)-PON and 50G-PON via Independent CEx

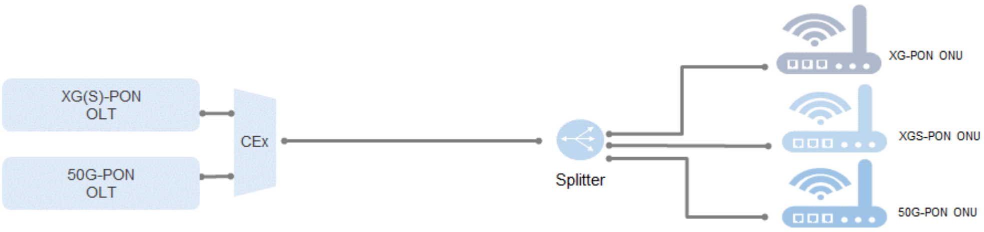
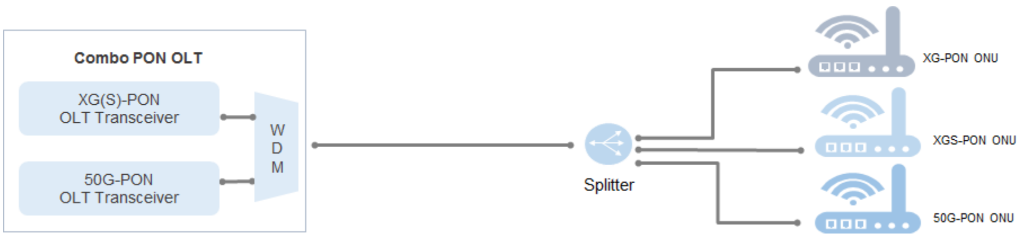


Fig. 2-2 Coexistence of XG(S)-PON and 50G-PON via Combo PON



2.3 Service Support Requirements

With high service quality and high bit rate capability, the 50G-PON system fully supports the various service requirements of home users and enterprise users. Moreover, the 50G-PON system can achieve better delay and jitter performance. 50G-PON must support traditional services, such as using POTS and T1/E1 emulation, high-speed dedicated line (with frame and without frame) and new packet services, and must support Ethernet packets with up to 9,000 bytes.

For mobile backhaul services (especially 5G services), it should support time transfer (such as ITU-T G.984, ITU-T G.987, ITU-T G.989 and ITU-T G.9807 series) and low transmission delay.

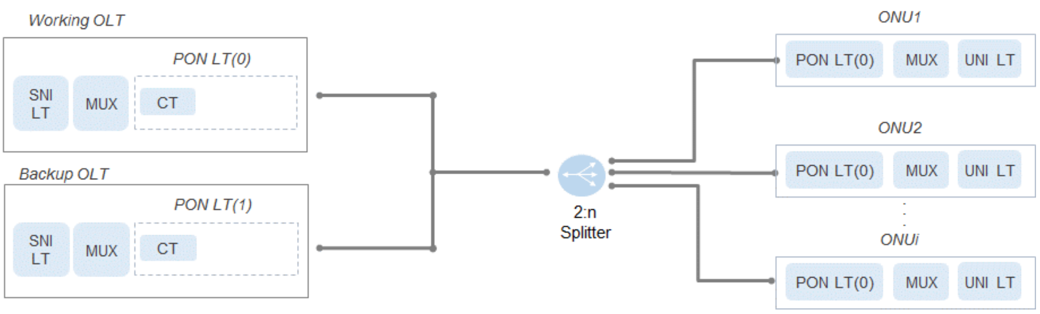
To support wireless transmission requirements, including OTDOA-based location service, the 50G-PON ONUs should keep the ToD synchronized to the precision of about 100ns specified in ITU-T G.8273.2.

2.4 Protection Requirements

50G-PON protection will become more and more important in supporting enterprise applications and high-value home user applications, especially in the multi-service coexistence scenarios. 50G-PON needs to provide end-to-end protection to avoid service interruption to thousands or even tens of thousands of users when optical fibers or devices are faulty. The protection mode can be Type B or Type C.

