



# WHITE PAPER ON TECHNOLOGICAL DEVELOPMENTS OF OPTICAL NETWORKS



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# Contents

<b>About This Document</b> .....	<b>1</b>
<b>1 Recent Advances in Optical Networking</b> .....	<b>2</b>
1.1 Coherent Detection with DSP.....	3
1.2 Software-Defined Transceiver and Flexible WDM Network.....	4
1.3 Electrical-Layer Optical Transport Network (OTN) Scheduling.....	4
1.4 All-Optical Switching.....	6
1.5 High-Speed Photonic Components.....	8
1.6 Other Enabling Technologies.....	10
<b>2 Challenges of Optical Networking in the Cloud Era</b> .....	<b>11</b>
2.1 Emerging Services of Future Optical Networks.....	12
2.2 Requirements on Future Optical Networks.....	12
<b>3 Evolution Trends of Optical Networks</b> .....	<b>15</b>
3.1 Backbone Network.....	16
3.2 Metro Network.....	16
3.3 T-SDN.....	16
3.3.1 Automatic Control.....	17
3.3.2 Open Orchestration.....	17
3.3.3 IoT Intelligence.....	18
<b>4 Conclusion</b> .....	<b>21</b>

## Figures

<b>Figure 1-1</b> Advances of optical transmission technologies in recent years. ....	2
<b>Figure 1-2</b> Rapid advance in coherent detection based on ODSP .....	3
<b>Figure 1-3</b> Common application scenarios of software-defined transceivers and flexible-grid WDM. ....	4
<b>Figure 1-4</b> Architectures for optical switching in the wavelength dimension .....	7
<b>Figure 1-5</b> Superchannel based electrical and optical layer scheduling. ....	7
<b>Figure 1-6</b> Evolution and trend of optical switching technologies. ....	8
<b>Figure 2-1</b> Emerging services and applications to be supported by optical communication systems in the cloud era.....	11
<b>Figure 3-1</b> Evolution trend of optical networks.....	15
<b>Figure 3-2</b> A new SDN-based optical transport network technology platform.....	18

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## About This Document

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Optical network is widely regarded as the backbone of the modern internet. Future optical network applications in the cloud era will be diverse and the demands of these new applications will not be limited to bandwidth. For instance, 4K/8K video traffic and AR/VR are sensitive to network latency, financial and industrial automation networks require high security, and cloud leased lines need to provide bandwidth on-demand. Moreover, the massive growth in bandwidth requires 10 to 100-fold decrease in cost and power consumption per bit. Accompanying these technological challenges in the cloud era are opportunities for the optical networking industry.

In this white paper, we first review major recent technological advances in optical networking, such as digital signal processing (DSP) enabled coherent detection, large-scale photonic integration, superchannel transmission, and software-defined transport networking (T-SDN). We then analyze the driving forces for the future development of optical networking in the emerging cloud era, and the future challenges and opportunities that it faces. With the consideration of these challenges and opportunities, we describe the future trends and evolution paths in key areas such as overall network architectures, core network technologies, metro network technologies, and novel T-SDN technologies in the upcoming cloud era, aiming to more effectively support future generations of internet, 4K/8K video, AR/VR, cloud computing, data center interconnect (DCI), internet of things (IoT), and 5G mobile network, as well as the smart home and smart city initiatives.

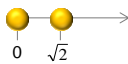
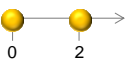
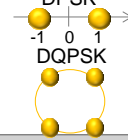
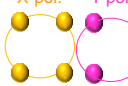
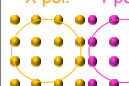
**Keywords:**

Optical networking, cloud computing, T-SDN, 4K/8K, AR/VR, DCI, 5G mobile network.

# 1 Recent Advances in Optical Networking

As shown in Figure 1-1, the optical fiber transmission data rate of a single wavelength channel has increased from 2.5 Gb/s in 1985 to 400 Gb/s in 2015, representing a 160-fold increase over 30 years. The main technologies involved include high-speed electrical-optical modulation, high-speed optical detection, hard-decision forward error correction (HD-FEC), differential phase shift keying (DPSK) and differential quadrature phase-shift keying (DQPSK), coherent detection based on optical digital signal processing (ODSP), soft-decision forward error correction (SD-FEC), polarization-division multiplexing (PDM), quadrature amplitude modulation (QAM), and faster-than-Nyquist (FTN) modulation and demodulation. With the introduction of superchannel technology, the channel data rate can be further increase to beyond 1 Tb/s.

**Figure 1-1** Advances of optical transmission technologies in recent years.

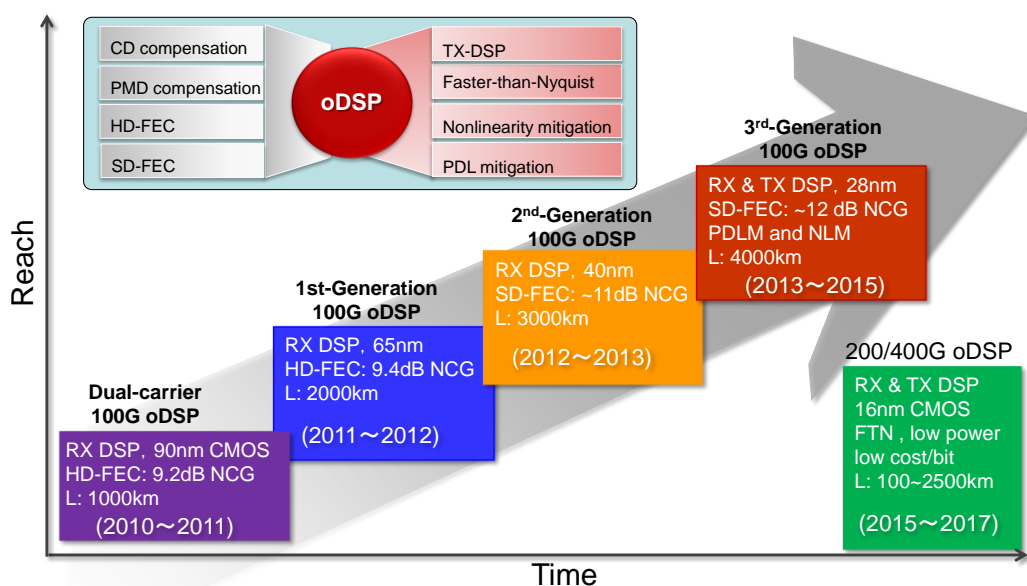
Year:	1980	1990	2000	2010	2020
<b>Data rate per channel</b>	2.5 Gb/s	10 Gb/s	40 Gb/s	100 Gb/s	200G/400G/1T and beyond
<b>Modulation format (typical)</b>	OOK (NRZ) 	OOK (RZ) 	DPSK DQPSK 	PDM-QPSK X-pol. Y-pol. 	PDM-16QAM X-pol. Y-pol. 
<b>System features (newly added)</b>	Single-span, Single-channel	Multi-span with EDFAs, WDM	DWDM, Raman amplification, and ROADMs	1:N WSS, CDC-ROADMs	Flexible-grid WDM, M:N WSS
<b>System capacity (typical)</b>	2.5 Gb/s (single channel)	400 Gb/s (40 WDM channels)	1.6 Tb/s (40 WDM channels)	8 Tb/s (80 DWDM channels)	20 Tb/s (50 flexible-grid WDM channels)
<b>System reach (typical)</b>	100 km (single span)	1000 km	1000 km @40G 3000 km @10G	2000 km @100G	4000/2500 km @100(200)G
<b>Enabling technologies</b>	Optical modulation and detection	High-speed modulation, HD-FEC	Differential phase-shift-keying	Coherent detection with ODSP	SD-FEC, PDM-QAM, FTN, Superchannel

