Technical White Paper on

Single-Wavelength 400G LH Optical Transport

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1. Logic and Rules of Optical Network Evolution

As a basic pipe network of network traffic transport in a long term, the optical network can offer large-capacity, high-rate, and LH rigid pipes. As applications and demands such as 4k video, cloud-network convergence and "East-to-West Computing Resource Transfer" popularize and develop, the optical network is evolving into the high-quality comprehensive service network, characterized by intelligent, fine-granularity and precise service processing. With the industrial cycle of communications networks at the pace of almost one generation every ten years, as shown in Figure 1.1, the optical network has undergone a series of transformation and evolution from 3G and 4G to 5G and even 6G. This chapter analyzes and summarizes the internal logic and basic rules of its evolution and upgrade.

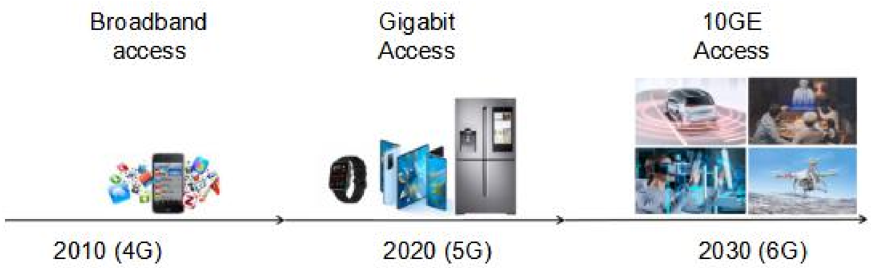

Figure 1.1. Inter-Generation Network Evolution

1.1. Network Traffic Continuously Grows and Transport Access Faces Bandwidth and Latency Pressure

The growing network traffic brings huge bandwidth pressure to transport access, which is always the fundamental driving force for optical network acceleration and capacity expansion. According to the forecast by Cisco, the Compound Annual Growth Rate (CAGR) of global IP traffic is 26% in 2017-2022, and video services account for 71%[1] by 2022. The annual traffic growth rate of the mobile network reaches 46% faster than the fixed network, while the annual growth rate of the average mobile access bandwidth is only 27%. The Omdia thinks the 2019-2024 network traffic forecast result [2] also indicates that the CAGR in recent years is close to 30%, and the ITU believes that the CAGR of mobile traffic in 2020-2030 is up to 55%[3], as shown in Figure 1, so the demand for network bandwidth growth will be very strong in the next few years. Driven by national strategies or major projects, such as Broadband China, FTTx, East-to-West Computing Resource Transfer and digital economy, new applications and new service demands characterized by big video, multiple users and high bursts are rising dramatically, which lead to network traffic surge. Cloud computing, IoT, HD video, and industrial interconnection are now dominating the applications. Oriented to the future 6G, network applications will focus on 3D immersive experience, and new applications represented by Extended Reality (XR), smart interaction, holographic communication and digital twin will emerge as the mainstream [3].

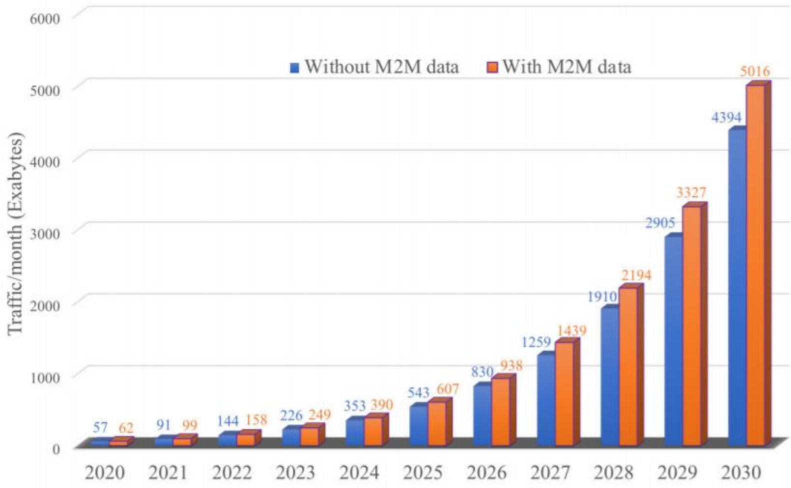

Figure 1.2. ITU Forecast for Global Mobile Traffic Growth Trends (Source: ITU-R Research Report)

New applications and services not only enrich our lives and facilitate our work, but also raise higher requirements for network bandwidth, latency, and reliability. The research shows that these new 6G-oriented applications have requirements for display, bandwidth, latency, and reliability in [4], as shown in Table 1.1. Massive data and broadband connections are basic attributes of future applications. The network should offer large-capacity transport, ensure low latency, high reliability, and make services real-time and secure. These indexes require new communication technologies, network architecture, and O&M systems. Therefore, network upgrade and evolution are inevitable.