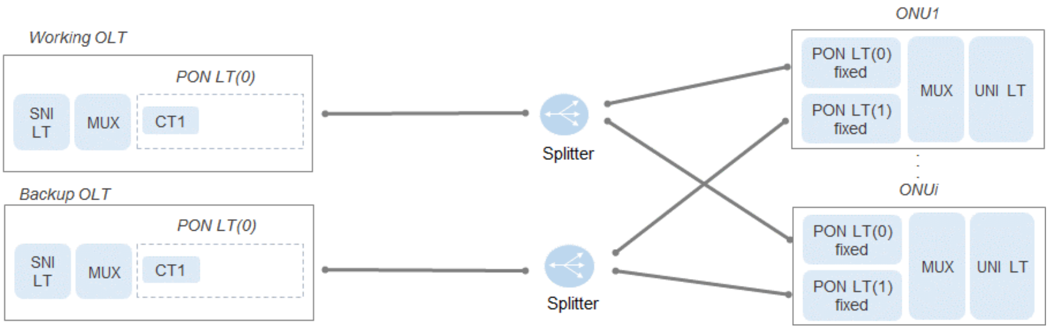
When Type B protection is adopted, the OLT and feeder fibers will be protected, see Fig. 2-3.

Fig. 2-3 Type B Protection - 1:1 Redundancy



When Type C protection is adopted, that is, the duplex system (1+1 model), the ONU has two fixed transceivers, see Fig. 2-4. Therefore, the fault can be recovered at any time after the standby OLT is switched over.

Fig. 2-4 Type C Protection - 1:1 Redundancy



2.5 Security Requirements

Like the traditional PON system, 50G-PON is based on shared media. All ONUs on the same PON receive complete data. Therefore, measures must be taken to avoid spoofing.

To prevent spoofing, the identity authentication mechanism must be standardized. The 50G-PON system needs to implement these mechanisms, and the activation of these mechanisms must be dynamically controlled by the operator, including but not limited to:

- Authenticates the ONU serial number and/or registration ID used for ONU registration.
- Client (CPE) authentication based on IEEE 802.1x.
- Needs a powerful identity authentication mechanism.

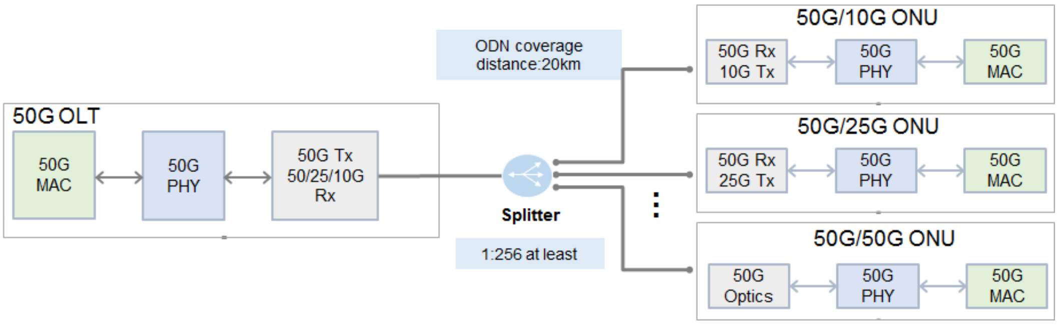
When the energy saving function is used, a low complexity but secure identity authentication method is also required to recover from the “sleep” mode.

To prevent data from being detected at the ONU, all downstream unicast data should be encrypted by using a powerful algorithm with good features, for example, Advanced Encryption Standard (AES). 50G-PON should also provide a reliable key exchange mechanism necessary for encrypted communication. The 50G-PON system must support uplink encryption and related key exchange, as well as the method of uplink encryption control during operation.