At the transport system level, the introduction of broadband optical fiber amplifiers, such as erbium-doped fiber amplifiers (EDFA) and Raman amplifiers, makes wavelength-division multiplexing (WDM) a reality. The single-fiber transmission capacity of optical fiber communication has increased from 2.5 Gb/s in 1985 to 20 Tb/s in 2015, representing a remarkable increase of 8000 times over the last 30 years. Additionally, optical fiber transmission links have also evolved from single span to today's multi-span links, transparent WDM network, and flexible-grid WDM.

## 1.1 Coherent Detection with DSP

During the early development of optical communication systems, intensity modulation/direct detection (IMDD) was used to implement optical transmission, achieving transport speeds of up to 10 Gb/s. As the speed reached 40 Gb/s, the advantages of DPSK/DQPSK technology became apparent. Today, in the 100 Gb/s era, coherent optical technology is becoming the mainstream high-speed optical communication system. Figure 1-2 shows the rapid development of coherent detection based on ODSP.

**Figure 1-2** Rapid advance in coherent detection based on ODSP



Currently, 100-Gb/s coherent-detection transceivers are in large-scale deployment and 400-Gb/s coherent-detection transceivers are commercially available. As the industry gradually advances toward 1 Tb/s and beyond, new technologies such as superchannel transmission, large-scale photonic integration, high-level QAM, and FTN are being introduced.

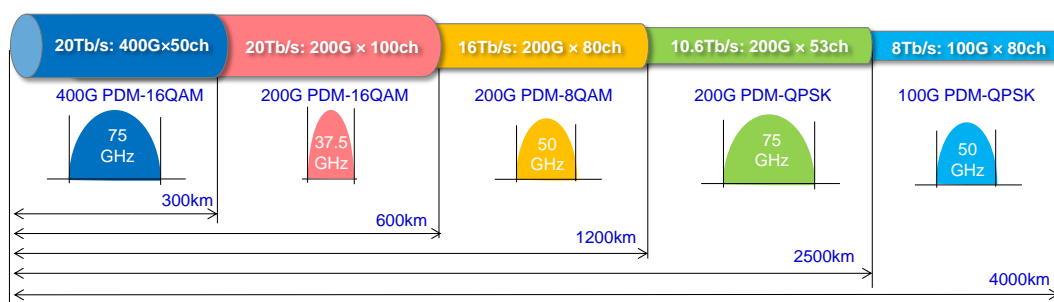
ODSP is a transport technology that marks the beginning of the digital era for the optical communication systems. ODSP is capable of compensating for chromatic dispersion, polarization rotation, polarization-mode dispersion, and certain fiber nonlinear impairments. It

can also mitigate signal degradation due to bandwidth limitations of the transmitter and the receiver. Future ODSP promises to be even more powerful, especially with the availability of next-generation sub-10-nm or even sub-5-nm CMOS technologies. Resource-intensive algorithms such as SD-FEC, fiber nonlinearity compensation, and others could be practically implemented. ODSP technology is expected to continue playing an important role in future high-speed long-haul optical transmission systems.

## 1.2 Software-Defined Transceiver and Flexible WDM Network

ODSP technology also enables more efficient utilization of high-capacity optical transmission systems through adaptive modulation with variable modulation bandwidth and adjustable modulation format. In flexible-grid WDM, channel spacing can be reduced from the typical 50 GHz to 37.5 GHz and 33.3 GHz, respectively increasing the number of C-band wavelength channels by 1.33 and 1.5 times to 128 and 144. For ODSP with 16-nm CMOS, which generally supports 100-Gb/s PDM-QPSK, 150-Gb/s PDM-8QAM, 200-Gb/s PDM-16QAM, and 400-Gb/s PDM-64QAM, the same hardware supports different transport distances and different modulation formats at different spectral efficiencies. When the transmitter and receiver both use ODSP, the transceiver can be software-defined, and the flexible-grid WDM can be supported. Figure 1-3 shows a common application scenarios of software-defined transceivers and flexible-grid WDM.

**Figure 1-3** Common application scenarios of software-defined transceivers and flexible-grid WDM.



## 1.3 Electrical-Layer Optical Transport Network (OTN) Scheduling

The architectures of optical networks become more complex as optical technologies evolve, including the emergence of multiple-ring or mesh network topologies that require optical switching between multiple fibers. With the development of large-scale integrated circuits, electrical layer switching technology is ahead of optical switching, therefore giving birth to OTN, an optical network system based on electrical-layer switching.



On October 9, 2009 in Geneva, the ITU-T Study Group 15 (SG15) officially developed version 3 of G.709, which includes the key technical characteristics (including ODU0, ODU4, ODUFlex and GMP) of OTN evolution, providing OTN with Ethernet-oriented multi-service carrying capacity. After 2010, optical networks grew increasingly complex and OTN technology was constantly adapting itself to emerging network architectures, such as ring and mesh network architectures. In 2013, CCSA led the development effort for "packet enhanced OTN device technical requirements" and other national industry standards, uniformly incorporating SDH cross-connect, packet switching, and ODU switching into a packet enhanced OTN device.

In the next five years, DC cloud services, 4K video, and 5G service bearer applications will become increasingly popular and traffic will grow at exponential rates. Super-high granularity and arbitrary diversity will become a major feature of bearer services. The industry is in full swing for beyond 100G optical transport technology research. As a representative of high granularity services, next-generation Ethernet services are driving the evolution towards beyond 100G OTN. Currently, IEEE is stepping up the development of standardization for 25GE, 50GE, 200GE, and 400GE Ethernet technologies, indicating the importance of high speed Ethernet interfaces for the future. This requires future OTN to have the capability of transporting high granularity services.