Table 1.1. Requirements of New Applications for Network Performance

Application	Cloud XR	Holographic communication	Smart Interaction
Display	8K	16K	--
Bandwidth	1Gb	1~10Gb	>10Gb
Delay	5~20ms	1~5ms	<1ms
Reliability	--	99.999%	99.99999%

1.2. Double Rate and Capacity Over the Same Transmission Distance and Cut Cost Per Bit

The optical transport access network transmits high-frequency optical carrier modulation signals in multiple low-loss fiber channels at the same time, so it has such advantages as high bandwidth, large capacity, strong anti-interference, energy saving, and LH transport without electrical regeneration. As the cornerstone of the communication network and information society, it plays an increasingly important role in the transport of data information. As shown in Table 1.2, the LH optical communications system basically follows the development rule of one generation per 4-5 years. Compared with the previous generation, the new-generation system increases the single-wavelength rate and single-fiber capacity by 2-4 times. Before 100G, the optical module mainly relied on the direct intensity modulation detection technology. On the line, the dispersion compensation module or fiber is used to overcome the influence of dispersion to enable LH transport. Starting from 100G, QAM and digital coherent detection become the mainstream trend in the industry. The powerful digital signal processing (DSPs) is used to compensate for various linear impairments of signals in optical fiber transport and module transceiving channels, such as dispersion, PMD, bandwidth restriction, and skew. This makes LH transport of single-wavelength high-speed signals possible. In addition, the baud rate and modulation code order can be extended to make the single-wavelength rate continuously evolve.

Table 1.2. LH Optical Communication Technology Evolution and Key System Features

Time	1998	2002	2007	2013	2018	2023	2028
Single-wavelength rate	2.5G	10G	40G	100G	200G	400G	800G
System capacity	0.2T	0.8T	3.2T	8T	16T	32T	64T
Baud rate (Gbd)	2.5	10	20	32	64	128	192/256
Band	C4T				C6T	C+L12T	S+C+L18T
Optical fiber	G652.D					G652.D/G654E, etc.	
Modulation and demodulation	Intensity Modulation Direct Detection/DCM			High-order modulation coherent detection/no DCM			
Cross degree and equipment form	2-4 degrees, FOADM			9-20 degrees, ROADM	20-32 degrees, OXC	32 degrees or more, OXC, OXC cascading	

During the actual deployment of the optical network and the upgrade and replacement of new and old equipment, the physical locations of the operator's equipment rooms and line sites, along with the length of the optical fiber link, are difficult to be changed. Therefore, to upgrade the optical network equipment, it is necessary to ensure that the existing optical fibers and site infrastructure are reused as much as possible, and the optical fiber type and site distribution are not changed, so as to save CAPEX to the maximum extent. Therefore, an important logic of the WDM optical transport system evolution is to increase the single-wavelength rate and optical fiber capacity while ensuring that the transmission distance is almost the same. In addition, according to the past experience of network operation, each generation of the system can guarantee at least 80 wavelengths on a single fiber are used for rigid demands, that is, rate upgrade. The number of wavelength channels cannot be reduced to ensure capacity multiplication. To keep the transmission distance unchanged and increase the rate, low-order modulation with a high baud rate is required, which means that a wider wavelength channel is occupied and the bandwidth of the optical transport system needs to be continuously expanded. In the 100G QPSK era, the 80-wavelength system only needs the 4THz bandwidth of the C band. In the 200G QPSK era, it needs to occupy the 6THz spectrum, corresponding to the extended C6T band. In the 400G QPSK era, it needs to occupy the 12THz bandwidth, corresponding to the extended L6T band. Third, as a single-wavelength rate is increased and a capacity is multiplied, the cost per bit of an optical transport device is gradually reduced to maintain relatively constant total infrastructure costs. As Figure 1.3 shows, according to the Dell'Oro analysis [5], the cost per bit of the WDM LH optical transport system has basically dropped by 20% per year over the past decade. This reduces the operator's investment pressure and allows it to maintain reasonable profit returns for more investment in network capacity expansion and cope with the annual 30% network traffic growth. It can be seen that the lower cost per bit is an important prerequisite and an original driving forces for acceleration and evolution of an optical transport network. This is mainly because a capacity of a single fiber is multiplied, and the costs of an optical system remain unchanged. However, after a single-wavelength rate rises, a quantity of optical modules and optical components falls significantly, and an average cost per bit declines. Unchanged transmission distance is a basic requirement for optical network upgrade. Doubling the rate and capacity is an evolution feature. Continuously reducing the cost per bit is a powerful driving source for network upgrade, and is also a prerequisite for the commercial success of new technologies.