3 Key 50G-PON Technology Analysis

Single-wavelength 50G-PON is located in the Central Office (OO) of the access network. It uplinks the service network and downlinks users through various ONU user interfaces. Single-wavelength 50G-PON supports a point-to-multipoint topology as well as video, data and voice services. Like GPON and 10G PON, single-wavelength 50G-PON uses wavelength division multiplexing to implement single-fiber bidirectional transmission, and uses TDM for downstream traffic and TDMA for upstream traffic to implement point-to-multipoint communication between the OLT and the ONUs.

Fig. 3-1 Single-Wavelength 50G-PON System Architecture



3.1 Wavelength Selection

The PON system has been developed for several generations, and different wavelengths are adopted in different standards. The wavelength resources of optical access networks are increasingly limited. In addition, the optical access networks are oriented to the vast number of users with diverse requirements, resulting in the coexistence of multiple PON generations in the existing networks. At present, only a small section of O band is available for 50G-PON, which is not sufficient for the 50G-PON systems. After considerable discussions by ITU-T, it has been determined that 50G-PON will not coexist with both GPON and 10G PON at the same time.

In addition, after the rate is increased to 50G-PON, a high-sensitivity receiver needs to be implemented so that the deployed ODN network can be reused. The front-end amplifier is an effective solution to improve the receiver sensitivity. However, the amplifier has out-of-band ASE noises, which affects the receiver performance.

Therefore, an optical filter needs to be added and the wavelength of the filter needs to match that of the transmitter. To avoid using adjustable filters, the transmitter wavelength needs to be narrowed to a certain range. Therefore, 50G-PON needs a wavelength scheme with narrow wavelengths. The specific wavelength selection scheme is still being discussed. Fig. 3-2 and Table 3-1 show the determined wavelength selection scheme of 50G-PON.

Fig. 3-2 50G-PON Wavelength Planning

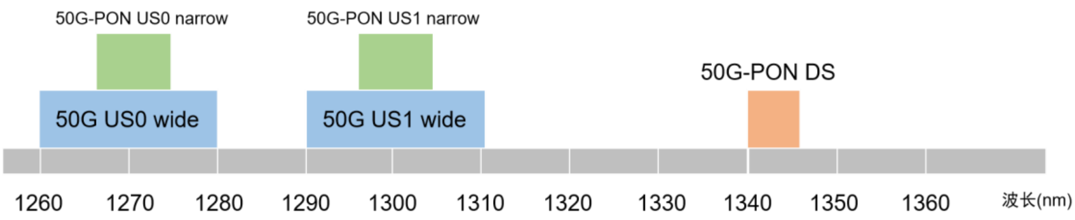


Table 3-1 50G-PON Wavelength Scheme

Item	**US0-wide 1260-1280nm**	**US1-wide 1290-1310nm**	**US0-narrow 1268-1272nm**	**US1-narrow 1298-1302nm**
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

3.2 Line Coding

In the initial discussion of ITU-T, several line codes such as PAM4, duobinary and NRZ were considered. Because the PON system requires a very high power budget, ITU-T finally selects the NRZ code with the best receiving performance.

3.3 Line Rate Selection

ITU-T has clarified the requirement for 50G-PON rate, and supports the combination of symmetric and asymmetric rates. The supported rate include 49.7664 Gbps downlink, as well as 9.95328 Gbps, 12.4416 Gbps, 24.8832 Gbps and 49.7664 Gbps uplink. There are little difference between 9.95328 Gbps and 12.4416 Gbps. It is estimated that three types of rates will be used: 12.4416 Gbps, 24.8832 Gbps and 49.7664 Gbps.