Additionally, the types and speed of future services are diversified, which drives the trend of OTN evolution towards increased flexibility. Future OTNs are required to extend its carrying capacity for any services greater than 100G. Meanwhile, changes in optical layer Flex Grid technology are also driving the evolution of OTN towards increased flexibility. The current light spectrum allocation of Fix Grid together with the fixed-line transmission rate of OTN is unable to take full advantage of the limited bandwidth of the optical spectrum. As Flex Grid technology matures, using technologies such as higher-order and multi-carrier modulation to achieve higher spectral efficiency can improve light spectrum resource utilization. The industry hopes that future optical transport networks can flexibly select the optical modulation mode, the size of the light spectrum, the number of carriers, and other parameters all based on the transmitted service traffic and the transmission distance to achieve the most optimized and efficient network configuration. OTNs need to provide flexible transmission rates and adapt to the evolution of the Flex Grid optical layer to meet the carrier's need for fine operation of optical spectrum bandwidth to maximize the bandwidth utilization of the network operators.

Another trend in OTN technology is programmability. Operators want to provide ultra-wide pipelines and fast wavelength modulation capabilities to adapt and finely process services with increased flexibility, provide more signal mapping control, and serve different operator, enterprise, and OTT customers using the same hardware platform. Additionally, new services can be deployed as soon as possible and be gradually upgraded, without needing to wait for long standard-setting cycles. While meeting the hosting requirements for any service, programmable OTN provides carriers with better control of the data plane, programmable client signal mapping, programmable multiplexing, and framing and overhead processing. Carriers can by themselves achieve new custom mapping methods and map existing or new client signals to ODUFlex pipelines, and under the control of Openflow, achieve L1 and L2 to L7 layer traffic grooming. Furthermore, programmable OTN can select simplified OTN functions based on customer needs quicker to satisfy non-traditional telecom markets, simplifying the usage and maintenance of OTN without increasing research and production costs. It is expected that after the next breakthrough in general-purpose processor performance, IT technology will inevitably seep into every corner of OTN electrical layer processing and even ODSP processing will be soften. The processing unit of each electrical layer function will standardize and become universal, coupled with the standardized interface

of ROADM devices and optical transmission equipment working together to enable multi-service hosting, grooming, and transmission capabilities on optical networks. Under the SDN/NFV trend, IT-based OTN will be possible.

## 1.4 All-Optical Switching

Although OTN is continuously evolving to meet the needs of new network trends, it has technological bottlenecks that are difficult to overcome. With the increase of OTN optical cross-connect (OXC) capacities, ODSP power consumption increases proportionally. The only way to decrease its power consumption is by reducing the manufacturing process of its chips, for example from 16-nm technology to 10-nm technology. With the arrival of the post-Moore's law era, the increased level of integration for integrated circuits will reach its limits. A chip's cooling ability will become the ultimate restriction and the continued reduction of power consumption becoming will become increasingly more difficult. The power consumption of future high capacity electrical cross-connects will become a heavy burden on the equipment room operations for carriers. Additionally, electrical switching requires O/E and E/O, which comes with relatively high latency. Therefore, the industry expects that technology will advance from electrical switching to optical switching, or all-optical switching.

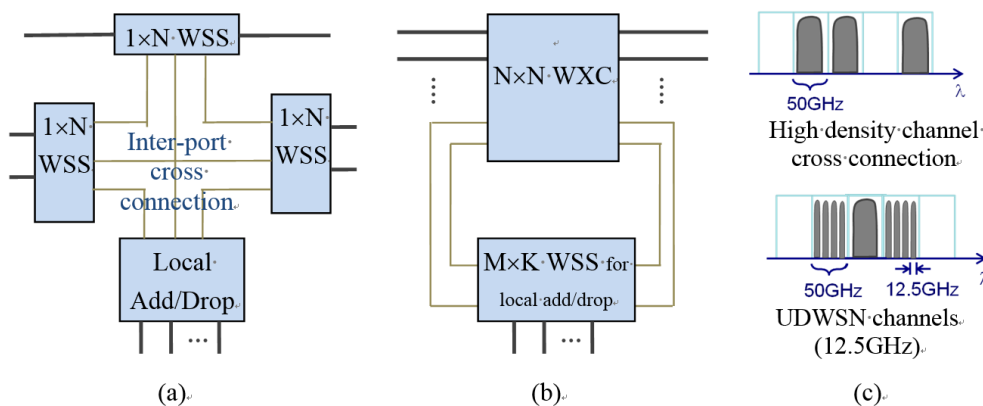
The original plan for achieving all-optical cross-connect was by extending optical add-drop multiplexing (OADM) to reconfigurable OADM (ROADM). Around 2010, the wavelength switching industry's mainstream commercial architecture evolved to a multi-dimensional ROADM (MD-ROADM) based on multiple  $1 \times N$  wavelength selective switching (WSS) units. Each WSS unit connects with the local add-drop switching unit and engages in reconfigurable wavelength adding and dropping. Based on the different implementation methods of local add-drops, there can be colorless, directionless, and contentionless (CDC) characteristics. CDC-ROADM refers to ROADM that has all three of these characteristics.

As shown in Figure 1-4 (a) and (b), optical switching systems based on multiple  $1 \times N$  WSS units is currently already being widely applied in the industry. However, there are also serious problems with this solution. It requires multiple  $1 \times N$  WSS modules, leading to high cost and high space usage (wasting sub-rack slots), and complex fiber optic interconnect between ports. To address these issues, Huawei recently introduced a new technology, which takes  $N$  units of  $1 \times N$  WSSs and integrates them into one  $N \times N$  wavelength cross-connect unit (WXC). Furthermore, the current mainstream CDC MD-ROADM architecture's add-drop side requires a large number of optical amplifiers and multicast switches (MCS), resulting in high costs and declining performance of the optical signals. Huawei proposed and implemented the replacement of all the optical amplifiers and the MCS structure with compact  $M \times K$  WSS units, greatly enhancing the cost-effectiveness, energy-efficiency, and affordability of CDC ROADM.

With the improved efficiency of the optical signal spectrum and the increased use of optical switches in metro networks, there is a need for wavelength optical switching with finer granularity, e.g., to realize ultra-dense wavelength switching network (UDWSN). Multiple sub-channels within a 50-GHz channel slot can use a DSP-based single optical transceiver to transmit and receive. Denser and larger quantities of wavelength provisioning and switching will allow the amount of service access and direct optical layer switching capacities of optical networks to increase significantly in response to the upcoming 4K/8K video, 5G, virtual reality (VR) and augmented reality (AR), and other high-bandwidth and low-latency

applications. Figure 1-4 (c) takes 12.5-GHz granularity as an example and compares UDWSN with a common current wavelength-switching scheme.

**Figure 1-4** Architectures for optical switching in the wavelength dimension



(a) MD-ROADM based on multiple  $1 \times N$  WSS units, (b) CDC MD-ROADM based on  $N \times N$  WXC and  $M \times K$  WSS, (c) Comparison between dense wavelength switching and ultra-dense wavelength switching.