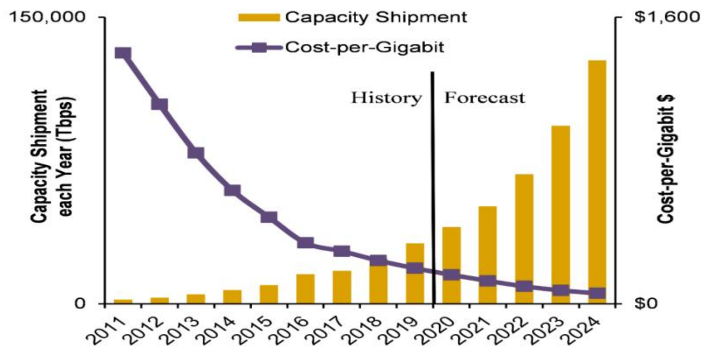

Figure 1.3. Evolution of The WDM LH Optical Transport System Capacity and Cost Per Bit (Source: Dell'Oro)

1.3. Pluggable and Low-Power Optical Modules Become the Mainstream

An important factor that differentiates the optical network from the data communication is that the optical network needs to consider performance, size, power consumption and costs together, which is mainly reflected in the form of a coherent optical module in an optical transport system. In the early 100G era, the form of the coherent optical module is mainly the embedded MSA, such as 5x7 inches, and 4x5 inches later. It is assembled with discrete coherent optical components, such as modulators, receivers, Driver, TIA, ITLA, and coherent DSPs, which are large in size and high in power consumption. With breakthroughs and development of chip, component integration and Packaging technologies, the coherent optical component has a much higher integration, and an CFP or even an CFP2 coherent optical module that supports hot swapping emerges. In this case, the coherent optical module mainly consists of CDM+ICR+ITLA and a coherent DSP. Further, as the InP and SiP integrated platform matures, the CDM+ICR may be encapsulated into an ICRM (generally the SiP), and the CDM+ICR+ITLA into a TROSA (generally the InP). Therefore, components are further integrated, and costs and power consumption decline. In recent two years, the 2.5D/3D Packaging process has matured, and it has become possible to encapsulate ICRM+DSP into MCM, which increase the effective bandwidth of optical modules by more than 10% and are now applied to 200G and 400G coherent products on a large scale. Meanwhile, as one of the cores of the coherent optical module, the performance, power consumption, and area of the DSP are greatly improved with the improvement of the CMOS chip process, as shown in Table 1.3. The new CMOS processes of each generation has obvious improvement in PPA (performance, power consumption, and area [6]. For example, compared with the previous-generation 16nm process, the 7nm DSP ASIC improves the performance by about 30%, and reduces the power consumption by 60% and the area by 70%. This makes possible some more advanced DSP shaping or equalization algorithms in a chip, increases performance or functions of the DSP, and reduces overall power consumption to offer smaller pluggable modules [7], such as OSFP and QSFP-DD, as shown in Table 1.4.

Table 1.3. CMOS Process Node Evolution and Performance Improvement

	2011 40nm->28nm	2015 28nm->16nm	2018 16nm->7nm	2020 7nm->5nm	2022 5nm->3nm
Performance (%)	50	60	30	15	10
Power	-40	-60	-60	-30	-20

consumption (%)					
Area (%)	-26	-50	-70	-45	-42

After more than 10 years of development, coherent optical modules still evolve in the direction of high performance and low power consumption. The former corresponds to the form with the fixed MSA Packaging, and the latter to the pluggable form. However, under the pressure of energy saving, emission reduction, low-carbon and environmental protection, operators are in urgent need of low-power-consumption modules. Some switches and routers are limited by panel slots and ports, so they have more clear requirements for module sizes. According to statistics, among the coherent optical modules delivered in China in recent years, pluggable modules account for over 90%. of course, the OTN telecom market is different from the traditional data communication market. The telecom market has clear requirements for the transmission distance. Therefore, the module needs to assure performance while reducing the size and power consumption. This is guaranteed through the advanced DSP. Although the bonus of the CMOS process gradually decreases after the chip enters the 5-nm stage, based on the IEEE international component and system roadmap (IRDS), the chip manufacturing process can still continue improving. For example, it is expected to reach 2.1nm in 2025, 1.5nm in 2028, and 1-nm in 2031. Undoubtedly, this will continue to support continuous speed-up and power consumption reduction of coherent DSPs, and open the possibility to keep the B400G coherent optical module small and pluggable.

Table 1.4. Basic Parameters of Coherent Optical Modules

Module Form	**Dimension (L×W×H/mm)**	**Power Consumption (W)**	**Picture**
MSA(5x7')	177.8*127*33	90	
MSA(4x5')	127*101.8*25	45	
CFP	144.8*82*13.6	32	
CFP2	107.5*41.5*12.4	24	

