WHITE PAPER ON HUAWEI MS-OTN LOW-LATENCY NETWORK SOLUTION

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About This Document

Modern communication networks are established based on fiber communication. Most people have thought that information transmission at the light speed is so fast that does not cost any time. However, as the internet industry evolves, a large number of emerging network services have become widely available, thereby raising strict requirements for network latency. Even a difference of several microseconds may impact the quality of the network service, And a few hundred meters of fiber may lead to a huge difference in determining whether a network operator can carry the new service and enter the new market or not.

For example, 1 ms additional latency in financial leased line services may cut down the profits by more than one million US dollars. Widely-used Internet of Things (IoT) requires services to provide instant communication between devices. Various cloud services and collaborative computing between data centers require millisecond-level communication. In addition, 4K video service can only bring good experience at a really low latency. All these new services are both challenges and opportunities for the industry, and the Optical Transmission Network (OTN) technology turns out to be the most suitable solution to fulfill these requirements on latency, since it provides not only the lowest network latency, but also the highest stability among all the other competing technologies.

In the first section of this white paper, detailed requirements of the emerging network services like financial lines, IOT, cloud computing and on-line entertainment are introduced. Comprehensive analysis on network latency and its optimization methods are discussed in the second chapter. In order to further address low-latency requirements, in the third chapter, Huawei has concluded four major features (also known as “PGM2”) of today’s low-latency networks：

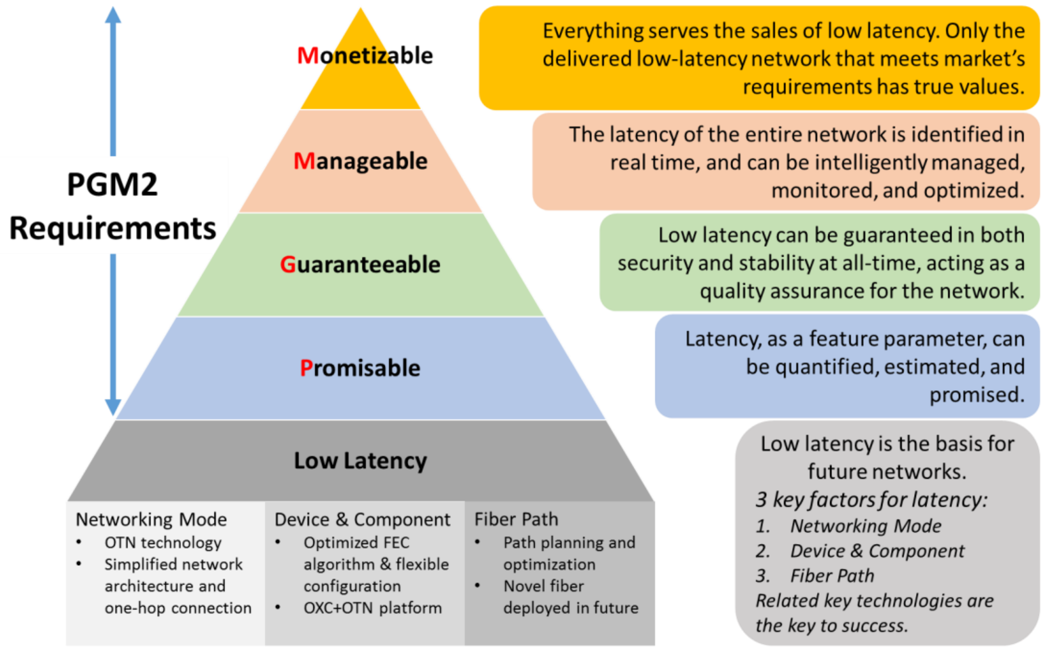
Promisable: latency can be accurately calculated and promised.

Guaranteeable: latency can always be guaranteed regardless of the traffic load or any accident.

Manageable: the intelligent network can efficiently manage, monitor and deploy required latency.

Monetizable: the ability of turning low-latency network into cash, which may require some new business model.

The final chapter summarizes Huawei's experience on the construction of low-latency networks. The OTN+T-SDN solution effectively implements the PGM2 of low-latency networks so that the networks can better carry low-latency services including financial service line services, IoT services, cloud services, and online entertainment services, thereby driving networks to develop towards lower-latency but ultimately higher-value networks.



Keywords: Low latency, OTN, simplified network, physical hard pipe, T-SDN, financial private line, Internet of Things, cloud services, 4K, AR/VR, PGM2

Contents

1 Low Latency: Guaranteed Good Service, Experience, and Competitiveness

While people are typically connected with network bandwidth, bandwidth only represents the size of communication channels provided by the network. For real-time services, network latency indicates the difference of information transmission from the source to the sink and must satisfy a variety of requirements.

Latency is an important performance quantifier for telecom networks. Information transmission is just like goods transportation. A truck's loading capacity is like the network's bandwidth while the speed of it is like the network latency. In voice, Internet, and video services, large latency will cause many issues including call delay, slow webpage access, and video stalling, all of which seriously affect user experience. For example, latency in online searching indicates the result feedback speed after the searching keyword is entered on a searching website such as Google and Baidu.

With information saturation becoming an accepted norm, more stringent requirements have been placed on network latency in interactive entertainment services, financial transaction services, and other real-time services. Based on Google statistics, every 0.4s increase of network response latency will decrease search quantity by 8 million times. Amazon also reveals that every 1s increase of its network response latency causes an annual business loss of up to 1.6 billion US dollars.

A low latency standard has become a key factor affecting current business success and safety, as well as an important network performance quantifier for evaluating the telecom network quality.

1.1 Economic Benefits of Latency

In the financial market, latency has the most obvious economic value. Over 100 years ago, the Rothschild family quickly obtained the first-hand information about Battle of Waterloo before the market does by the communication on horseback and then promptly decided the stock transaction, achieving great profit over 2000%.

Today using the high frequency trading (HFT) method, securities organizations can complete a transaction only within several milliseconds. In a recent report it was estimated that within 1 ms, over 1 million US dollars can be traded in HFT transactions. According to statistics, HFT transactions have occupied 70% of the total transaction amount in the Wall Street securities market, obtaining over 90% profits of the market. Based on an analysis detailed by TABB, an international research and consulting firm, HFT dealers can obtain profits of up to 21 billion US dollars every year by only using the latency arbitrage policy.

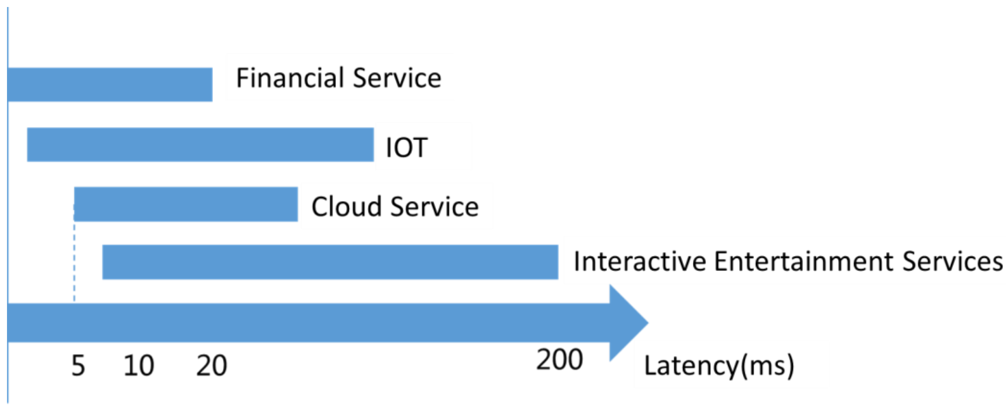
Due to the importance of latency for financial transactions, some network companies have heavily invested in the construction of low-latency networks. In 2011, Level3 Communications, an American multinational telecommunications and Internet service provider, built a low-latency network from New York to Los Angeles. The construction costs of the low-latency network were 1.5 times higher than that of a competitor's network but the latency was 1.5% lower. Therefore, the low-latency network had an auction price 50 times higher than a network with common circuits. The investment on low-latency network construction ultimately brought huge benefits for Level3.

Here are other cases to prove the importance of latency. As described in Flash Boys, Chicago Metal Exchange interrelated with New York Stock Exchange, which was 1150 km away, and HFT could make full use of the transaction latency between the two markets to obtain huge profits. Initially, Original Cable constructed an optical network with 14.5 ms RTT for financial trading companies. In 2010, American Spread Networks invested hundreds of millions of US dollars to construct an optical network whose round trip time (RTT) latency was decreased to 13.1 ms by 1.4 ms, and rented the network to financial trading companies by increasing the rentals by 10 times, winning great profits.

The preceding cases witness the importance of latency.

1.2 Latency Requirements of Various Services

Figure 1-1 Latency requirement for various services



Different services have different latency requirements. Based on their latency requirements, low latency services are classified into four types:

1. Financial — Most sensitive to latencies, therefore most demanding.

2. IoT — Includes telemedicine and vehicle telematics, both of which have different latency requirements.
3. Cloud — Latency directly affects the cloud application experience and data backups are demanding of latency requirements since they directly affect the safety of the data.
4. Interactive entertainment — Network bandwidth and latency affect the network throughput and QoS of 4K, AR/VR, online games, and other services.

1.2.1 Financial Services: Strictly <1ms Latency and Wide Profit Margins

Financial services have strict demands on network latency — to a sub-microsecond precision. According to TABB, being 5 ms slower than competitors in processing financial electronic transactions (including the time taken for computer system processing and network transmission) could result in a 1% loss of profits. Being 10 ms slower increases this loss to 10%. Every 1 ms latency results in the loss of 4 million US dollars.