Currently, major industry manufacturers are focusing on accelerating CDC-ROADM development. There have been breakthroughs in a number of core technologies, which will soon achieve full commercial use. After the CDC-ROADM, all-optical cross-connect may continue to evolve towards an all-optical network. One trend is fine-grained and flexible bandwidth allocation. Currently, flexible and fine-grained optical switching has already been achieved in superchannel-based transmission with a wavelength channel granularity of more than 50 GHz. Figure 1-5 shows superchannel based electrical and optical layer scheduling, which further enhances system spectrum utilization and system transmission capacity.

**Figure 1-5** Superchannel based electrical and optical layer scheduling.

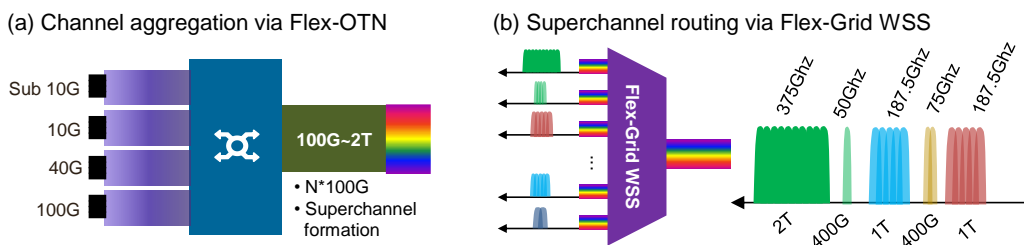
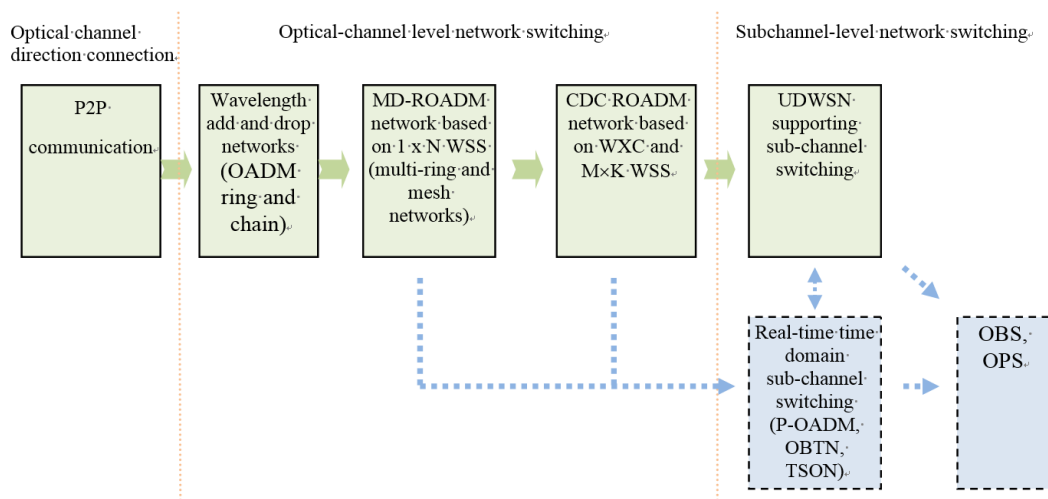


Figure 1-6 shows the evolution and trend of optical switching technologies. Evidently, with the increasing demand and requirements for MD-ROADM,  $1 \times N$  WSS-based MD-ROADM

networks are evolving to  $N \times N$  WSS WXC-based and  $M \times K$  WSS-based CDC ROADM networks. Furthermore, support for a UDWSN network with a finer-grained light spectrum and sub-channel switching will increase optical networks and optical layer switching capabilities, supporting the exponentially increased pipeline connections and future large-bandwidth and low-latency services.

**Figure 1-6** Evolution and trend of optical switching technologies.



Additionally, after the CDC ROADM, a time-domain optical switching technology is another potential evolutionary path, but there are many challenges. Well-studied technologies include optical burst switching (OBS), optical packet switching (OPS), and optical label switching (OLS). These technologies were introduced in the 1990s, but they have not been commercialized, mainly due to the lack of optical buffers and practical fast optical switching arrays. Therefore, in the interim, a simplified time-domain sub-channel granular optical switching technology will serve as a transitional technology, including packet OADM (P-OADM), optical burst transmission network (OBTN), and time-shared optical network (TSON). A simplified sub-channel time-domain optical switching technology will be implemented on all wavelengths with equally timed optical bursts that are time-aligned. This avoids the optical-domain alignment and scheduling for optical burst block, and easily achieves burst adding and dropping.

## 1.5 High-Speed Photonic Components

Optical component performance, design, and manufacturing are necessities for implementing high-performance optical communications systems, and are also the foundation of the optical communications industry chain. Optical components provide various functions and the implementation of these functions requires different materials. Traditional optical components, however, are composed of discrete parts. The manufacturing process of these parts is redundant and needs a lot of manual commissioning and verification, which is inefficient and costly, greatly restricting the development of optical components. Photonic integration technology, especially the silicon photonics technology that uses the large-scale

semi-conductor manufacturing process (such as CMOS), requires low-cost materials (Si), but provides high production efficiency and high integration. The power consumption and volumes of the components using such technology account for less than 20% of traditional optical components. In recent years, the technology has been put into commercial use and is leading a new industrial revolution in optical component technology.

Photonic integration technology was introduced during the mid-1990s. At the early stage, optical components were made by multiple types of materials including silicon dioxide and III-V compound materials, which greatly increased the integration of the system which was composed of original discrete parts. However, manufacturing of the integrated optical components made by various materials was complex and costly. The optical communication industry desired a unified platform with higher integration and lower manufacturing costs to implement single slice integration and photonics integration. Driven by the wide silicon application in integrated circuits, the industry has been dedicated to achieving functions of photonic components using silicon materials from the 1980s. Fabless manufacturing (separation of design and manufacturing) of photonic components was implemented following the existing CMOS process, rather than the costly photonic component manufacturing process. Additionally, silicon and silicon dioxide have a large refractive index difference, and silicon waveguides can implement submicron optical waveguides, greatly reducing device scales and processing costs.

In 2004, researchers from Intel and Cornell University led the report in Nature magazine on GHz high-speed silicon photonic modulators based on the Mach-Zehnder interferometer structure and microring resonant cavity structure. Currently, silicon photonics technology matured and been put into commercial use on optical communication systems. Silicon photonic 100 Gbit/s coherent optical modules represent the highest-level commercial application of silicon photonics technology.

Silicon photonics technology is leading an epoch-making technology transformation of the optical network industry from the discrete-component era into an integrated-chip era that features automation and large-scale production. The influence of the technology is akin to the impact on the electronic circuit industry caused by the transformation from the electron tube era to the transistor integrated circuit era. Silicon materials, however, are not the best choice. Graphene, a type of two-dimensional material, is currently used on photonic components. Compared with silicon, graphene can theoretically bring higher bandwidth, low drive voltage, and smaller dimensions. Additionally, the manufacturing of graphene components is compatible with the silicon-based CMOS process. Therefore, the current silicon photonics technology and process can be used for manufacturing graphene components. Using graphene materials in photonic components means combining the advantages of the two types of materials, implementing next-generation beyond-silicon photonics technology.