QSFP-DD	89.4*18.3*8.5	15	
OSFP	100.4*22.9*13.0	30	

1.4. New-Generation Modules Improve the LH Transport Capability of the Previous Generation

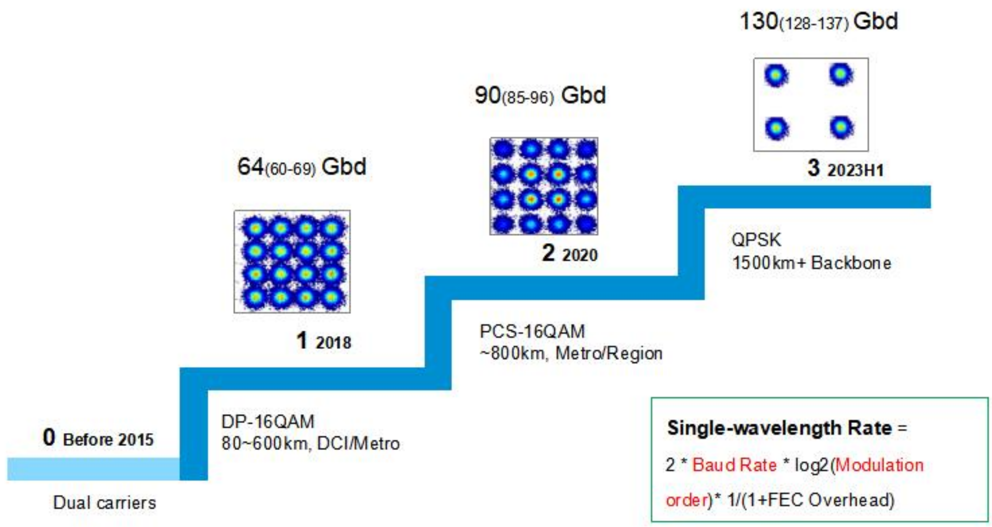

Figure 1.4. Main Features and Transport Capability of a Single-Wavelength 400G System

The same coherent optical module supports multiple rates and modulation formats, and the support for different application scenarios is also an important feature of optical transport system evolution. For different application scenarios such as MANs and backbones, the 400G transport system uses distinctive technologies to balance transport performance, spectrum efficiency, and costs. Figure 1.4 summarizes the main features and capabilities of the single-wavelength 400G optical transport system. The 400G technology can be divided into three generations. In the first generation, the baud rate is 64Gbd, which supports DP-16QAM metro transport and has been put into commercial use. In the second generation, the baud rate is about 90Gbd, which supports PS-16QAM medium-haul and LH transport and has been piloted on a small scale. The third-generation baud rate reaches 130Gbd, which supports DP-QPSK ULH trunk transport and will be commercially available. It should be noted that, because coherent optical modules generally support multiple rates, multiple systems and programmability, they have different maximum modulation rates that meet practical OTN distances, such as 100G, 200G, 400G, and 800G, and are compatible with low-rate modulation rates. Table 1.5 contains modulation formats, application scenarios, and Packaging forms of coherent optical modules at different rates. It can be seen that the medium-/short-haul code pattern with high bit bandwidth is added to each generation of high-rate optical modules to solve the LH transport capability of previous generation modules. For example, 400G optical modules mainly support 400G 16QAM (medium-/short-haul) and 200G QPSK (LH), which are mainly affected by three factors. 1) On the demand side, as CDN and cloud services are deployed, the data center is closer to users. Most network traffic does not need to be terminated through LH trunks in the range of medium-/short-haul MANs and data center interconnection. At present, the MAN traffic has exceeded the trunks, and is growing rapidly. Therefore, compared with LH trunks, MAN applications face the pressure of capacity and bandwidth earlier, and the demand for capacity expansion and upgrade is more urgent. 2) In terms of capabilities, early optical components and DSPs (DA/AD)) have slightly insufficient bandwidth, and cannot allow high-baud code-pattern applications. 3) In terms of industry chain, the new-generation short-haul/MAN applications and the previous-generation LH ones share the industry chain. For example, the 400G optical module mainly employs the 64Gbd component, which not only enables 400G metro and DCIs, but also solves the problem of insufficient LH transport capability of the previous-generation 200G. For another example, the 800G optical module will mainly adopt the 130Gbd component to support 800G metro transport and 400G LH trunk application. In addition, MSA fixed modules are usually used in the early stage, and are replaced by CFP2 pluggable modules later. For instance, both 90Gbd 800G and 130Gbd 1.2T optical modules are MSAs. It is estimated that the 130Gbd coherent optical module will evolve into the CFP2 pluggable one with the further maturity of the 130Gbd industry chain in the next 1-2 years, and it supports the rate reduction as well as 90Gbd 400G and 800G modulation modes.

Table 1.5. Modulation Format, Application Scenario, and Packaging Form of Coherent Optical Modules at Different Rates

	Modulation Format	Application Scenario	Packaging Form
200G optical module	200G 16QAM/8QAM/PS16QAM, 100G QPSK	100G LH backbone, 200G metro	MSA/CFP2
400G optical module	400G 16QAM 200G QPSK/8QAM/PS16QAM	200G LH backbone, metro, 400G metro/DCI	MSA/CFP2
800G optical module	800G PS64QAM, 400G PS16QAM	400G provincial backbone, 800G DCI	MSA
	800G 16QAM/PS16QAM, 400G QPSK/16QAM/PS16QAM, 200G	200G LH backbone, 400G LH backbone, provincial backbone, 800G metro	CFP2

	QPSK		
1.2T optical module	1.2T 64QAM, 1T PS64QAM, 800G 16QAM/PS16QAM, 400G QPSK/PS16QAM	200G LH backbone, 400G LH backbone, provincial backbone, 800G metro, 1T/1.2T DCI	MSA