A high-accuracy, low-latency network requires both the decrease and control of latency. In stock trading for example, when a purchase of stock A involves several stock exchanges, if one in particular has a lower latency, they can complete the transaction before other exchanges. This information is released to the market immediately, increasing the price of stock A for other exchanges. Accurately monitoring the latency status of each line and using a smart management scheduling latency ability will ensure that no information is released to the market uncontrollably before transactions are completed.

In financial markets, profit and loss are separated by a few milliseconds. Dedicated financial lines therefore have the greatest and most demands on latency.

1.2.2 IoT Services: 1-100 ms, Most Extensive Type of Service

In the IoT era, network latency is of even greater importance to user experience and commercial success of products.

In telemedicine, network latency directly affects interactive medical procedures and sometimes even the patient's physiological response. In remote monitoring, the patient's control signal and the monitoring center's transmission latency must be less than 50 ms. In remote medical consultation, interaction between the patient and medical personnel must have a latency of less than 150 ms. Telesurgery requires an even lower transmission latency between local operations and remote diagnostics.

In vehicle telematics, especially in highly automated smart driving applications, network latency directly affects control of steering, braking, and even the lives of those in the vehicle. A vehicle traveling at 60 km/h moves 17 cm every 10 ms, making network latency extremely important in remote operations like intelligent traffic management and remote scheduling. A network latency of less than 10 ms and 99.999% network availability is necessary to ensure road traffic safety.

Latency is obviously very important in special network-based activities. Here it includes network, mobile, and server processing latencies. Under circumstances where the mobile and server processing latencies are equal, a lower network latency will confer a greater advantage in red packet grabbing. According to test results, WLAN RTT can take 20 ms under light load conditions and LTE RTT can take 100 ms. 3GPP specifies that the real-time 3G standard latency is lower than 30 ms. The lower the network latency, the more advantageous for the user.

McKinsey predicts that the global IoT market will reach a market space of USD$11 trillion by 2025. As IoT further develops into telemedicine, intelligent transportation, driverless cars, and other fields, demands on network latency will only increase. Network latency will have a serious impact on the commercial success of applications and even personal safety.

1.2.3 Cloud Services: 5-50 ms, Major Market in Future Network Applications

Cloud services are the major trend of network development in the future. Almost 80% of all applications will be in the cloud, and users can access new content and feedback from the cloud via applications.

To attract users, cloud service providers often advertise having the latest virtual technologies and software services. These are but vectors and content of cloud services. The decisive factor in the cloud service experience also includes the cloud bearer network latency and throughput. To obtain a competitive advantage, cloud service providers continuously improve on the Internet cloud while telecom operators improve on the cloud bearer network. This is to reduce network latency and expand network bandwidth, satisfying the requirements for user experience and cloud service development.

The cloud services most sensitive to latency are cloud computing and data backup. Upon a user request, a service response must be made in 0.2 seconds or user experience will obviously deteriorate. The 0.2 seconds include the network latency for the user end to receive the command, send it to the server for processing and feedback and for information to travel to and from the network.

Data center disaster recovery has great demands on network latency. Disaster recovery has two indexes — recovery time objective (RTO) and recovery point objective (RPO). RTO represents the time taken for data recovery after a disaster happens, while RPO represents the time between when the last backup copy was made before the disaster happened and the time of data loss. The data center disaster recovery center's transmission network must meet the requirements of real-time backup.

The lower the RPO and RTO, the better the disaster recovery ability. However, this also increases the requirements of the transmission network. Typically, network latency is less than 10 ms in data center disaster recovery. The VMware financial data center, however, has a latency of less than 5 ms.

1.2.4 Interactive Entertainment Services: 7-200 ms, Key Services in the Transformation of Future Networks

Image sharpness in 4K video conferencing and other interactive services can be represented by the network throughput of real-time video information transmission.

$$\mathbf{Throughput} \le \mathbf{min}(\mathbf{BW}, \frac{\mathbf{CWND}}{\mathbf{RTT}}, \frac{\mathbf{MSS}}{\mathbf{RTT}} \times \frac{\mathbf{1}}{\sqrt{\mathbf{p}}})$$

Throughput represents network throughput — the amount of data passing through the network in a unit of time. **BW** represents bandwidth. **RTT** represents the time taken for a request for video services to be sent from the user to the server, and for the content to be sent back to the user. **CWND** (congestion window) is a variable with a maximum value of 64K bytes that represents the size of the packet being sent in real-time. **MSS** (maximum segment size) represents the maximum length of each segment. In TCP, this is usually 1460 bytes. **P** represents the bit error rate and is associated with the transmission system, environment, and other factors.

From the formula above we can see that in interactive entertainment services, throughput and RTT share an inversely proportional relationship with the rate of packet loss, P. Huawei test results have shown that a 20 ms RTT is required to provide users with a smooth 4K video experience.

Augmented reality (AR) is the capture of real objects and addition of virtual information labels to them. First, the images are uploaded through the network to the server for analysis and calculation. Then, the results are sent back to the display interface, resulting in a latency. In AR, the latency must be less than 100 ms.

Virtual reality (VR) has even higher requirements for network latency. To experience continuity and reduce vertigo, VR needs an end-to-end latency of less than 20 ms wherein network latency is lesser than 7 ms.

Online games require fast, real-time human-computer interaction. The latency between operating command and game response must be less than 200 ms. Excessive latency will cause a delayed response and choppy gameplay. Players with a lower latency will have better control and enjoy a better gameplay experience.

A low latency network will bring a better entertainment experience to users, aiding in the commercial success of products.

2 Network Latency Distribution and Critical Optimization Technologies

Factors affecting network latency can be classified into three main categories:

- Network mode

  Much like the backbone of the entire network, it sets the tone for network latency.
- Equipment and components

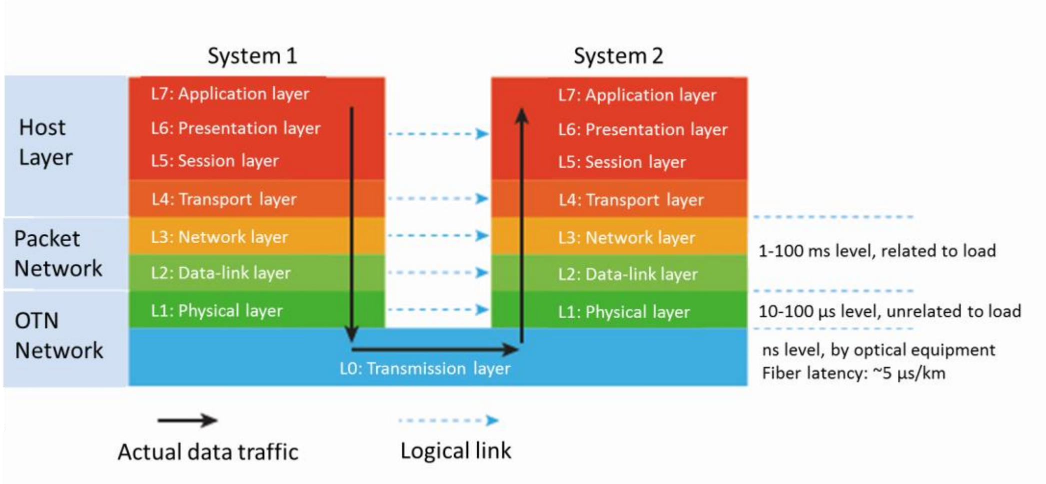
  Time is taken for signal processing by equipment and components.
- Optical fiber path

  The speed of light in a standard single-mode optical fiber is about 200000 km/s. The latency introduced by optical fibers is about 5 μs/km.

2.1 Networking Mode: Simplified OTN Is the Best Networking Technology for the Lowest Latency

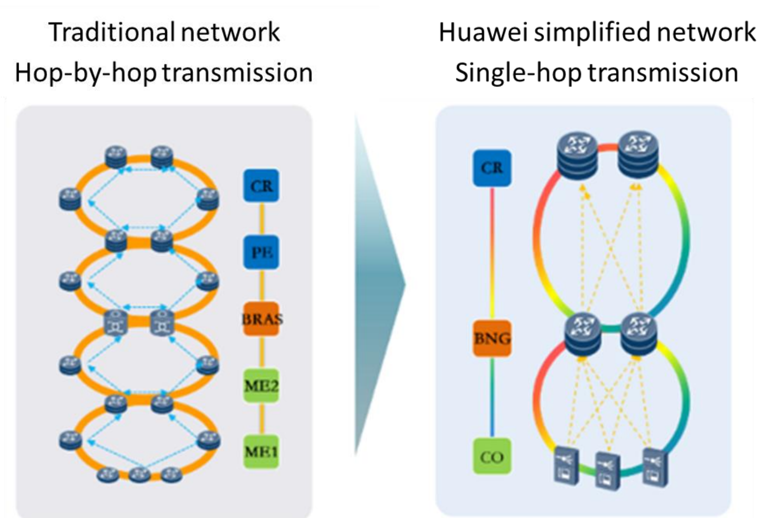
According to the OSI model, the communications network is divided into seven layers. The lower the layer, the closer it is to the physical transport layer, and the less involved it is to information processing, resulting in less latency. OTN is a WDM-based network transmission technology and devices process information at the lowest layers — L0 and L1 — where latency is closest to the physical limit. Since most of the total latency comes from optical transmission, OTN technology therefore has the lowest latency and is the best choice in establishing a low-latency network.