3.4 FEC Correction Technology

When the rate of the 50G-PON line is increased, the receiver sensitivity will decline. It is necessary to improve the transceiver performance to reuse the ODN network that has been deployed in large numbers. To lower the requirement for high-speed optical component indexes, 50G-PON introduces low-density parity check (LDPC) (17280, 14592) to implement FEC forward error correction by referring to IEEE NG-EPON. The encoding efficiency is about 84.84%. Compared with 10G PON RS (255, 221) coding, the BER before correction can be reduced to 10-2, and the receiving sensitivity can be increased by about 2 dB.

The LDPC algorithm is divided into hard value input and soft value input based on the decision method of the output data. Hard-value data is a 01-bit sequence after equalization decision, and is sent to the LDPC decoder to be decoded. The soft value input is the raw data that has not been decided, and the log-likelihood ratio (LLR) of the input signal, thus improving the error correction performance. Soft value input needs to be followed by the equalizer, and the ADC needs to perform digital sampling of original signals.

3.5 Common TC Technology

50G-PON supports the PON-MFH (Mobile Fronthaul) application scenario, that is, PON-based 5G mobile Fronthaul. In this scenario, the OLT and the ONU provide service transmission between CU and DU, and 50G-PON is required to support low latency. 50G-PON implements low latency mainly through the following technologies: dedicated activation wavelength (DAW), coordinated DBA (Co-DBA), and allocation period reduction.

- Dedicated activation wavelength: The dedicated activation wavelength can be a newly defined wavelength or the wavelength of the PON system deployed before 50G-PON, such as 10G PON wavelength and GPON wavelength. The dedicated activation wavelength may be an independent upstream wavelength. Under this condition, the dedicated active wavelength and the 50G-PON downstream wavelength complete the activation process, including ONU discovery and ONU ranging. The ranging result on the 50G-PON upstream and downstream wavelength is obtained through calculation. The dedicated activation wavelength can also be a pair of uplink/downlink wavelengths. Under this condition, the dedicated activation wavelength alone completes the activation process, including ONU discovery and ONU ranging. The ranging result on the 50G-PON upstream and downstream wavelength is obtained through calculation. The dedicated wavelength activation technology avoids opening the quiet window on the 50G-PON uplink wavelength, and successfully cancels the delay caused by the quiet window.

- Coordinated DBA (Co-DBA): The OLT learns about the upstream service transmission requirement of the ONU through the upstream device CU, and allocates the bandwidth to the ONU in advance, so that the service data can be cached as little time as possible in the ONU.
- Allocation period reduction: Reduces the time interval for the ONU to obtain the bandwidth allocation, thus reducing the service data cache time in the ONU. Each T-CONT can be allocated up to 16 times in the 125us period, that is, up to 16 burst can be sent in the 125us period.

To achieve ultra-50Gbps rate transmission, the channel binding technology of multiple channels can be used.

In channel binding, service data packets on the sending side are divided into several data units. For each data unit, the data packets are sent in the earliest channel among multiple channels. If there are multiple earliest channels, the data packets are sent in the channel with the smallest number. This rule is used until all data units are sent. On the receiving side, one data unit is received on the earliest channel among multiple channels. If multiple channels have the earliest receiving time, the channel with the smallest channel number is selected. After all data units are received in accordance with this rule, each data unit is assembled into service data packets in accordance with the receiving sequence.

In addition, due to different wavelengths, data units have different transmission delays on different channels. The sequence of data units transmitted on multiple channels on the receiving side may be different from that on the transmission side. Therefore, the data unit sequence recovery technology is required. Currently, the specific technology has not been determined in the standard. One possible technology is to send PSBd synchronously on each channel in the downlink direction and set a unified time reference point. The sending and receiving sequence of the data unit is based on this reference point and the upstream direction is similar. The other possible technology is that the sender determines the relative position of the data unit sent by each channel and marks this relative position in the data frame, and the receiver restores the data unit sequence according to these relative position relations.