1.5. Continuous Architecture Innovation Boost Optical Network Intelligence and Improves O&M Experience

Optical networks are transforming from basic transport channels to quality service networks, with significant changes in network scale, service capabilities, and O&M efficiency. This requires optical network equipment vendors, operators, and industry chain peers to build a superb network network with large capacity, high bandwidth, low latency, high reliability, intelligence, and easy O&M through architecture innovation and technological breakthroughs. Large capacity and high bandwidth are made possible through single-wavelength acceleration, band extension, and new multi-core and less-mode or hollow core fiber. Considering the actual engineering situation, over the next 3-5 years, the optical system architecture based on C+L-band extension, together with single-wavelength 400G and 800G rates, will be the mainstream commercial route. Oriented to future medium-/long-term applications, new optical fibers and OA technologies will become more important to improve bandwidth and transmission distance. Optical network planning and site architecture simplification leads to low latency. Optical network planning and site architecture simplification lead to low latency. Driven by the construction of the computing power optical network, more reasonable optical-layer and electrical-layer path planning shortens the optical path as much as possible between electrical nodes and the end-to-end connection allows optical bypass. The site architecture is based on technological innovation and minimalistic structure. As Figure 1.5 shows, highly integrated and smarter OXCs are used to replace ROADMs for equipment miniaturization, intra-site fiber-free connection, automatic discovery and verification of NE connections, and easy use and maintenance of one board in one direction, greatly reducing service debugging and commissioning time. The reliability of an optical network depends on the W/ASON which offer fast and reliable recovery and protection on optical and electrical layers respectively against multiple fiber cuts and for automatic rerouting. The technologies based on the AI algorithm, digital twin modeling, and optical transport performance (QoT) prediction can be introduced to further enhance service reliability, and change from passive O&M to active or even predictive O&M.

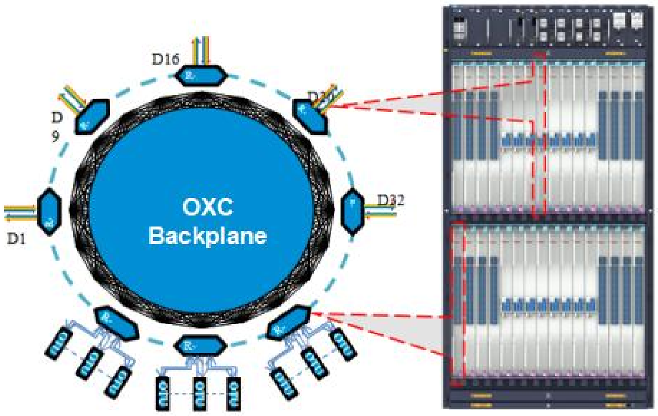

Figure 1.5. OXC Site Structure and Functions

Intelligence and easy O&M are key attributes of the next-generation optical network. Both domestic and foreign O&M suppliers and equipment vendors are actively discussing and formulating the standard [8,9] related to the classification, key functions and features, and application scenarios of autonomous optical networks. Figure 1.6 shows the main research progress. At present, according to the intelligence and automation in network intent, perception, analysis, decision-making and execution, the autonomous network can be divided into L0-L5. The final goal of network evolution is 1) "zero touch, zero wait and zero fault" convenient operation experience. 2) "self-configuration, self-healing and self-optimization” network O&M experience. Different levels of intelligence are defined as follows:

L0 – manual O&M: The system offers the auxiliary monitoring capability, and all dynamic tasks need to be executed manually.

L1 – auxiliary O&M: The system can execute specific repetitive subtasks according to the pre-configuration to improve execution efficiency.

L2 – partially autonomous network: In a specific external environment, the system can enable automatic closed-loop O&M for specific units according to predefined rules or policies.

L3 – conditionally autonomous network: On the basis of L2, the system can sense environment changes in real time, and perform self-optimization and self-adjustment in specific network specialties to adapt to the external environment.

L4 – highly autonomous network: Based on L3, the system enables predictive or proactive closed-loop management of the networks driven by service and customer experiences in a more complex environment across multiple network domains to make analysis and decisions.

L5 – completely autonomous network: It is the ultimate goal of telecom network evolution. The system has the full-scenario closed-loop autonomous capability oriented to multiple services, multiple fields, and the full lifecycle.