In the future, silicon photonics technology working with graphene materials can achieve various optical switching, optical routing, optical logic, optical storage, and optical signal processing functions of next-generation all-optical networks. When the manufacturing technology of photonic components makes progress like the microelectronic manufacturing technology, a new type of photonic component using photonic crystals and artificial materials will come into application in the near future. These components are superior in implementing a new optical manipulation mechanism and have the potential to change the component types and structures of existing optical networks, dramatically simplifying optical networks and implementing revolution of the optical communications industry.

## 1.6 Other Enabling Technologies

- **Ultra-low loss fiber + Raman amplifier**

The use of ultra-low loss fibers and Raman amplifiers increases high-speed transmission distance. The loss coefficient of the optical fibers currently deployed on live networks is about 0.22 dB/km (over 1550 nm wavelength). The attenuation coefficient of ultra-low loss fibers is only about 0.17 dB/km. The optical power loss over a transmission span of 80 to 100 km with ultra-low loss fibers is 4 to 5 dB lower than with that with common fibers. The use of distributed Raman amplification can further improve the optical signal-to-noise-ratio (OSNR) performance of the transmission link, typically by ~5 dB. Using ultra-low loss fibers and Raman amplifiers together can thus substantially increase the transmission distance and/or system capacity.

- **C+L band transmission**

Transmission channels can be extended to the L band. The use of the C+L bands can support almost 200 50-GHz-spaced wavelength channels. The L-band transmission scheme was proposed in the early 2000, but it was not deployed commercially at the time due to technological limitations and cost issues. The technical process and performance (including optical power and gain) of L-band components have developed recently, and are expected to continue to mature over the coming years. The technology suppressing nonlinear interference, such as that caused by stimulated Raman effect and cross-phase modulation, is more complete. The C+L band transmission scheme may be first applied on a few long-haul backbone networks where existing fibers are insufficient and new fibers are difficult to deploy.

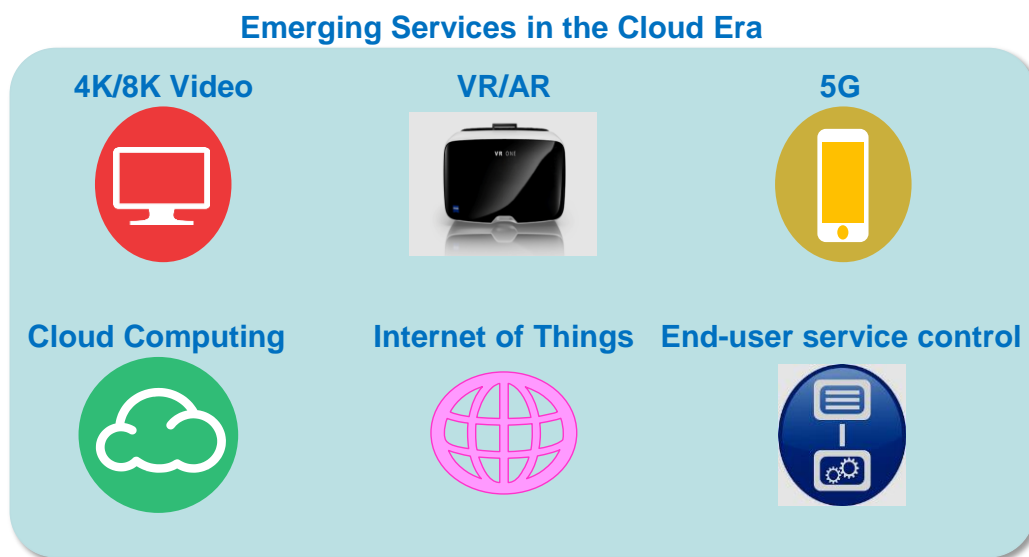
- **Non-orthogonal FTN transport technology**

Traditional optical transmission technologies use orthogonal transmission. In a non-orthogonal FTN system, the frequency spacing is less than the symbol rate of the signals. However, in an orthogonal frequency spectrum system, the frequency spacing is far greater than the symbol rate of modulation signals. Even though the non-orthogonal system experiences crosstalk, DSP technology can be used for crosstalk cancellation. The non-orthogonal signal processing technology and the high symbol rate with the lower-order modulation format can achieve the same spectral efficiency and single-fiber capacity as those in the higher-order modulation format, and increase the transmission distance by taking the OSNR advantage. Optical transmission systems may soon evolve from orthogonal systems to non-orthogonal systems to improve the spectrum efficiency.

# 2 Challenges of Optical Networking in the Cloud Era

The development of optical communications technology is stimulated by the emerging services shown in Figure 2-1. ICT industry developments such as DC cloud interconnection services, ultra-bandwidth video services, and 5G mobile network services will drive future optical communications industry development and architecture transformation.

**Figure 2-1** Emerging services and applications to be supported by optical communication systems in the cloud era.



## 2.1 Emerging Services of Future Optical Networks

- **DC cloud interconnection service**

With Internet development, the traditional metro+backbone enterprise private line services gradually evolve into cloud private line access+cloud DCI backbone services. DC-centric network construction focuses on backbone network reconstruction quality (such as latency and QoS), requiring a simplified network architecture, large-bandwidth pipelines, and one-hop transmission at the optical layer. In addition, the backbone networks must be highly reliable, and provide flexible optical-layer grooming and protection against multi-point faults.

- **Ultra-bandwidth video service**

Video traffic accounts for more than 70% of pipeline traffic, and more than 60 operators worldwide provide video services as a basic service. Most of the operators are planning to launch ultra-HD (4K) services. South Korea and Japan are planning to implement live 8K video for the 2016 Olympic Games and 2020 Olympic Games. Sharp increases in video services demand correspond to increase network bandwidth demands. Data bandwidth will increase geometrically with future development of new video technologies such as VR/AR, 360-degree panoramas, high-speed photography, and multi-angle MV. DC-dependent metro NFV is the target architecture suitable for future ultra-broadband application. The architecture not only reduces the number of network nodes by more than 30% and network construction costs, but also ensures high bandwidth, low latency, and flexible reachability between CO and VBRAS, guaranteeing excellent video experience and future-proof reliability.

- **5G mobile network services**

The 5G bearer technology is applied to various services including the Internet of Things (including Internet of Vehicles), voice services, and data services. As the wireless 5G spectrum range is enlarged, the single-wavelength transmission bandwidth without signal compression can reach 200G in future under the 200M spectrum width. Because there are various types of 5G services, and the mechanisms and network nodes for processing services are different, different network function slices, pipes, and QoS levels must be provided for the services.