Figure 2-1 7 layers of the OSI model and latency in each layer



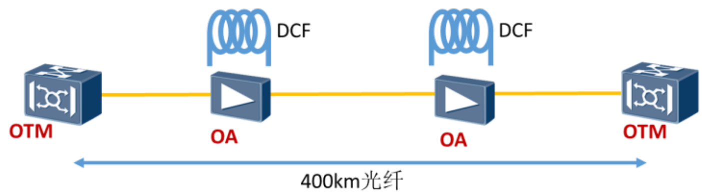
Based on OTN, network latency can be further reduced by simplifying the network structure. Currently, 60% of traffic passes through the intermediate path of the metro network. In traditional metro networks, services were transported hop-by-hop, resulting in a long network service path and large costs in transfer resources of intermediate sites. Overall network latency is also increased. Using OTN as the transport layer, the 5-layer metro Ethernet network can be optimized into the 3-layer CO-BNG-CR with flattened and simplified network architecture. Services are now transported by single-hop, greatly reducing intermediate forwarding, and reducing overall network latency.

Figure 2-2 Simplified network; single hop transmission

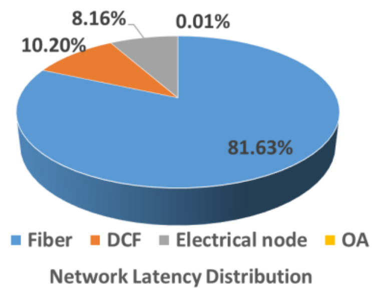


The following figure shows the latency distribution using a typical OTN-based 10G network as an example.

Figure 2-3 Typical OTN-based 10G network latency distribution



	Latency（µs）	Remark
400km fiber	2000	5µs/km
DCF	250	0.625µs/km
2 electrical sites	200	100µs/site
2 OA	0.2	
total	2450.2	



2.2 Equipment and Components — Reducing Latency at the Optical Layer Through FEC Optimization

From the latency distribution shown as above, the latency introduced by equipment and components makes up only a small proportion of the overall latency. However, this proportion is significant for two reasons:

a) With the rise of a large number of network services and the increasing demands on latency, even a microsecond-grade optimization of latency can bring about a great benefit to the user. For example, one of the most important features in dedicated financial lines is the speed in which transactions are made. One microsecond advantage here is enough for traders to take the market lead.

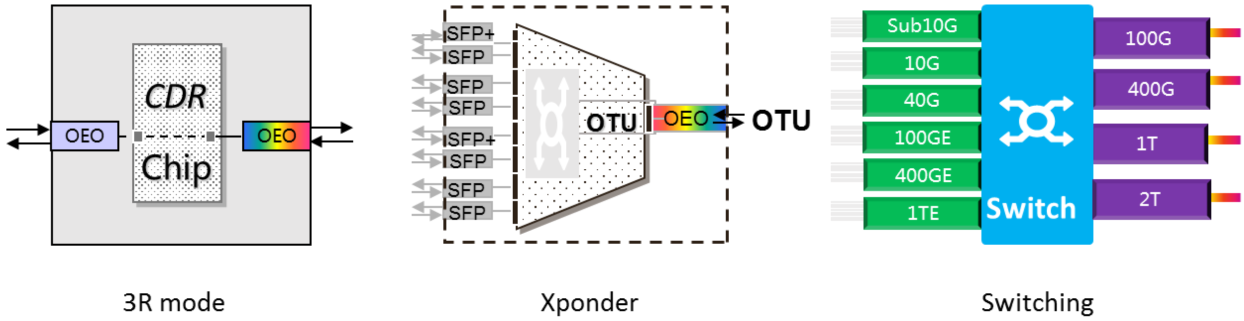
b) Equipment and components are a practical entry point in optimizing network latency and there is room for much improvement in this area. Fiber paths that have been laid have a relatively fixed value while the speed of light traveling within optical fiber cables remains unchanged. By optimizing latency from components and equipment, the overall network latency can be pushed closer to the physical limits of optical transmission.

OTN devices can be divided into two types — those of the electrical layer and those of the optical layer. Electrical-layer devices mainly introduce latency from signal processing while optical-layer devices introduce latency from light transmission.

2.2.1 Electrical-Layer Devices — Optimizing the FEC Algorithm, Increasing Transmission Distances, and Supporting Flexible Configurations

In different application scenarios, OTN electrical-layer devices can work in the following modes:

Figure 2-4 3 typical operating modes for OTN equipment



Below are the typical latencies of these operating modes:

Operating Mode	One-Way Latency of a Single Node (Except FEC)	One-Way Latency of a Single Node* (Introduced by FEC)	Total Latency
3R mode	ns-grade; negligible	No introduction by FEC	ns-grade
Tributary-line mode	~5 us	3-50 µs, depending on the application scenario	8–58 µs
Centralized switching mode	~20 us	3-50 µs, depending on the application scenario	23–70 µs

*Under some scenarios, the latency introduced by FEC at transmitter-side and receiver-side are not the same. The latency values listed here are all average values.

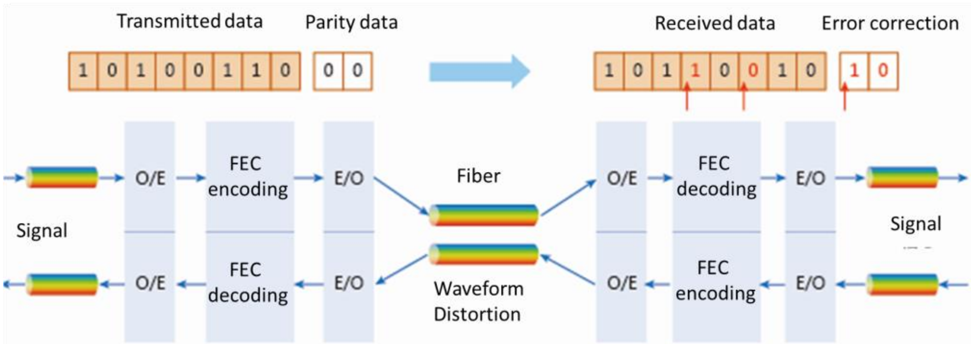
**3R = Reshaping, Retiming, and Regenerating

In addition to the latency that caused by Forward Error Correction (FEC), latency is chiefly composed of:

- Service encapsulation mapping: 5–15 µs, including GFP, GMP, and ODUk mappings
- OTN switching: 1–2 µs
- Other: 0–2 µs

FEC is a widely used OTN network coding technology whose function is to increase transmission distance with less repeater in the link. It works by adding redundant parity data to information being sent, which is then checked and corrected using this parity data during the decoding process, thereby resisting signal impairment caused by the transmission. This improves the reliability of the communication system, effectively reducing the system's bit error rate and boosting the transmission distance.

Figure 2-5 FEC's positioning in optical communications



The following table shows Huawei's FEC algorithms under different scenarios, and the corresponding latency values. Generally speaking, the greater the distance, the greater the signal impairment and signal waveform distortion. FEC algorithms require longer to correct errors, thereby introducing additional latency. Therefore there are differences between FEC's efficiency in metro and long-distance scenarios. In addition, 100G FEC has much less latency than 10G FEC. It takes 0.01 ns to transfer one bit of data using 100G FEC, but 0.1 ns to transfer one bit of data using 10G FEC.

FEC Algorithm	FEC Latency on Transmitting Device	FEC Latency on Receiving Device	Overall Latency	Applied Scenario
100G FEC	3.1 µs	3.7 µs	6.7 µs	Metro
	6.1 µs	6.7 µs	12.7 µs	Long-haul
10G FEC	0.1 µs	10 µs	10.1 µs	Metro
	3.1 µs	94 µs	97.1 µs	Long-haul/Ultra long-haul

Therefore, latency can be reduced through the following methods:

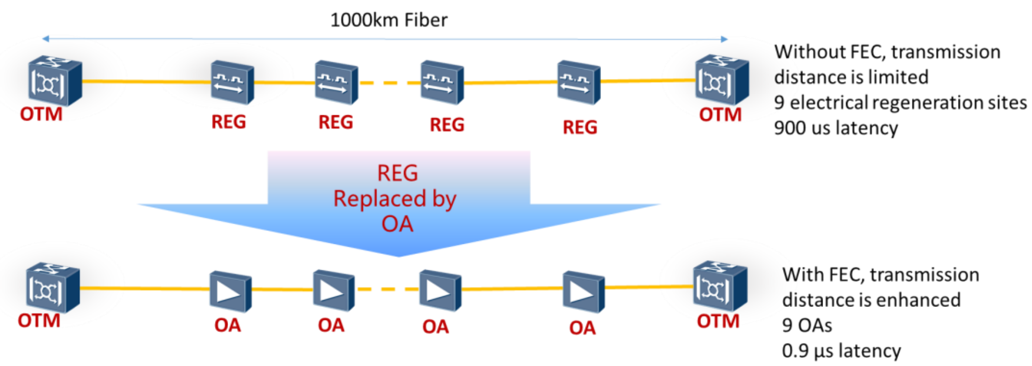
a) **Using a higher rate signal**. 100G FEC has much less latency than 10G FEC.

b) **Flexibly configuring FEC's correction capability according to the application scenario.** To deal with different system bit errors, configure the FEC algorithm with the least latency, rather than the FEC algorithm with the strongest error correction.

c) In future, optimizing the FEC algorithm is expected to further reduce FEC latency, **with 100G FEC latency in metropolitan scenarios is expected to drop to about 3 μs.**