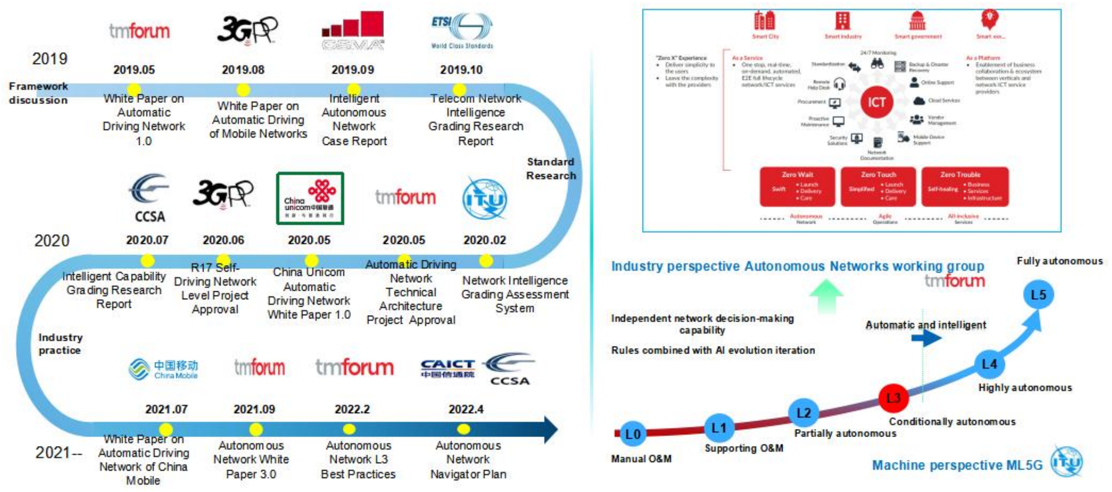

Figure 1.6. Progress in Autonomous Network Research

According to the above definition, the current optical network is basically on the L3, and is expected to reach the L4 in 2024. In the process of improving optical network intelligence, technologies such as top adjustment-based digital optical labels, optical sensing-based same-route detection, AI-based optical component/optical cable fault/system soft fault prediction, digital twin-based online optimization and closed-loop control, will play an increasingly important role, and continuously improve the automation and intelligence of optical networks in the full lifecycle of planning, construction, maintenance, optimization, and operation.

2. Challenges of Optical Network Evolution

Traffic growth drives the inter-generation evolution of optical networks, which is reflected in two aspects: single-wavelength rate and system bandwidth increase, and network O&M simplification and intelligence. This undoubtedly gives the optical communications industry a great opportunity for technical research and commercial application, but challenges also come. First, some Optical system impairments are sensitive to the rate. The higher the rate, the more sensitive the cost, such as dispersion and skew. Second, the Euclidean distance of the high-order modulation pattern declines remarkably, and the anti-noise and anti-interference capabilities are too weak to support LH transport. On the other hand, new technologies, such as new space-division multiplexing, hollow core fiber, and low-noise distributed Raman amplification, which are expected to deliver larger capacity and longer-haul transport, are limited by the protection and reuse of existing optical fiber/cables, sites, and other infrastructure investment, so it is difficult to put them into commercial use. After the bandwidth of optical devices reaches 100Gbd, new material platforms and new Packaging processes, such as lithium niobate film materials and 2.5D/3D co-Packaging processes, are required to further improve the bandwidth and performance. After the bandwidth is extended to multi-band transport, on the one hand, the bandwidth of components needs to be expanded, which requires development and introduction of new amplifier, WSS, optical module, and the like. On the other hand, a strong stimulated Raman scattering effect exists in an optical fiber, so that optical power is transferred from a short wavelength to a long one, and introduced system performance is difficult to balance.

2.1. Optical system impairment Is Sensitive to Rate

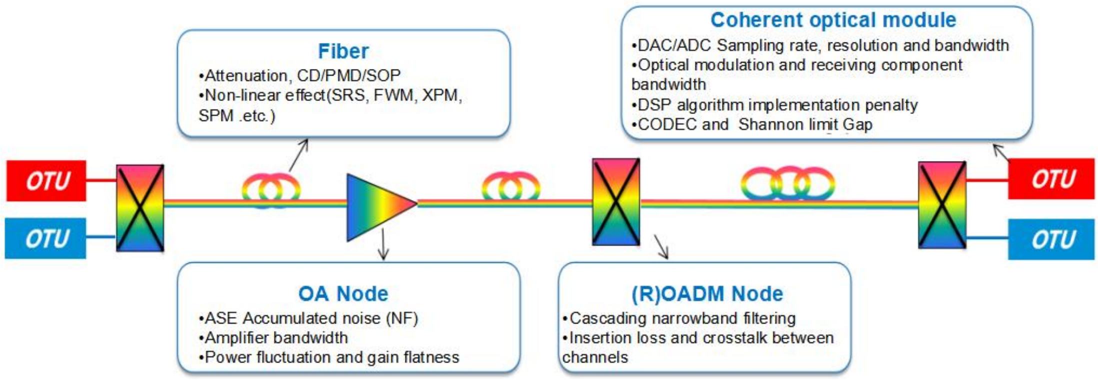

Figure 2.1. Basic Composition and Major Damage of the Optical Transport System

Figure 2.1 shows the optical transport system and its main damages. The optical transport system consists of OTU (optical coherent optical module), (R)OADM sites, LA (Line Amplifier) sites, and optical fibers. The damages include ASE noise, linear impairment of optical fibers (dispersion/PMD, SOP change, etc.), non-linear interference of optical fibers, (SRS, FWM, XPM, SPM, etc), undesirable damages of optical components (bandwidth, resolution limitation, implementation costs of DSP algorithm, FEC and theoretical differences), and interference and imbalance of channels (crosstalk, imbalance, skew, etc). Even if the modulation format is kept unchanged, some channel damages also become more sensitive as the single-wavelength rate rises.