## 2.2 Requirements on Future Optical Networks

Over 30 years of development, network communication has gone through roughly three phases: voice, Internet, and video. Driven by DC cloud interconnection, ultra-bandwidth video services, and 5G services, optical communication networks will evolve into simplified networks in the future. The major demands on simplified networks are large bandwidth and one-hop transmission with low latency. In the cloud era, networking is DC-centric. Therefore, networks must support quick service provisioning, full automation, and open collaboration, and network security mechanisms must be enhanced to improve network reliability. These are the typical requirements and challenges of the next generation optical communication networks.

- **High bandwidth**

From the day when optical communication emerged, bandwidth has been a foremost consideration. As the transmission capacity of communication systems increases, especially in



the WDM era, high-speed transmission performance has made significant progress. Such progress is akin to Moore's Law in the semi-conductor field. The single-wavelength WDM transmission rate has been increased from 2.5 Gbit/s in 1996 to 400 Gbit/s in 2016. Using Flex Grid 100 wavelengths as an example, the single-fiber capacity reaches 40 T. In recent 10 years, however, the transmission bandwidth development of optical communication systems has slowed significantly, and now lags far behind the Internet traffic increase speed. The industry is seeking an effective breakthrough technology. Various forms of spatial multiplexing technology may be the final capacity expansion measure.

- **Low latency**

Future networks will be DC-centric. CDNs will downshift to vBRAS/vEPC, and CO nodes will be connected to local data centers (LDCs) in one hop mode. Ring networks will evolve to mesh networks, simplifying network architecture. Consequently, the requirements on latency will be extremely strict. For example, for a high-frequency trading financial company, a 1 ms speed improvement in each transaction may increase revenue by one hundred million USD a year.

Network games are also sensitive to latency. According to 3GPP standards, good network game experience can tolerate latency of no more than 10 ms. Future networks need to implement one-hop transmission over optical wavelengths between the source and sink. This not only eliminates the possibility of packet loss on nodes except the source and sink but also prevents the malicious cycle that hundredfold bandwidth increases require hundredfold increases to electrical-layer processing performance.

- **Quick service provisioning**

In the current WDM system, E2E provisioning of the service on one wavelength requires many manual operations be performed onsite and many boards be purchased. Service provisioning in WDM systems takes several weeks to several months, depending on network structure. In the cloud era, users require real-time and on-demand bandwidth. For these purposes, the service provisioning speed of traditional WDM is unacceptable. Therefore, minute-level near-real-time service provisioning is key to next generation optical networks.

- **Full automation**

Unlike SDH and Ethernet networks, WDM networks are analog systems with complex planning, design, installation, commissioning, and fault locating. These have become the major factors that obstruct WDM system application. Next generation optical networks should be fully automated to simplify O&M. To be specific, network planning and design are automatically performed by software; hardware is colorless, directionless, contentionless, and Flex Grid; fault locating can be performed using a professional fault diagnosis system based on big data.

- **Open collaboration**

Future networks will evolve to cloud DCs to provide increasingly competitive cloud services. This puts high requirements on open collaboration for intermediate bearer networks. More interconnections are required between optical network systems for multi-point and multi-domain collaboration, therefore implementing quick service matching and reducing network construction costs by sharing hardware resources. A typical change of the enterprise private line is the conversion from offline mode to online mode, which is a typical Internet+transformation application scenario. Private line VIP customers can use PCs or mobile terminals to apply for, adjust, or delete services easily. Compared with traditional

business models requiring customer service centers, this improves customer experience and decreases operator O&M costs. In DCI scenarios, the cloud DCs of multiple cloud service providers are dynamically interconnected on demand, meeting requirements of remote VM migration, data disaster recovery and backup, service load balancing, and quick response to emergencies. These improvements help provide optimal cloud service experience to customers. Carrying of ultra-bandwidth video means on-demand multicast services. That is, multicast service trees are set up, adjusted, and deleted as required to meet the requirements of dynamic video traffic changes.

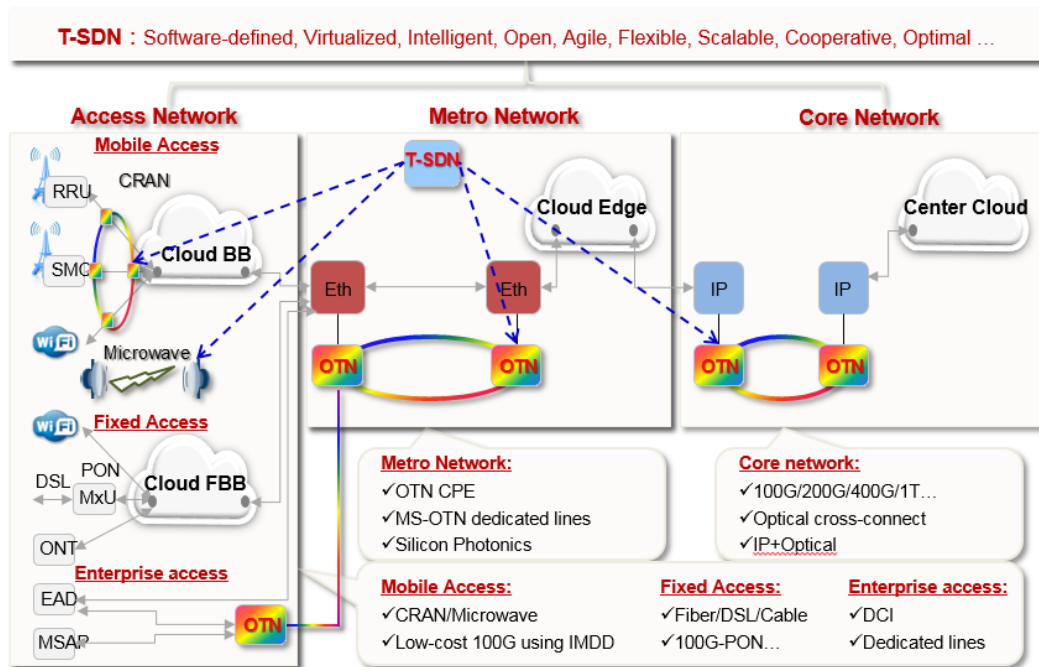
- **High reliability**

Security of current telecom networks is guaranteed by high reliability of functional modules, and 1+1 and 1:1 system backup and network-level recovery mechanisms. A failure of a protection and recovery mechanism will impact different networks and services differently. Among these factors, the reliability of system components is the main factor. To improve the reliability of system components, devices require refined manufacturing, and each functional module must undergo many reliability tests (such as long-term temperature cycle tests). As a result, telecom devices are expensive. It is clear that networks will be more deeply involved in social life in future, and interruption of network services will result in more significant consequences. Therefore, more reliable protection and prevention measures must be taken. The next generation optical communication system introduces a second-level interruption recovery mechanism to ensure security, and adopts a flexible scheduling mechanism to improve reliability. When a fault occurs in a system (for example, a financial IT service system), services can be migrated to other idle modules. This ensures the high reliability of the entire system and reduces costs (because 50% equipment redundancy is not required).