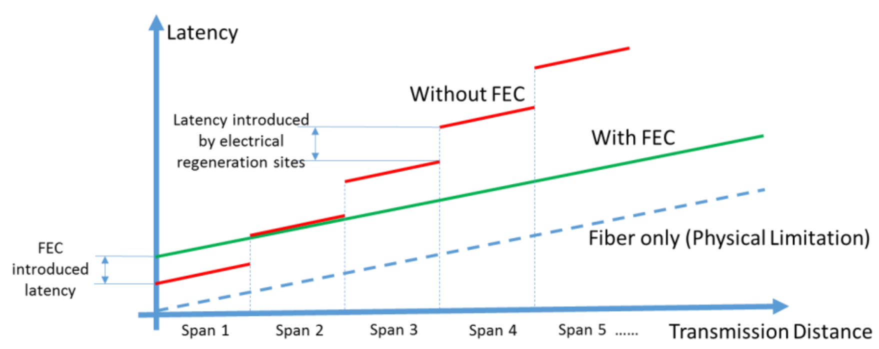
The FEC process does introduces a small amount of latency to the equipment while increasing the transmission distance. However, **when you look at the network as a whole, FEC actually results in the dramatic reduction of network latency.** Over a 1000 km connection without FEC, for instance, then an electrical regeneration site is placed every 100 km (each regeneration site introduces approximately 100 μs latency). This results in a total of 900 μs of latency being introduced across the entire link by regeneration sites. Whereas on a link where FEC enhances the transmission capacity, no regeneration sites are needed, these instead being replaced by OAs (such as EDFA, each of which introduces only around 0.1 μs). The latency introduced across the entire link by OAs is less than 1 μs. Therefore even the maximum calculated latency resulting from using FEC of 100 μs is still less than the 800 μs resulting from not using FEC.

Figure 2-6 Overall latency across links being reduced by FEC



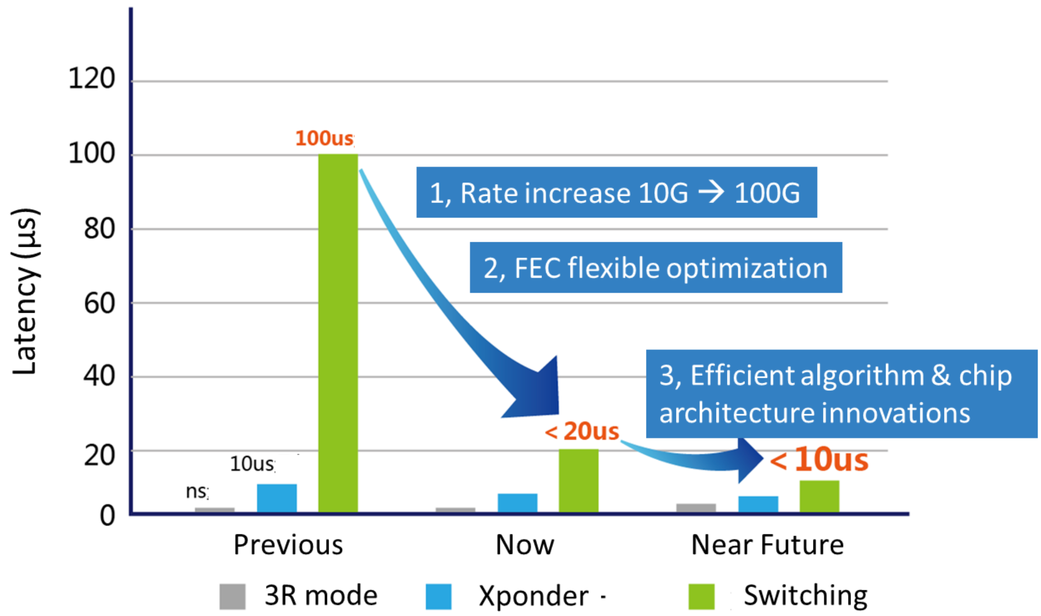
Therefore, OTN devices use a powerful FEC algorithm to greatly improve transmission distance, and can reduce the number of electrical regeneration sites by using OAs instead, thereby reducing overall network latency as shown below.

Figure 2-7 FEC's influence on network latency of different transmission distance



In the early 10G era, due to the limited capabilities of algorithms and chip technology, the maximum latency of an OTN devices was 100-μs level. Today, the latency can be reduced down to 20μs thanks to the increased data speed and optimized FEC with the ability of flexible configuration. Even in some short-distance applications, FEC can actually be disabled in order to further reduce latency. In addition, Huawei's high-performance boards, in part due to being based on the industry's top FEC algorithms, support more OSNR tolerance than the industry. This allows for transmission over even greater distances with less regenerators, reducing the overall latency in long-distance transmission. In future, more advanced chip architectures and manufacturing technologies will be applied, **reducing total latency on OTN devices to less than 10 μs.**

Figure 2-8 Three Steps for Reducing the Latency of Huawei's OTN Electrical-Layer Devices



2.2.2 Optical-Layer Devices: Optical Switching OXC+OTN Integrated Photoelectric Platform Will Reduce Latency to the Nanosecond Level

In many applications, it is impractical to realize E2E fiber connection through optical layer, due to the difficulties in actual fiber path planning. Instead, intermediate node forwarders are needed. As a result, electrical-to-optical and optical-to-electrical converters were introduced, which bring with them additional latency. The industry generally wishes a transition from electrical processing to optical processing wherever possible, aiming for all-optical networks as their final goal. This would remove unnecessary intermediate OE/OE converters and processors, significantly reducing latency.

OTN devices based on the WDM optical network technology are very strong in optical wavelength switching, which is huge advantage over other technologies. When a signal passes through a node device, optical communication is achieved directly through optical-layer devices, with only the desired wavelength channels downloaded and processed electrically, with other wavelength channels directly passed through at the optical layer. Now, **intermediate node latency is limited to that caused by optical fiber within devices. This can be reduced by 3 orders of magnitude, from originally dozens of μs to less than 50 ns.** In combination with strong FEC algorithms, this significantly increases the transmission distance, allowing the realization of direct, end-to-end communication through optical layer, which in turn reduces overall network latency.

Future network service development will result in increasing demands for high bandwidth and low latency. Forwarding through the electrical layer will make it difficult to meet these demands, and so it is necessary to introduce more optical layer solutions. In the face of these challenges, Huawei proposed the solution of OXC (Optical Cross-Connection) + OTN, integrating both optical layer and electrical layer, in order to meet the high bandwidth and low latency demands of large networks.   With OXC, we are able to realize fiber-free connection and switching by using the optical backplane technology, shortening the fiber path, reducing latency, eliminating device exterior fibrillation, and greatly reducing the device's O&M costs.

Another key technology is the means to monitor signals at the optical layer. In the original electrical-layer signal, line monitoring information can be stored in the signal's overhead bytes. When the network moves to the optical layer, this monitoring information also needs to move with it. Huawei's perturbation modulation technology can directly implement monitoring of the relevant channel at the optical layer without going through the process of decoding or electrical-to-optical conversion. In this way, latency is further reduced and system reliability is improved.

These advanced optical-layer technologies make up the Huawei OXC low-latency optical switching platform. When being used in conjunction with Huawei's flexible and mature OTN electrical-layer platform, the Huawei OXC low-latency optical switching platform can meet the high bandwidth and low latency requirements of recent and future networks. OXC and OTN photoelectric integration solutions enable the flexible and rapid deployment and switching for a variety of scenarios and granularities.

In the long-term future of networks, demands for high bandwidth and low latency will only become more stringent. Now, through ultra-dense wavelength switching networks (UDWSNs), the optical layer is divided into more sophisticated subchannels in order to meet more sophisticated scheduling needs of smaller granularities. Optical-layer switching will move to the network edge, to respond to an increasingly wide range of 4K video, virtual and augmented reality, and other high bandwidth and low latency applications.

2.2.3 Other Latency-Reduction Measures: Coherent Communications with Raman Amplifiers Deployed

Common optical fibers have 15 to 20 ps/nm*km dispersion at C-band. Dispersive pulse broadening occurs during signal transmission, causing signal overlapping and distortion. In a non-coherent system, dispersion compensation fibers (DCFs) are generally used to compensate for the dispersion, so that bit error requirements can be satisfied.

The core diameter of a DCF has been decreased to achieve a negative dispersion coefficient of –80 ps/nm*km to –120 ps/nm*km but will increase fiber attenuation. The negative dispersion of the DCF will offset the positive dispersion of common optical fibers and restore the distorted signals. Based on the dispersion coefficients of DCFs and common optical fibers, the length of the required DCF is generally 12.5% to 20% of the common fiber length. This increases the overall network latency.

In a coherent optical communications system, the digital signal processor (DSP) is equipped with a dispersion compensation module at the receiver side. Since the local oscillator has a very stable frequency, the DSP can compensate for the dispersion of the received beat signals at a distance of up to 1000 km.

Compared with traditional EDFAs, Raman amplifiers have larger operating spectrum ranges and lower noise figure which helps increase the system transmission distance by 30% and reduce the number of electrical nodes, leading to a lower overall latency.

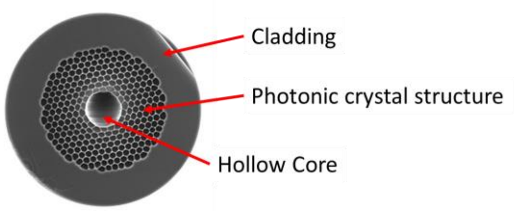
2.3 Fiber Path: Optimizing Fiber Path and Using New Low-Latency Fibers

Because a physical distance exists, latency in fiber paths cannot be eliminated. Standard single-mode optical fibers introduce about 5 μs/km latency, accounting for over 80% of the overall network latency. Therefore, in order to reduce network latency, careful designs of shortest or optimized routing path is needed during network planning.