The influence of optical fiber dispersion on signals is a quadratic relationship with the baud rate. Therefore, when the baud rate is up from 64Gbd to 90Gbd or even 130Gbd, the dispersion tolerance/compensation of 400G signals will face new challenges, and a new equalization compensation algorithm architecture is needed. In terms of a non-linear cost of an optical fiber, although a higher incident power may be allowed after a baud rate is increased, after an OSNR tolerance of a high-speed signal gets higher, a performance cost caused by non-linear interference is larger for the high-speed signal. Due to the limited bandwidth of core electrical chips and optical components inside the optical module, high-speed signals experience greater filtering damages, and thus strong inter-symbol interference (ISI) is introduced. Therefore, stronger balancing algorithms are required for compensation. On the other hand, the high-speed signal has lower tolerance to damages such as polarization-dependent loss/gain (PDL/PDG), amplitude and phase imbalance between four channels, and delay (skew). In addition, a high-speed signal occupies a wider spectrum, so it is more sensitive to multi-channel crosstalk.

2.2. Limited Transmission Distance of High-Order Code Pattern

When the baud rate and device bandwidth remain unchanged, the high-order modulation pattern is an important way to increase the single-wavelength rate. However, when QPSK is evolved to 8QAM, 16QAM, and even higher-order QAMs such as 64QAM, it can be seen on the constellation diagram that the higher the modulation order is, the denser the constellation diagram is, and the smaller the minimum Euclidean distance between symbols is. In this way, the probability of error in symbol decision on the channel with noise and interference is greatly increased, and the OSNR tolerance is larger, greatly limiting the transmission distance. On the other hand, the higher-order QAM is more sensitive to such damages as the effective resolution (ENOB), jitter, ITLA line width/frequency offset, modulator and optical fiber non-linearity of the ADDA, which further shortens the transmission distance. To improve the OSNR tolerance for higher-order modulation, the probabilistic constellation shaping (PCS) or geometric shaping (GS) algorithm is usually used in the industry together with the optimized FEC algorithm to provide the OSNR shaping gain of the 1-2dB. Although this technology has been successfully put into commercial use, compared with standard QAM modulation and demodulation, this technology has a higher peak-to-average power ratio (PAPR) of signals and is more sensitive to non-linearity, and introduces overhead to increase the baud rate and power consumption. Therefore, the overall performance is still lower than that of higher baud rates and lower-order modulation signals.

The fiber (G654.E) with ultra low loss and large effective area replaces the existing G652 one, or the existing span distance is reduced to decrease the span loss and increase the incident power, which is expected to improve the transmission distance of the high-order modulation pattern by more than 50%. In addition, the distributed Raman amplification (DRA) replaces the existing EDFA to reduce the accumulated ASE noise on the optical fiber link, which can also increase the transmission distance by more than 50% to facilitate LH transport of high-order signals. Even theoretically, because a non-linear refractive index of a hollow core fiber is lower than that of a common quartz fiber by 3-4 orders of magnitude and has a low loss, the hollow core fiber technology is also an important alternative solution for high-order modulation LH transport. However, the constraints of optical fibers and amplifier types in the existing network restrict the application of new technologies, such as Raman OA, new fibers, and new sites, and the increase of capacity and transmission distance. The main impact is that, when a new network is designed or an existing network is upgraded, there is a need to maximally protect infrastructure investment and control costs, which limits the introduction of new technologies and solutions. As a result, the EDFA+G652 optical fiber is the most typical configuration at present, and the best practical solution for the 400G LH trunk line is to increase the baud rate and use the lower-order modulation formats such as QPSK. However, the introduction of G654E, DRA and hollow core fiber still faces the practical problems of high cost, difficult maintenance and low maturity.

2.3. New Materials and New Packaging are Needed Due to Limited Bandwidth of Optical and Electrical Components

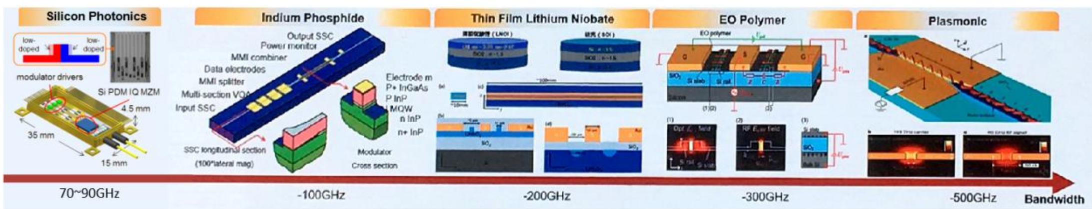

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Figure 2.2. Optical and Electrical Modulation/Detection Bandwidth Limit of Different Material Systems