# 3 Evolution Trends of Optical Networks

DC cloud interconnection, ultra-bandwidth video services, and 5G services will lead the evolution of optical communication systems to the major five network features: high bandwidth, low latency, high reliability, quick service provisioning, and open collaboration. Future technology development will match development of future optical communication systems. Figure 3-1 shows the evolution trend of optical network systems.

**Figure 3-1** Evolution trend of optical networks.



## 3.1 Backbone Network

Backbone networks will continue to develop in the following aspects:

- Single-channel rate improvement (100 Gbit/s, 200 Gbit/s, 400 Gbit/s, 1 Tbit/s) and performance improvement
- High-level and large-capacity optical switching and wide WSS application
- IP+optical synergy
- High-density optical chip integration and silicon photonics maturity

## 3.2 Metro Network

Metro networks will continue to develop in the following aspects:

- Reduction of transceiver costs, power consumption, and volume. For example, 100 Gbit/s coherent optical transceivers are developed as CFP and even CFP2 modules.
- Implementation of low-cost non-coherent optical transceivers with a per-channel 100 Gbit/s rate by combining intensity modulation/direction detection (IMDD) and ODSP, for example, combining 20 GHz optical and electrical components and Poly-binary PAM-4 or DMT modulation.
- Simplified and optimized networks.
- Popular application of enterprise private line services.
- More-in-depth mobile bearer.
- DCI.

## 3.3 T-SDN

Early optical communications systems had a simple structure and single function, and their networks were run by hardware. Decades of development have brought significant complexity. Now, devices are deployed alongside multiple others that may be older, have different functions, and comply with different standards. This carries significant management and maintenance overhead, impeding the ability to serve customers. Finding a solution to improve O&M efficiency is urgent.

Software management and control technologies such as SDN and NFV have emerged. These technologies will bring vitality to the optical communication system and drive the hardware system to run more efficiently. The industry will reconstruct networks by separating control and forwarding, opening interfaces, virtualizing network functions, and applying IT technologies. This will increase service innovation and customer satisfaction and reduce management and maintenance costs. The development of optical communication management and control technologies involves three phases: automatic control, open orchestration, and IoT intelligence.

### 3.3.1 Automatic Control

Before 2000, SDH optical networks were manually configured and the network management system (NMS) served only as an assistant management tool. While voice services comprised most traffic, traffic was not significantly dynamic and automation was not popular. Therefore, an SDH network could satisfy service bearing and operating requirements. After 2000, the rapid growth of Internet services drove the optical network to evolve towards an IP-based network (MSTP). More IP services were carried and the network scale became increasingly large. Later, the automatically switched optical network (ASON) control plane technology was introduced, implementing automatic resource and topology discovery, automatic service provisioning, and automatic service restoration on the optical network. The optical network successfully evolved from manual management to automatic control, satisfying network service development requirements.

### 3.3.2 Open Orchestration

Since Apple launched the first generation iPhone in 2007, the rapid development of mobile terminals and innovation in wireless network technology (3G/4G to 5G) have led to an explosive growth in mobile Internet traffic. Meanwhile, the infrastructure of Internet service providers is evolving from traditional data centers (DCs) to cloud DCs so as to satisfy enterprise and personal computing and storage requirements, especially associated with social, video, and game uses. The concurrent development of the terminal and the cloud poses high requirements for "on demand, openness, orchestration, and self-service" on intermediate bearer networks.

However, the telecommunication system is closed and complex. Although automatic management and control technologies such as ASON can reduce O&M complexity, they cannot resolve all the problems facing operators. For example, operators still endure long time to market (TTM), multi-domain network orchestration is still difficult, networks at different layers work independently, and network resource usage is low. More importantly still, the current transport network system cannot solve challenges brought by over the top (OTT) services.

In 2008, the SDN concept was introduced at Stanford University, starting intelligent-network transformation. Later, the Transport-SDN (T-SDN) technology emerged in the optical network domain, kicking off a trend of intelligent-network transformation and revolution of telecommunication system architecture. Gradually, the new generation transport network architecture with a controller as the core has been formed and recognized by the industry. As the intelligent core component of the entire network, the centralized controller not only completes centralized management of network resources, but also performs complex functions based on upper-layer service requirements. Such functions include global network planning, resource slicing, traffic prediction, and big data analysis. High-performance algorithms of the controller implement all these functions. In addition, the controller can provide transport capability externally by using open northbound interfaces (NBIs), breaking the vertical barrier. This feature allows upper layer customers to proactively design networks to be more flat and convenient and accelerates service innovation as NBIs implement ICT convergence.

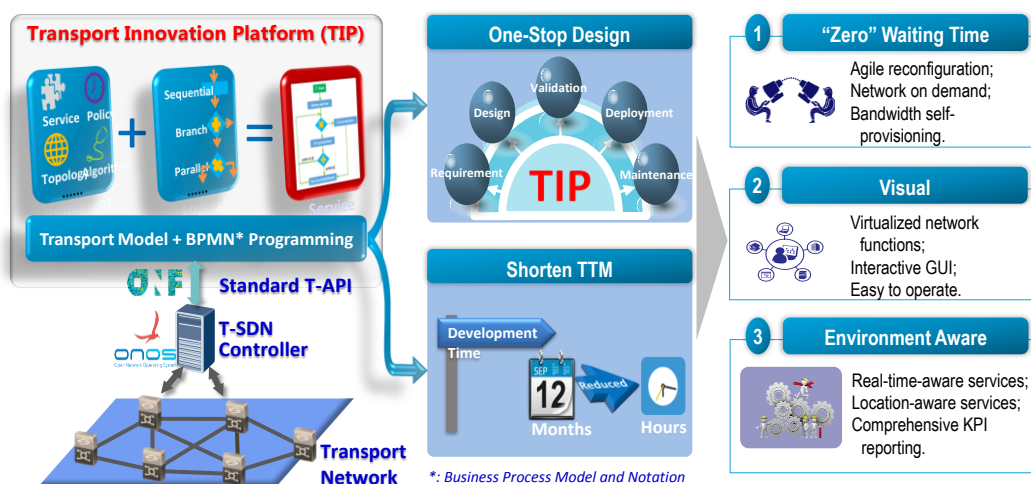
T-SDN technology drives the current transport network towards increased virtualization and openness. T-SDN not only brings vitality to traditional services, but also meets network requirements of new services. For example, the typical virtual transport network service (VTNS) not only provides various typical network services such as point-to-point virtual

private lines, point-to-multipoint virtual multicast networks, and multipoint-to-multipoint virtual private networks, but also meets customers' dynamic, on-demand bandwidth requests and requirements such as minute-level online service provisioning and self-O&M of virtual networks.