Currently, a fiber path's latency level depends on the fiber core material. The refractive index of glass is 1.5, which is higher than the vacuum refractive index (1). Therefore, the speed of light in optical fibers is about 65% of the speed of light in a vacuum. New optical fiber technologies, such as hollow photonic crystal fibers, can achieve a transmission speed close to the speed of light in a vacuum.

The photonic crystal structure of hollow-core photonic crystal fibers restricts the light in the fiber path's hollow core, resulting in a speed that is 95% of the speed of light in a vacuum. The latency in photonic crystal fibers is about 3.5 μs/km. This technology is still in the research phase, and hollow photonic crystal fibers have a loss about 10 times that of the common fiber loss. Once the large loss issue is resolved, hollow-core photonic crystal fibers will be commercially used to reduce 30% latency in fiber paths, and the overall network latency will be decreased by over 25% — a percentage which cannot be achieved by any equipment-level optimizations.

Figure 2-9 Hollow-core photonic crystal fiber



- Latency in common fibers: **5μs/km**.
- Latency in photonic crystal fibers: **3.5μs/km**.
- Latency in vacuum: **3.3 μs/km**

Source: https://www.thorlabs.com/thorproduct.cfm?partnumber=HC19-1550;
Source: Nanophotonics 2013; 2(5-6): 315–340

2.4 Latency Reduction Summary

Network latency is mainly caused by device components and fiber paths. On an OTN, OTN devices account for a small part of the overall latency, while fiber paths account for a large part of the overall latency. However, optical fibers are limited by deployment conditions and leave limited space for optimization. Main latency reduction measures are as follows:

Networking mode:

- Deploy the OTN that has the lowest latency.

Device component:

- Flexibly configure FEC based on application scenarios to reduce latency penalties.
- Optimize FEC performance to extend the transmission distance and reduce regeneration sites.
- Use the advanced OTN optical-layer technologies to achieve direct optical connection and switching, as well as to avoid unnecessary electrical-layer processing.
- Implement coherent communications with Raman amplifiers deployed.

Fiber path:

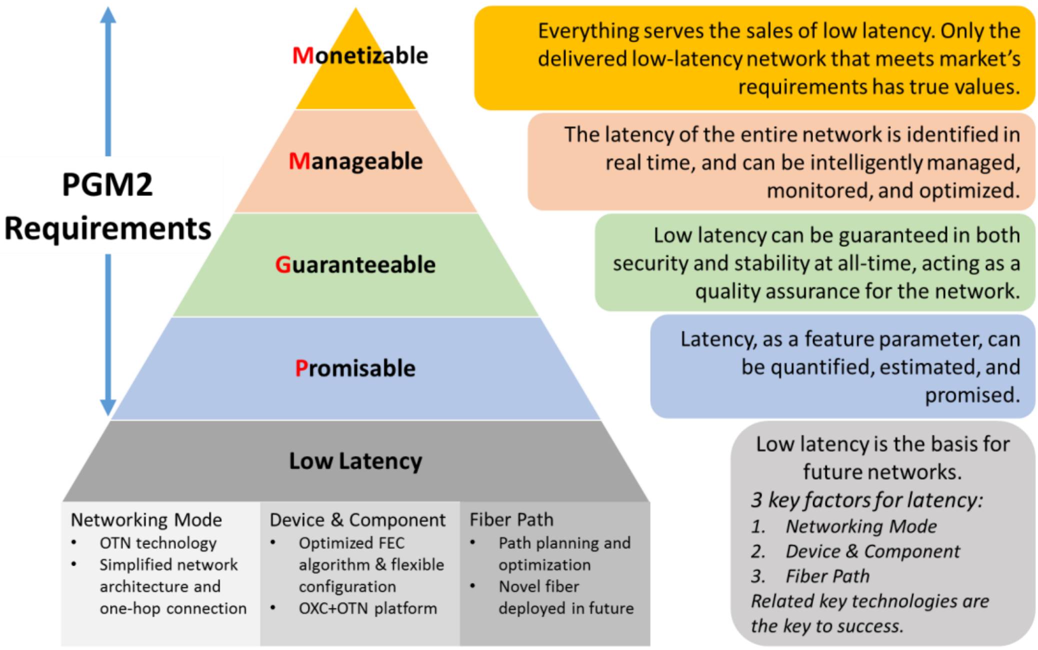
- Optimize fiber routes and paths.
- Use new low-latency optical fibers in the future to achieve a transmission speed close to the speed of light in a vacuum.

3 Low-Latency Network Requirements – PGM2

The earliest requirements for low latency emerged from leased line services in the financial sector. In particular, the fiber project between the New York Stock Exchange and the Chicago Board Options Exchange became a social phenomenon in 2011 as low latency networks began to enter the public eye. It was a mere 1 ms latency advantage that made this leased line project accepted by more than 400 financial institutions on Wall Street. However, this project was still quite primitive at the time, without any line protection measures, and only manual management and maintenance support. The unique advantage this project held was that it was 1 ms faster than other competitors in the market. Based on this advantage alone, the price of similar leased lines is almost 10 times that of common leased lines.

Currently, the popularity of network services is at an all-time high. A low latency network does not just describe the low latency feature, it also describes a complete system solution covering finance, entertainment, and home scenarios. In addition, future low latency networks must possess the following features of PGM2: promisable, guaranteeable, manageable, and monetizable.

Figure 3-1 "PGM2" for today's low-latency network



3.1 Promisable — Accurately Promised E2E Network Latency

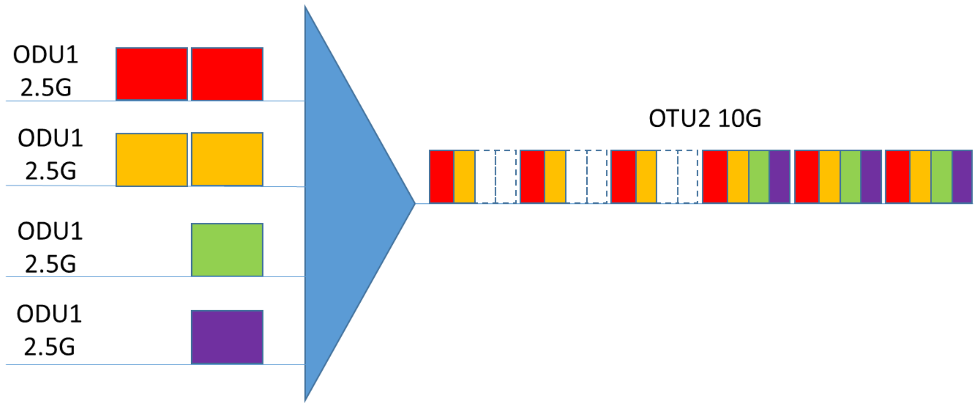
Being able to be promised is the very basic requirement for a low latency network. During project planning and construction, latency must be accurately estimated and committed, and its precision must reach the microsecond level.

On an optical transmission network, the latency values of node devices and fiber paths must be accurately determined. Because the latency value of fiber paths is determined by the fiber length, how to accurately determine the latency value of node devices becomes key to achieving the requirement of "Promisable".

3.1.1 OTN Latency Can Be Accurately Promised

OTN inherits the time division multiplexing technology from SDH to transmit data in frames. According to the G.709 standard, the frame size is always 4 x 4080 bytes. Time is evenly divided into several timeslots, and each timeslot corresponds to a channel. The latency value of each channel can be accurately promised

Figure 3-2 Time division multiplexing technology used in OTN



The time division multiplexing technology assigns the frames of the same size to the evenly divided timeslots. This ensures that each signal channel always requires the same time for transmission. As shown in the previous figure, an OTN node receives four channels of ODU1 input signals, and the transmission rate of each channel is 2.5G. After internal mapping and encapsulation, the OTN node transmits one OTU2 signal at a 10G rate. The time domain of the output signal is equally divided by the four channels of signals. Therefore, the time each signal passes through the OTN node is fixed and can be promised.

On a packet network, no fixed latency can be committed mainly because:

1. The smallest unit of packet switching is a packet. The packet length ranges from tens of bytes to ten thousands of bytes. When the data packets of different service flows compete for an egress, large packets may occupy transmission resources for a long time, causing a long wait time for small packets as well as extra latency.

2. The packet network is based on statistical multiplexing that assigns all channels to the same transmission pipe. However, the network egress has limited bandwidths. When the data transmission requirement exceeds the bandwidth limit, burst congestion occurs and the network latency is increased.

The nature of a packet network is to store-and-forward. The packet network temporarily stores the received packets and puts them into a queue for routing to the destination. When packet sending is possible, the packet network forwards the packets over corresponding routes. The cache mechanism itself will increase latency. Additionally, the packet length and statistical multiplexing are uncertain. As a result, devices cannot accurately commit latency values, and delay and jitter are presented. In practice, only a latency range can be committed.

The OTN has a fixed frame size and evenly divided timeslots, ensuring that node devices transmit all the received data without caching it. The OTN structure is accurate and compact, achieving accurately promisable latency.

3.2 Guaranteeable — Stable Latency that Can Be Guaranteed

Stability is the quality assurance mechanism for low latency. Low latency networks generally carry high-value applications and a short-time failure or jitter will bring significant loss. Therefore, unstable low latency has no practical value. The stability of low latency networks is crucial to users.