3.6 50G-PON PHY Layer Component

The PHY-layer component is one of the key technical problems that need to be solved in the PON system. The optical transceiver component that meets the performance requirements of the PON system is the core PHY component. With the increase of PON rate, in order to avoid introducing excessive dispersion cost in C band and avoid conflict with such system wavelengths as GPON, XG(S)-PON and TWDM-PON, uplink and downlink wavelengths are defined in the O band with low dispersion coefficient in the ITU-T G.9804 single-wavelength 50G-PON standard.

The 50G-PON PHY layer components mainly include optical transmission components, optical receiving components, Laser diode driver (LDD), burst TIA and clock recovery chip CDR (where, the upstream receiving direction requires burst clock recovery BCDR) and other key photoelectric components. The OLT optical transmission module can adopt EML and integrated SOA EML components. The OLT optical receiving component can adopt APD and integrated SOA PIN. The ONU is similar to the OLT. Unlike the OLT, the ONU driver needs to support the burst function, and the receiving does not need burst-mode clock data recovery (BCDR). The ONU optical transmission component with the upstream rate of 25 Gbps/10 Gbps can also use DML.

At present, the core photoelectric components in the industry are not mature yet. The optical component solutions, the indexes, standards, requirements, and the standards are still being discussed. There is no photoelectric component on the PHY layer applicable to 50G-PON OLTs and ONUs. The experimental and simulation results of mainstream manufacturers in the industry indicate that 50G-PON using the 50G EML transmitter and the 25G APD receiver is expected to obtain a single-wavelength rate of 50 Gbps. Although 50G EML optical components are available in the industry, they are mainly used for Ethernet 400GE optical modules with low transmit optical power (chip-level output optical power: 4-5dBm) and low extinction (>4 dB). The indexes used for 50G-PON need to be further improved. The 1342nm downlink 50G EML is absent. The 25G APD industrial chain is basically mature, and has been commercially used in optical modules such as Ethernet 50G ER and 100G/200G ER4 optical modules. Only a few manufacturers can provide a small batch of 50G APD samples. In terms of key electrical components, LDD and downlink receiving continuous TIA can reuse the data communication product components in the industrial chain. However, the LDD of the uplink burst laser driver lacks dedicated chips, and the uplink burst TIA component and burst clock recovery chip do not have available components.

3.7 Comparison of 50G-PON and 10G PON Technologies

Table 3-2 Key Technologies of 50G-PON and 10G PON

Item	50G-PON	10G PON
Line rate (DS)	49.7664 Gbps	9.95328 Gbps
Line rate (US)	9.95328 Gbps, 12.4416 Gbps, 24.8832 Gbps, 49.7664 Gbps	2.48832, 9.95328 Gbps
Line coding	NRZ	NRZ
FEC	LDPC (17280,14592)	RS (248,216)
Quiet window	Open on DAW	Only open on working wavelengths
CO-DBA	Support	Not support
Maximum burst frame per T-CONT per 125us	16	4
Coexistence of the same ODN	Coexist with 10G PON	Coexist with GPON

Item	50G-PON	10G PON
Channel binding	Supports TC-layer channel binding	Service-layer channel binding
Slicing	Support	Not support

3.8 Further Research Directions of 50G-PON

At present, some technical contents of 50G-PON have been determined, and some contents and directions have yet to be further researched and determined. The following two directions may be the focus of follow-up attention:

- The PON network will support the exclusive bandwidth requirement of multiple operators or services in the future. Its support for hard slicing is an important feature, which will support the establishment of rigid pipes for PON downlink scheduling, and will affect the existing PON protocol framework. If 50G-PON supports this feature, how to be compatible with deployed networks such as XG(S)-PON needs to be discussed further.
- In order to meet the coexistence of optical modules with different the rate of 10 Gbps, 25 Gbps, and 50 Gbps, the uplink optical power budget of 50G-PON is relatively tight. The problems including latency and the contradiction between performance and cost caused by the introduction of LDPC to improve the error correction capability needs to solved.