To apply for a traditional enterprise private line service, customers need to submit applications and go through a long and complex process before receiving services. Technologies such as the VTNS, however, bring traditional offline service provisioning online. VIP private line customers access the web Portal provided by operators, and apply, adjust, or maintain desired private line services. The controller automatically provides services for customers by means of online planning and resource slicing, improving customer experience, reducing operator O&M costs, and increasing resource usage. Virtual private networks and virtual multicast networks can support new transport services such as DCI, enterprise private network, and 4K/8K bearer services.

T-SDN continues to develop rapidly under sound guidance from industry leaders. The technology will provide comprehensive network system management and control capabilities, including quick service response, resource configuration optimization, simplified O&M, and open third-party orchestration. Figure 3-2 shows a new SDN-based optical transport network technology platform that aims to provide better user experience.

**Figure 3-2** A new SDN-based optical transport network technology platform.



### 3.3.3 IoT Intelligence

Networks evolve to accommodate continuous increases in traffic, access terminals, dynamic service bursts, and differentiated services. With the coming cloud era, IoT will materialize and bring great challenges to bearer networks. Future T-SDN will solve these challenges and have more powerful intelligent capabilities.

The biggest change is deep service awareness. Intelligent T-SDN obtains traffic data from various services, performs big data analysis and prediction, and automatically optimizes bearer networks to adapt to service changes. Mostly importantly, such technology provides virtual slicing network services based on service characteristics. T-SDN enables the division

of one physical bearer network into multiple sliced networks with different service bearer characteristics. For example, a network could be sliced into a real-time, low-latency, small-bandwidth network and a non-real-time, large-bandwidth network. This feature meets bearing requirements of services with different traffic characteristics.

Over the next 5 to 10 years, IoT will change our lives in exciting and unexpected ways. The bearer network of the IoT will become fluid, posing greater challenges to its management system.

[*Large bandwidth*] Ultra-large bandwidth scheduling is a great challenge to reasonable network resource allocation. Any partial network change requires global measurement, challenging the processing capability of the management and control system.

[*Frequent change*] Network services are ever-changing. This challenges the network management and control system to concurrently process and optimize a large number of services and predict future network changes.

[*Quick response*] "Zero-wait service provisioning" and "zero-interruption switching" will become common requirements of major services. This will require that the network management and control system quickly respond to network events.

[*Various types*] Future networks will face various requirements. The network management and control system needs to support on-demand and online network function loading, challenging the online programming and fast innovation capabilities of the software platform.

[*High requirement*] Service interruptions on future networks will have great impacts. Therefore, more reliable protection and preventive measures must be taken in network design and development.

With great challenges will come great network transformation. Deep integration of advanced software and network management technologies is key to solving these challenges. Top-notch IT technologies, such as cloud computing, big data analysis and prediction, and artificial intelligence, will become vital to the network management and control system. This will allow the network management and control system to undergo a qualitative change from "intelligent" (proactive command execution) to "wise" (self-decision making).

[*Deep management and control integration on software*] In the future, the management of lower-layer physical devices and the control of upper-layer services will be deeply integrated. For example, the deep awareness of physical components' performance parameters and prediction of component faults affect the route selection of upper-layer services at different levels. This requires quick response and seamless combination of control over dynamic services and management on static physical devices. The future management and control system will be built on a more advanced network operating system. Various network control and management functions are modular and will be combined, and various functional modules to implement management and control functions will cooperate closely with each other through software.

[*Real network programming*] T-SDN implements network programming using software so as to create new network functions. This is completely different from "automatic network configuration." The future transport network is oriented to numerous interconnections and faces many network function requirements. The demands for fast programming innovation and deployment are increasingly apparent and are decisive factors for constructing a prosperous transport network ecosystem. Transport network technologies are complex and place high requirements on personnel skills. Service innovation also requires complex

programming, making the innovation and development of transport services more difficult. In the future, T-SDN will overcome this bottleneck. Modular design and encapsulation of basic functional components and innovative "intent-oriented" transport network programming will achieve ICT programming integration, greatly reducing the difficulty in programming innovation and encouraging operators and third parties to innovate and create a prosperous transport network ecosystem.

[*Self-learning and artificial intelligence*] Future network management and control systems will not only be deeply aware of bottom-layer physical information and upper-layer network and service information in the space dimension, but also integrate historical network data. Deep analysis and continuous learning from this data helps operators to quickly and accurately make predictions and decisions. For example, after obtaining the traffic data of various services, the system performs big data analysis and prediction, automatically optimizes and adjusts the bearer network, or provides data for decision-making. In addition, by monitoring and analyzing historical data of hardware parameters, the system can identify service deterioration risks and take measures in advance to prevent interruption of important services.

[*Cloud computing*] The future network management and control system needs to process and save a large amount of data in real time. This functionality is beyond the capability of a computer server. Therefore, so-called cloudification of the network management and control system and concurrent storage and computing are inevitable. Meanwhile, "holographic" software computing will be widely used in cloudified controllers to ensure that server or storage device faults do not affect network management and control. This makes the management and control system far more reliable.



# 4 Conclusion

The future network applications of cloud DCI, HD video, and 5G services will include a variety of new scenarios. In addition to increased bandwidth, these will require low latency, high reliability, fast provisioning, and support for open collaboration. For instance, self-piloting automobile, tactile Internet, and next-generation video services are sensitive to network latency, and financial and industrial automation are sensitive to network reliability. Meanwhile, dedicated cloud services need fast provisioning. These are huge challenges that future telecommunications networks face, but they also bring with them opportunities to the optical network industry, because only an optical communication system technology can tackle these challenges. Core technologies that help optical networks to successfully address these challenges include 4K- and LCoS-based multi-dimensional multi-channel WSS next generation CDC ROADM. Silicon photonic integration technology is also helping to advance the integration and cost-effectiveness of optical devices and modules, while ODSP and high baud rate devices have helped in the creation of large-bandwidth, long-distance, transport technologies based on the T-SDN super controller.

Looking further into the future, with breakthroughs in scientific progresses and solving technical difficulties, optical networks look set to become the standard, as we head towards the era of all-optical networks. Firstly, the scope of optical coverage will further increase. At the device level, optical connections are already used within chassis, but will soon be as common between boards, and even on chips themselves. At the network level, optical connections will be used to connect to network devices, to people's homes, and even connecting between people and "things". Optical wireless will integrate with optical cable networks, leading to the management and control required by optical networks to expand by orders of magnitude. The optical network management and control mechanisms of the future will therefore be more efficient and flexible in order to deal with these increasing demands. Secondly, the application functionality of optical technology will be further enhanced, as optical logic becomes more practical, and the switch to full optical wavelength occurs. Optical technology will also implement a range of additional features, such as optical AD/DA conversion, optical Fourier transformation, optical regeneration, and various types of display technology including AR and VR. Since these latter technologies are already based on optics at the display level, their integration with optical networking technology will be an organic one. The Internet of Things will spread further, and all types of sensor technology will mature alongside this spread. It is expected that in the future, optical communications and the related industries it drives will only continue to make greater and greater contributions to the progress of human civilization.