Guaranteeable low latency is embodied in the following aspects:

1. Stability — The low latency specifications do not change with time or network load.
2. Security — The OTN network can withstand disasters and unexpected accidents.

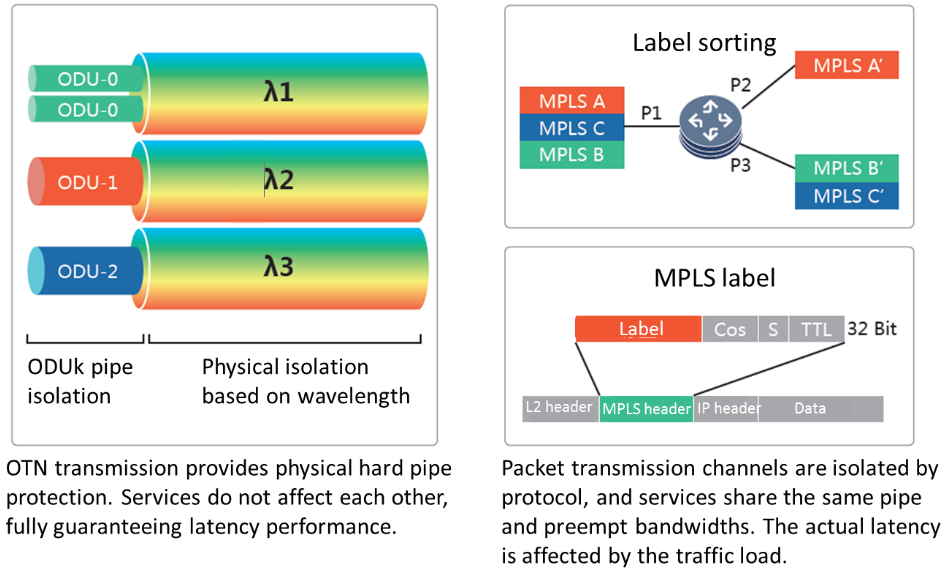
3.2.1 Frequency Domain and Time Domain Dual Assurance of the OTN's Physical Hard Pipes

The physical hard pipes of OTN are guaranteed in the large-granularity and small-granularity dimensions:

1. The large-granularity dimension is physically isolated by frequency domain. OTN is based on the wavelength division multiplexing (WDM) technology. After modulation, each signal is transmitted on a unique wavelength channel. In this manner, the physical hard pipes of signals are isolated in the spectral frequency domain.
2. The small-granularity dimension is physically isolated by time domain. OTN also uses the time division multiplexing (TDM) technology and fixed frame size, so that small-granularity channels can use independent time domain resources and implement physical isolation.

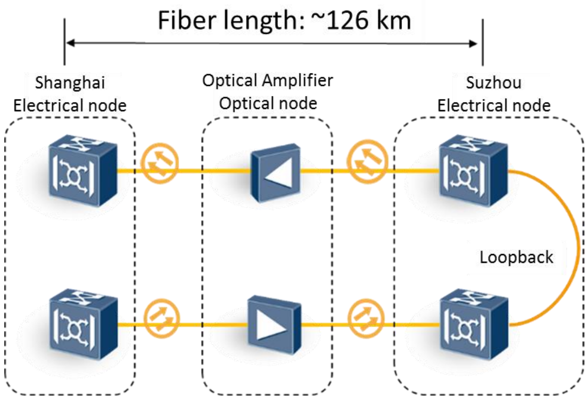
Based on frequency domain and time domain dual assurance, no latency increase or packet loss occurs on OTN networks when the load is heavy. The hard pipe protection mechanism of OTN is based on the purely physical isolation, but not with labeling or priority sorting like what has been used in packet transmission.

Figure 3-3 Comparison of OTN physical hard pipe and packet transmission



To check network latency stability, Huawei performed loopback tests on the live network from Shanghai to Suzhou. The one-way fiber length was about 126 km, covering two hops, two electrical nodes, and one optical node (EDFA optical amplifier).

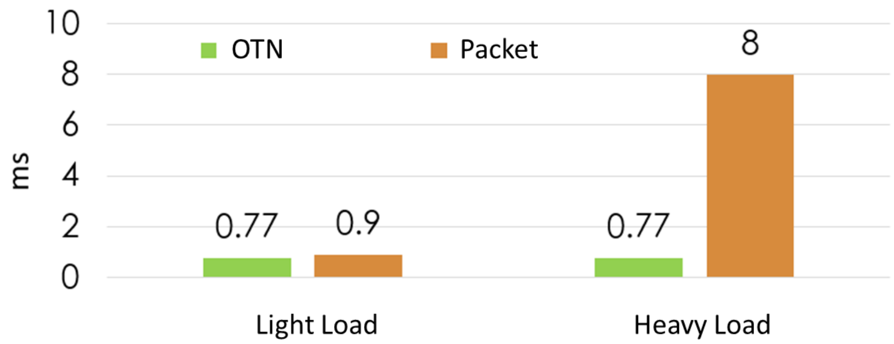
Figure 3-4 10G loopback test on the Shanghai-Suzhou OTN



During these tests, Huawei compared the OTN network and packet network. It was found that the latency of the OTN network was stable regardless of the network load. In the test environment, the latency was always lower than 0.8 ms. On the two networks, Huawei performed the test for more than 24 hours, and the latency fluctuation was less than 0.25 µs. In fact, with Huawei's OTN equipment, the availability is better than five nines (99.999%).

The latency of the packet network with a light load was close to that of the OTN network. However, when the load was heavy, the packet network latency increased from 0.9 ms to 8 ms. This test demonstrated the affect that network load has on packet network latency.

Figure 3-5 Latency comparison of OTN and Packet Network on the live tests



The following provides detailed quantitative analysis. The measured latency values of the OTN are very close to the theoretical calculation results, whereas the measured latency values of the packet network are related to the network load and fluctuate dramatically.

Theoretical calculation results of the Shanghai-Suzhou network

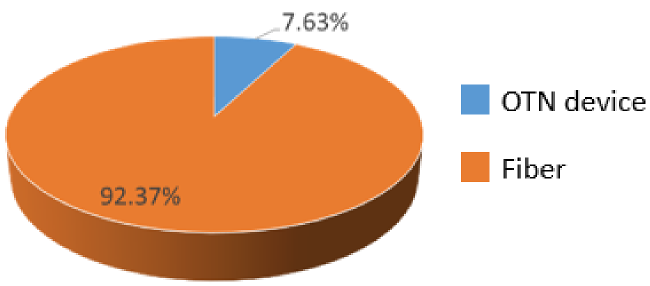
latency source	Link Information	Introduced Latency	Percentage	Remarks
Fiber path	126 km	630 µs	81.8%	Fiber latency: 5 µs/km (Dependent on the total fiber length in loopback tests)
DCF	126 km	78.75 µs	10.3%	DCF latency: about 0.625 µs/km
Electrical node	Passing two electrical nodes	60 µs	7.9%	Single-node latency: about 30 µs
Optical node	Passing one optical node	0.1 µs	-	Single-node latency: 0.1 µs
Total	-	768.85 µs	100%	-

The measured latency of a single OTN equipment is listed as shown below:

Latency Source	Data Path	Measured Latency(μs)
10G tributary board	10GE→ODU2e	8.8
10G line board	ODU2e→OTU2e	9.4
Cross-connection	-	3
GFEC	-	10
Total	-	31.2

Carriers have also paid close attention to latency stability. In June 2016, Huawei partnered with a leading carrier in China to perform a 100 Gbit/s Shanghai-Nanjing-Suzhou WDM line test. The Shanghai-Nanjing-Suzhou line contained 726 km fibers and four OTM sites. The theoretical round-trip latency value was 7.86 ms and the actual round-trip latency value of 100 Gbit/s OTU4 services was 7.859 ms (and that of 100GE services was 7.858 ms). More than 90% latency was introduced by optical fibers, and the actual latency value was very close to the theoretical latency value. During the test, the test result was stable. No value change occurred on 3 digits after the decimal point. The following figure shows the test results.

Figure 3-6 China Telecom tested result: latency distribution of the Shanghai-Nanjing-Suzhou line



3.2.2 ASON Multi-Path Protection for Low Latency Networks

Low latency services are generally high-value services, and a transient interruption may affect integral functions causing significant losses. Therefore, to reduce latency without interrupting services, protection mechanisms must be also used. Two indicators must be considered when protection mechanisms are used:

1. Fault recovery time:

According to common requirements, the fault recovery time must be equal to or less than 50 ms. Some low latency services have even stricter requirements.

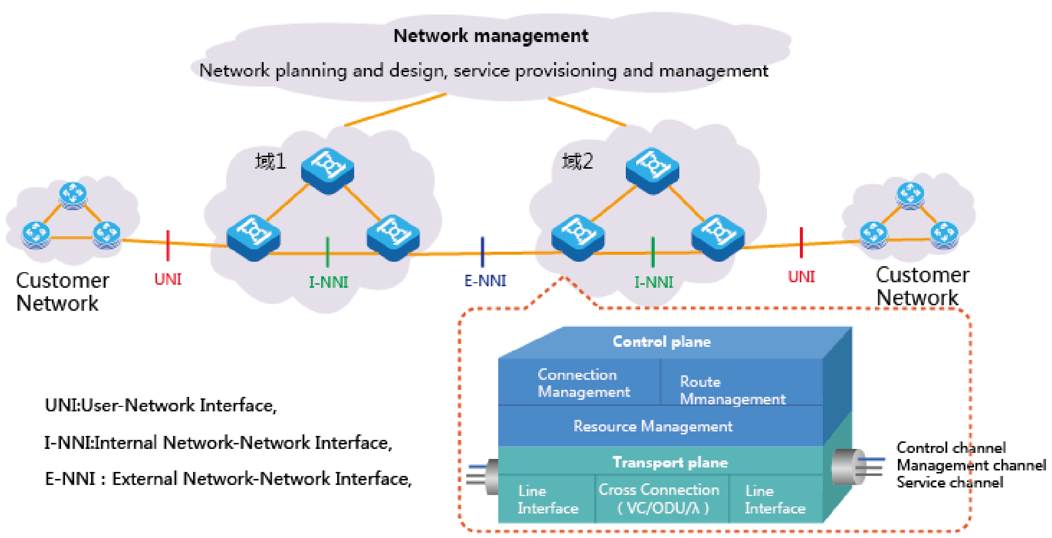
2. Protection line latency:

Unlike common requirements, the protection line latency of a low latency network must be on the same level as the original service line, or the protection line that has similar latency with the service line must be preferentially selected. The latency difference between the original service line and protection line must be minimized and considered in the early network planning.