4 50G-PON Application Scenario Analysis

4.1 Home Ultra-broadband Access

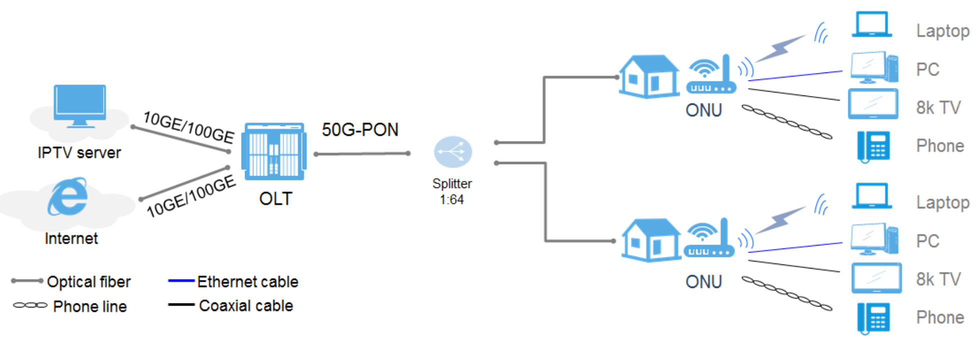
50G-PON mainly provides the high-speed Internet access, video and voice services to the home customers when it is applied in the home broadband access scenario. In order to meet the ever-increasing fixed network bandwidth requirements, especially 4K/8K, AR and Cloud VR, the typical bandwidth requirement is 1-5 Gbps per home, the access network needs larger bandwidth, and the PON technology needs to evolve continuously.

Table 4-1 Key Technologies of PON

VR Video	Time of Commercialization	Panoramic Bandwidth	FOV Bandwidth	RTT Latency	Packet Loss Ratio
Entry	-2 years	120M	48M	20ms	2.4×10^{-5}
Experience	3-5 years	630M	155M	20ms	1×10^{-6}
Extreme	6-10 years	4.4G	1.1G	10ms	1×10^{-6}

Fig. 4-1 takes Gigabit to home as an example to analyze the user bandwidth convergence ratio of the 10G PON and 50G-PON port. As can be seen, 50G-PON can provide a larger convergence ratio, a larger bandwidth channel, lossless compression and extreme user experience to users.

Fig. 4-1 Gigabit to Home Deployment Diagram



10G PON: 10G/64 (split ratio)/1G=1:6

50G-PON: 50G/64 (split ratio)/1G=1:1

Considering an actual installation of 50% and a concurrent rate of 70%, the actual downlink bandwidth requirement of 64 subscribers is 64*50%*70%*1G=22G. The calculation proves that 50G-PON can meet the requirements of higher installation rate and concurrent rate.

In addition, the high bandwidth and low latency requirements of home broadband services depend on the high throughput and low latency requirements of 8K HD video, AR, and Cloud VR services.

With reference to China Telecom's white paper on low latency optical network technology, and according to the formula in Fig. 4-2, TCP throughput is limited by three factors: bandwidth, RTT, and the packet loss rate ρ. Suppose that the bandwidth is sufficient, and the packet loss rate is not considered due to good network quality, latency becomes the decisive factor. If the latency is too large, the users' bandwidth experience cannot be improved. In this case, the problem cannot be solved by only improving the bandwidth, this phenomenon is called "bandwidth black hole."

Fig. 4-2 Throughput Formula

$$\text{Throughput} \leq \min\left(BW, \frac{CWND}{RTT}, \frac{MSS}{RTT} \times \frac{1}{\sqrt{\rho}}\right)$$

Suppose the bandwidth (BW) is 10 Gbps and the unidirectional delay is 10 ms (the round trip time RTT is 20 ms). According to the above formula, the maximum throughput of the TCP protocol is only 26.3 Mbps, much lower than the network bandwidth. The industry generally believes that the throughput of real-time large-throughput services such as 4K/8K HD video should be 1.5 times of the actual code stream rate to ensure service quality. As a result, the 4K HD video requires a throughput of 30-45 Mbps, and the maximum RTT is 12-17 ms according to the above formula.