Automatically switched optical network (ASON) introduces the control plane into an OTN. The control plane dynamically manages network connections and allocates resources. It also provides automatic fault protection and recovery, thereby making the OTN more intelligent. In addition to traditional protection mechanisms, ASON provides dynamic rerouting and restoration to enhance network reliability.

Traditional 1+1 protection can withstand only one fiber cut, but ASON can withstand multiple fiber cuts based on rerouting and restoration functions. A higher network meshing degree indicates more available restoration trails and higher ASON reliability. Huawei OTN equipment provides the latency monitoring function for users to learn real-time latency status and preferentially select the trail that has similar latency with the original service trail, minimizing network latency.

Figure 3-7 ASON Network Model

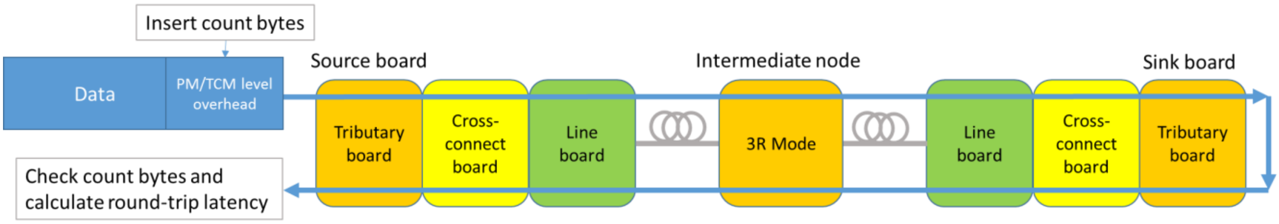


3.3 Manageable — Real-Time Management, Monitoring, and Optimization

3.3.1 Standard-Defined Test + OTDR — Dual Assurance for High-Precision E2E Latency Monitoring

The G.709 standard defines a common latency test method inserting count bytes to implement E2E latency measurement. The following figure shows the latency test method defined by the G.709 standard.

Figure 3-8 Latency test method defined by the G.709 standard



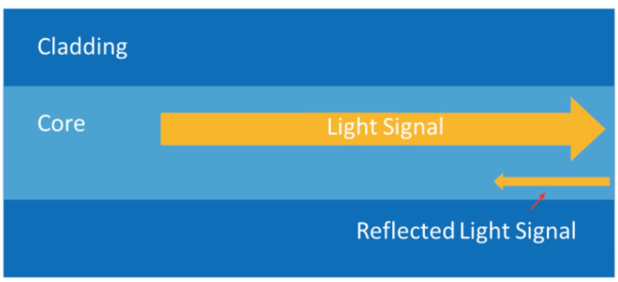
Insert count bytes (that is the clock count at the counting start time) on the source board. Data passes through an optical fiber to reach the sink board, and then is transmitted back to the source board. Check the count bytes again, and obtain the E2E latency data based on the clock frequency using the following formula.

$$T_{E2E} = \frac{(\text{Final clock count} - \text{Initial clock count})}{\text{Clock frequency}} / 2$$

Another fiber path monitoring method is optical time-domain reflectometry (OTDR). When optical signals pass through a fiber connector, a very small amount of energy is reflected. The reflected energy peak time can be measured to accurately determine the fiber length and required time for the optical signals to traverse the fiber. In addition, based on the Rayleigh reflection, the OTDR can quickly and accurately locate the fiber fault point such as a fiber defect or cut. It achieves fast fault pre-warning and location, ensuring smooth network operation.

The following figure shows the working mechanism of the OTDR.

Figure 3-9 OTDR measurement principal



Huawei WDM products OSN 1800, OSN 6800, OSN 8800, OSN 9600, and OSN 9800 support the standard-defined test and OTDR methods. Both test methods are used to ensure high reliability, high precision, and real-time E2E network latency monitoring. For ODU4 services, the latency measurement precision reaches 1 μs.

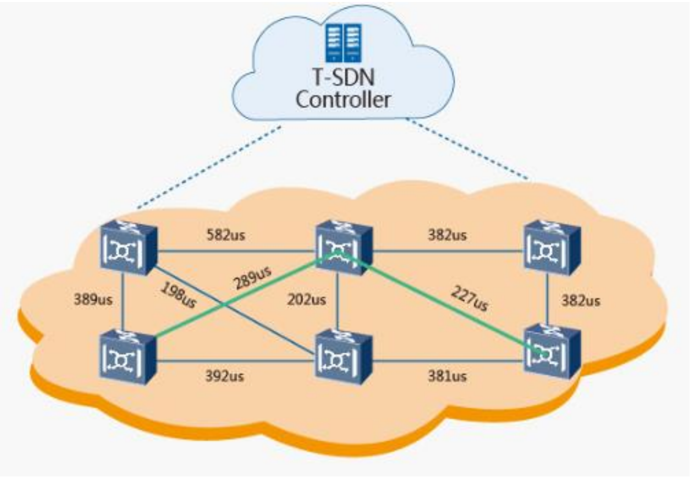
3.3.2 T-SDN — Intelligent Management and Optimized E2E Network Latency

After all E2E latency data is collected, the T-SDN controller can be used to manage and optimize the overall network latency in real time. On a Huawei OTN network, after optical-layer services are provisioned, the NE automatically triggers the latency measurement function for electrical-layer links. This reports latency data to the T-SDN controller without any manual intervention, achieving automatic management, monitoring, and optimization.

1. Fiber path optimization

The T-SDN optimizes optical routes and searches for the fiber path with the lowest E2E latency among global resources.

Figure 3-10 Fiber path optimization by T-SDN



2. Protection for low latency paths

Based on the smooth evolution of ASON, the T-SDN protects low latency paths. When a network fault occurs, the T-SDN preferentially selects the path on a similar latency level for switching.

3. Real-time latency monitoring and pre-warning

The T-SDN periodically scans and measures network latency, and monitors E2E latency data of the entire network in real time. It identifies the latency change of each line and checks whether an abnormality occurs. If an abnormality is found, the T-SDN immediately reports an alarm and switches services to the protection line. The following figure shows the real-time latency monitoring page of Huawei. This page can display latency test results in real time and measure the latency of a specific path.

Figure 3-11 The interface of latency real-time monitoring

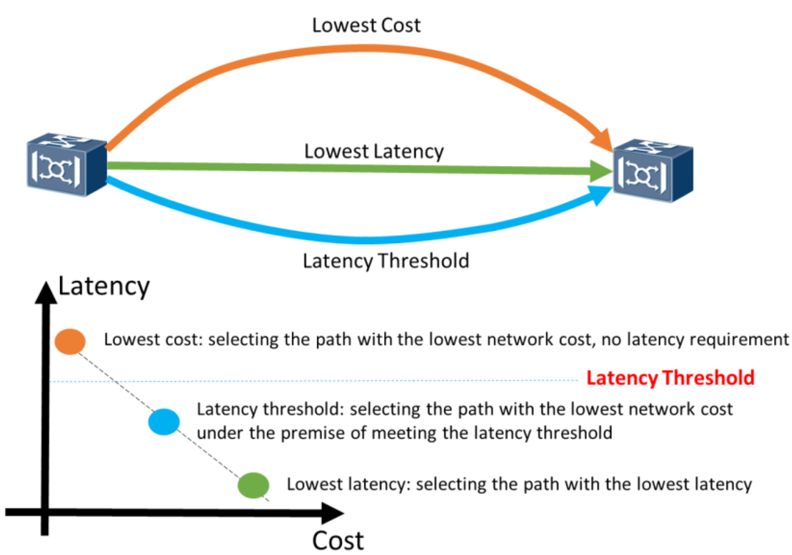
4. Quick latency scheduling

Within certain network capabilities, the T-SDN adjusts the latency performance of leased lines and allocates low latency lines based on customer requirements.

5. Unified resource management over the entire network

For some specific services, latency is only one of the important indicators. For example, both latency and bandwidth affect the experience of 4K video services. Therefore, the latency and bandwidth must be considered and configured during service management to achieve the best experience. In addition, from a network-wide perspective, resource utilization indicators such as traffic coexistence and bandwidth utilization must be considered in terms of satisfying the service latency requirement. The path that satisfies the service latency requirement and has the lowest total network cost must be selected to fully utilize existing network resources. A line latency threshold must be set, so that the powerful T-SDN can be used to monitor and calculate all network resources of each dimension to find the path that meets the threshold requirement and has the lowest total network cost.

Figure 3-12 3 types of latency management strategy based on T-SDN



Huawei T-SDN supports the latency threshold setting. For different scenarios, the following latency selection policies can be used:

1. Lowest cost: There is no latency requirement, and the overall network resource utilization is considered during path selection. This policy is suitable for the applications insensitive to latency.
2. Latency threshold: A latency threshold can be set. Under the premise of meeting the latency threshold, the path with the lowest network cost is selected. The line latency is not necessarily the lowest.
3. Lowest latency: There is no network cost requirement, and the path with the lowest latency is selected. The policy is suitable for the users who have the most strict latency requirement.

3.4 Monetizable — Latency Is a Network Resource Supporting Quantitative Sales

Low latency is required by many new network services and has huge market value. Similar to network bandwidth, network latency becomes a network resource supporting quantitative sales and a part of network competitiveness. In particular, network latency is critical to leased line services. To maximize the low latency feature and its market value, latency resources must be monetizable. This requires that low latency lines meet the requirements of new services and the following conditions:

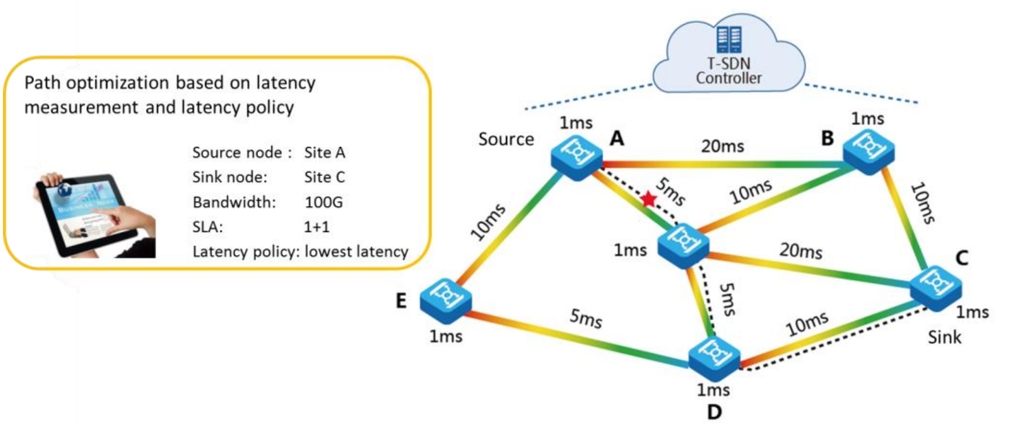
- **Promisable**: The E2E network latency can be accurately promised which is the very basic requirement for a low-latency network
- **Guaranteeable**: The latency performance also needs to be extremely stable and can be guaranteed at all-time regardless of disasters or unexpected accidents. Latency can be quantitative and commercially promoted as a network resource only when it is reliable and can be guaranteed.
- **Manageable**: The T-SDN can be used to implement intelligent line management, optimization, and quick resource scheduling in order to fit different kinds of business models for low-latency network.

3.4.1 Leased Line Service — the Tipping Point of Low-Latency Networks

Enterprise leased line is a private link dedicated to communication connections between different departments of an enterprise or governmental organization. It generally carries important information, such as voice communication, remote conference, file transfer, financial transaction, and control signal, and has high requirements for security and low latency. With the gradual popularization of enterprise informatization, the leased line service becomes the first step towards low-latency networks. Low-latency leased lines have been specifically required in the market.

The OTN supports various leased line technologies such as SDH, WDM, and Ethernet, and provides stable low latency lines based on ODUk hard pipes. The T-SDN provides controllers to schedule resources on the entire network and implements path-specific latency measurement, route selection, E2E service management, and inter-vendor orchestration.

Figure 3-13 OTN+T-SDN for leased line service



As shown in the previous figure, the leased line bearer network is based on OTN and T-SDN and provides physical connections to guarantee fixed routes and stable latency. It also supports real-time latency measurement on the entire network or a section and selects the route with the lowest latency as required, achieving the PGM2 requirements.

3.4.2 Future Business Modes of Low-Latency Networks

For carriers with network infrastructure resources, low latency will certainly become a key factor in improving core competitiveness.

Based on low latency, Huawei proposes the following business modes for the future:

1. Leased line renting

Enterprise customers rent exclusive leased lines that can meet certain latency requirements. The simplest mode is to sell low-latency network resources. The lower latency indicates a higher price, and the price increases with the latency reduction non-linearly. Users can select leased lines based on the network latency requirement.

2. Latency on demand

In some special scenarios, low latency resources can be quickly scheduled and reserved. For example, during an online shopping rush or a future AR/VR event live broadcast, low latency resources can be allocated for related lines to achieve better experience.

3. Latency customization based on service requirements

Based on specific application scenarios, appropriate network latency is used, and network resources with the lowest latency are reserved for the users who have higher requirements to improve resource efficiency.

4 Huawei Advantages in Low-Latency Networks

Huawei, a long-term contributor to optical network technologies, has recognized the importance of low-latency in future network communications and social life and has accumulated in-depth technical experience and market understanding.

Based on low-latency OTN technologies, Huawei fully promotes simplified network architecture and one-hop transmission to further reduce network latency and improve latency stability. In addition, Huawei has leading algorithm capabilities and offers flexible FEC configurations. In the future, Huawei will be able to reduce the latency of electrical-layer devices to lower than 10 μs. Based on advanced optical-layer straight-through and switching technologies, Huawei has established the OXC+OTN optoelectronic integration platform to achieve the lowest E2E network latency, which is close to the physical limit of common fiber transmission.

Based on physical hard pipes of OTN, Huawei devices can be accurately promised (achieving "Promisable") and guaranteed E2E low latency at all-time regardless of accidents or workload (achieving "Guaranteeable"). The stability of communication networks using Huawei equipment has been verified by carrier’s tests. The network latency jitter is less than 0.25 μs, which is almost undetectable. And the availability can be better than five nines(99.999%). The latency is highly stable. Huawei also has extensive experience in ASON construction, and can guarantee the minimum impact on low latency lines in disasters or accidents.

All Huawei WDM products support the standard-defined test and OTDR method for latency measurement to ensure high-precision E2E online latency monitoring (accurate to 1 μs). Based on all feedback, the T-SDN controller implements real-time and intelligent management, monitoring, and optimization on the latency of the entire network. It also considers both the latency and total network cost and uses the latency threshold setting to achieve comprehensive route optimization (achieving "Manageable").

The comprehensive OTN+T-SDN solution of Huawei enables the sale of secure and reliable network pipes with the lowest latency (achieving "Monetizable"). Based on T-SDN, this solution provides accurate management and monitoring capabilities, and has been applied in many low-latency leased line projects and verified and well accepted by the market.

4.1 Commercial Case Study of Huawei OTN+T-SDN Low-Latency Leased Line Solution

Carrier L is the third largest integrated carrier in country C. It develops high-value financial leased lines for banks and securities traders to make strategic breakthroughs and increase revenues. Because of inter-province settlement and electronic transaction services, customers require low latency leased lines. However, the existing networks of carrier L are isolated by national backbone and administrative regions such as province and city. The provisioning and O&M of leased lines require hierarchical operations in nations, provinces, and cities separately, and the transmission latency is unperceivable and uncontrollable, failing to meet customer requirements. In addition, competitors provide fixed and perceivable low-latency leased lines as selling points, putting great pressure on carrier L.

Carrier L proposes the construction of low-latency financial private networks across national backbones and provincial and city networks for customers, achieving E2E O&M and real-time latency detection and display of services and guaranteeing ultra-low and stable latency.

Carrier G is the second largest carrier in country P. Its network carries more than 100,000 enterprise leased line services, which have brought huge revenue for carrier G. However, carrier G is facing great external and internal challenges:

1. External challenge:

Due to the homogenous competition of leased line services, carrier G has to reduce prices to maintain its market share. Consequently, profits decrease.

2. Internal challenge:

Multiple private network vendors coexist, inter-vendor service provisioning is slow, and leased line bandwidth increases dramatically. However, legacy devices cannot meet the capacity and new service development requirements, and carrier G's leased line services lack continuous competitiveness.

To maintain the leased line market share and improve competitiveness, carrier G plans to construct new SDN-based private networks, provide service differentiation capabilities and value-added services such as latency-specific sales, and resolve the E2E service grooming issue.

In the previous commercial use cases, both carriers choose Huawei OTN+T-SDN solution. Based on advanced OTN technologies, this solution guarantees low latency leased lines and has high market competitiveness. It also provides secure and reliable leased lines, achieves inter-vendor transmission, and enables low latency services to be "Manageable" and "Monetizable".

5 Summary and Outlook

With the popularization and application of various network applications, low latency becomes the core competitiveness of service bearer networks and a key to enter emerging markets. For example, for only Internet of Things (IoT) in 2025, the global market scale of low latency is expected to reach USD 11 million. The broad markets and huge business interests will promote networks to develop towards low latency.

Based on the WDM with advanced optical-layer technologies, OTN uses powerful electrical-layer algorithms and provides high switching capabilities, ultra-low latency, and stable and secure low-latency pipes. The total OTN latency is close to the current physical limit of fiber transmission, making the OTN the best choice for low latency networks.

Huawei combines electrical and optical technology advantages with the OTN to establish the OXC+OTN optoelectronic integration platform which enables low latency networks to meet the PGM2 requirements and effectively support various network services that have high latency requirements.

Future OTN will further reduce network latency, use more advanced chip technologies to simplify network structure, and promote all-optical switching and all-optical networks. It will also use new fiber technologies to extend the low latency limit and effectively carry increasing finance, IoT, cloud, and online entertainment services, laying a solid foundation for a better connected world.

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