VR requires a user bandwidth of more than 1G, and a lower delay of 5 ms (RTT delay) to improve user experience.

Table 4-2 Requirements of VR Services for Bandwidth and Latency

Standard		Pre-VR	Entry-Level VR	Advanced VR	Ultimate VR
Video definition		3840*1920	7680*3840	11520*5760	23040*11520
Strong interactive VR service	Code rate	18 Mbps	60 Mbps (3D)	390 Mbps	680 Mbps
	Bandwidth requirement	50 Mbps	200 Mbps (3D)	1.40 Gbps	3.36 Gbps
	RTT	10 ms	10 ms	5 ms	5 ms
	Packet loss ratio	1.00E-6	1.00E-6	1.00E-6	1.00E-6

With reference to the above bandwidth and latency requirements, 50G-PON can effectively improve the bandwidth for the 4K/8K service of the home broadband HD

TV, and uses the low latency technology to reduce the latency performance of the access equipment, thus reducing the RTT of the entire network, and finally improving the throughput of the video service and user experience. In addition, if the forwarding delay of the 50G-PON system is less than 1 ms, the stringent service requirements of Cloud VR can be basically met.

4.2 Deterministic Campus Network

Information and communication technologies are integrated and penetrated into various industries, and digital transformation and upgrade of industries are accelerating. Industrial networks oriented to industrial users such as factories, ports, campus, and hospitals have different requirements for network transmission, and have higher requirements for network determinacy such as coverage, delay, bandwidth, security, and reliability.

Deterministic transport provides guaranteed delivery with low delay, low delay variation (jitter), and extremely low loss operates over the end-to-end network. Deterministic transport often expects extreme values), its main target is to guarantee the upper limit of these parameters.

Key parameters of the deterministic network include deterministic delay, deterministic bandwidth and deterministic packet loss. More parameters about deterministic network include periodic critical control data streams, maximum end-to-end delay, high availability etc, which are highly relevant to industrial internet.

4.2.1 Remote Medical Treatment

With the development of medical robots, doctors and nurses are expected to cooperate with professional medical robots in different areas to complete the operation process. The operation instructions are sent to the operation desk through the forward link of the network, and the HD images and signals on the operation site are sent to the remote medical staff through the backward link. The instructions issued by different medical personnel shall be delivered to the on-site robots in real time, cannot be delivered too early or too late (requiring low jitter). In this remote surgery scenario, to ensure the smooth completion of the operation, the end-to-end communication delay between the patient and the doctor must be less than 50ms, and the jitter must be less than 200 μs.

4.2.2 Electric Power Grid Relay Protection

A relay protection device is placed at each end of the power cable to send equal amount of current to the peer end over the network, and the local current is compared with the current received from the peer end. If the difference between the two currents is smaller than the limit, it indicates that the line is not faulty. Otherwise, it indicates that a fault occurs on the line. Since there is no time synchronization between the relay protection devices at both ends, it is necessary to use the time of RTT/2 to measure the unidirectional delay, and make operations according to the delay.

To ensure the accuracy of the relay protection system, the unidirectional delay between two directions should be less than 200ms and the jitter should be less than 50 μs. Nowadays, the relay protect devices are transported over wireless or wireline telecomm devices, so it will be a stringent requirement on low delay and jitter for the transport network.

4.2.3 Underground Mine Communication

Underground mine communication problems include:

- Signal coverage: The anti-interference, penetration, and coverage of wireless signals shall be considered.
- Signal transmission stability: Large number of operation terminals, complicated environments, transmission cables, and reliability.

The all-optical network built upon 50G-PON can be extended to all terminals in the mine to provide stable signal transmission. The types of terminals include sensor information collection, video monitoring, personnel communication, and remote control.

Deterministic requirements of underground mine communication:

- Bandwidth: 30 M-100Mbps
- Delay: 30 ms-100 ms

4.2.4 Smart Industrial Manufacturing

The smart manufacturing scenario imposes strict requirements upon network transmission delay, security and reliability in the data collection, industrial control, automation and man-machine interaction scenarios. The communication guarantee should reach the millisecond-level end-to-end delay and near 100% reliability.

The limitations of the traditional industrial network make it difficult to meet the requirements of various scenarios. Industrial networks used to be industrial buses, and then evolved into industrial Ethernet networks. However, they still have problems such as high costs, long deployment time, inconvenient deployment or unavailable deployment, poor network interoperability, and difficult troubleshooting, which cannot meet the high flexibility requirements of future customization for production lines.

Traditional narrowband industrial networks cannot support high-density access of industrial terminals as well as high concurrency and large data traffic. Even if some campus are switched to industrial Ethernet equipment, the maximum uplink bandwidth is generally no more than 10 Gbps, and the maximum uplink bandwidth of super-large campus usually do not exceed 40 Gbps. The next-generation 50G-PON technology can provide a larger access bandwidth than the 40 Gbps network, with obvious advantages in terms of bandwidth.

The industrial PON equipment is located in a workshop-level network in the industrial Internet architecture. Optical networks are connected to the equipment layer through the industrial-level access gateway (ONU) equipment. The ODN implements the integration of industrial equipment data and production data to form the industrial POL solution. Finally, the connection between the convergence gateway (OLT) and the enterprise IT network enables integrated networking of enterprises as well as reliable and effective transmission of industrial data.

Deterministic indexes include the parameters such as delay and jitter. In particular, jitter requirements are very important to industrial control networks. Industrial Ethernet switches can realize 1us. The deterministic delay depends on the service requirements, for example, the typical target requirement is 1 ms+/-20us. The next-generation 50G-PON technology supports deterministic forwarding technologies such as TSN and DetNet to ensure reliable and deterministic forwarding of industrial data on the industrial campus.

5 Summary

After years of development and commercial applications, the fiber-based PON technology with passive and point-to-multipoint features has been highly recognized in the industry and achieved success due to its comparative advantages over twisted pair/coaxial cables. The PON technology is developing in three directions:

- Application field expansion
  - All-optical access: FTTH is a traditional field of PON. It is being upgraded from GPON to 10G PON to provide gigabit bandwidth to the home.
  - All-optical home: Evolves from gigabit to home to gigabit at home. All-optical home networks are built upon optical fibers, allowing each room to deploy high-frequency and high-bandwidth Wi-Fi 6 wireless access.
  - All-optical campus: The POL technology replaces traditional Ethernet switches to build all-optical campus networks, and implements fiber-to-conference room, fiber-to-camera, fiber-to-office desk, and fiber-to-machine connections.
- Bandwidth quality improvement

GPON has been put into commercial use for more than 10 years. The FTTH network is being upgraded from GPON to 10G PON, with quadrupled bandwidth. It is beyond doubt that 50G-PON, which provides a bandwidth five times faster than 10G PON, is the next-generation PON technology of 10G PON.

People’s living habits are changing greatly under new situations. Online education at home and high-quality home-based office services have become a must, which propose higher quality guarantee requirements for FTTH networks and all-fiber home networks. The expanded applications of all-optical campus have higher requirements for network quality, ensuring the high efficiency of production and office activities on campus.

- AI network

No matter FTTH, all-optical home networks in thousands of homes, and all-optical campus networks that support the production activities of the campus, artificial intelligence is an important means to improve network quality.

- AI network operation and maintenance: automatically warns, locates, and recovers faults.
- AI-based network optimization: automatically improves network service assurance.

The contents of 50G-PON being researched include a bandwidth five times faster than 10G PON, determinacy, and measurement of endogenous AI. The introduction of these new technologies and features will bring about a qualitative leap to 50G-PON, and meet the requirements of the three development directions of the PON technology as mentioned above.