For a long time, two mainstream technologies have been used in the coherent optical device industry: traditional InP and new Silicon Photonics (SiP) technology platforms. The priority of the InP is that the bandwidth is relatively large. Essentially, it belongs to the direct bandgap material, so it can conveniently integrate the a, the SOA and the laser, but it has a small wafer size and a low yield, and needs air-tight Packaging which leads to high costs. The SiP devices, on the other hand, are compatible with the traditional CMOS semiconductor process and have advantages in size, cost, and power consumption, but have technical bottlenecks when the bandwidth exceeds 130Gbd. To improve the 400G transmission distance and support higher single-wavelength rate, new materials, processes, and platforms are required for optical components. Figure 2.2 shows the operating bandwidth potential of different material systems. The thin-film lithium niobate (TF-LN) is most likely to be put into large-scale commercial use in the near future due to its large linear electro-optic coefficient, high refractive index difference, low waveguide loss, and compatibility with silicon platforms. In the long term, breakthroughs in organic polymers and plasma materials are expected to allow the continued evolution of optoelectronic device bandwidths.

In addition to bandwidth limitations, the power consumption, Packaging size, and operating spectrum width of coherent optical devices also become new challenges. On the one hand, as the coherent optical module has a higher rate, its Packaging form is more compact, so the CFP2 coherent optical module is a mainstream because of telecom market application demands. A smaller volume of the coherent optical module imposes a higher requirement on the integration and bandwidth of the coherent optical component. Therefore, a more advanced component Packaging technology is needed to reduce a transmission length and attenuation of a high-speed signal, and increase a bandwidth of the component to reduce power consumption, as shown in Figure 2.3. In the 130Gbd stage, the SiP system adopts the opto-electronic co-Packaging technology to integrate DSP, CDM, and ICR into the compact MCM (the multi-chip component assembles multiple dies and other components on one multi-layer interconnection substrate). The InP system uses the micro-optical airtight Packaging technology to integrate ITLA, CDM and ICR into the TROSA. Take the SiP for example. Figure 2.3(a) shows the conventional 2D Packaging where a photon integrated chip (PIC) and a drive electric chip are placed horizontally, and a driver and a PIC are encapsulated together in a wire punching manner, and then are interconnected to the DSP on the module PCB. In this Packaging mode, high-speed analog signals need to be transmitted from the DSP to the PIC along DAC->PCB cabling->CDM cabling on the substrate->punched wire->driver->punched wire->PIC. As shown by the red line in the figure, this transport path is long and there are many connection interruption points. The loss and reflection caused by high-speed signals are difficult to meet the high-speed transport requirements of optical components. To further reduce the signal transport path length and signal loss, an MCM Packaging form is introduced into the SiP coherent optical component, as shown in Figure 2.3(b). First, the driver is directly mounted on the PIC in a flip-flop soldering manner. In addition, the DSP die and the PIC are also encapsulated on one substrate to combine the optical chip and the electrical one, as shown in Figure 2.3(c). This form shortens the transmission length of a high-speed signal as much as possible and ensures the bandwidth of the components while greatly reducing component size and Packaging costs.

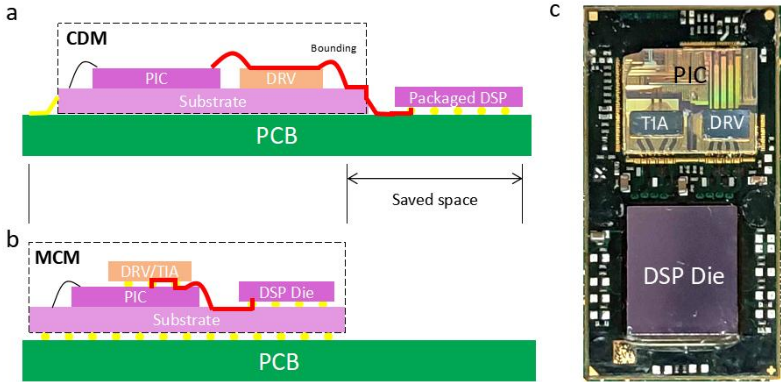


Figure 2.3. SiP Optical Component Packaging (a) CDM Packaging (b) 2.5D MCM Packaging (c) MCM Photo

On the other side, after a single-wavelength rate is up, a higher baud rate of an optical signal needs a larger channel spacing. To multiply system capacity and rate simultaneously, an optical transport system has to expand the existing spectrum band range. The current coherent optical communication is extended to the C+L band, so a coherent optical component also needs to support integrated C+L design. The band extension imposes a higher requirement on component wavelength correlation. In this case, a combination of a transmitting-end TF-LN and a receiving-end SiP has a better application prospect.

2.4. New Problems Caused by Bandwidth Expansion

On the premise of LH transport, single-wavelength rate rise, and maximum compatibility with existing infrastructure, optical system expansion to a wider band is an indispensable path for recent expansion and upgrade. In terms of necessity, LH high-speed transport, such as LH trunk 400G needs 130Gbd, the channel spacing must be extended to about 150GHz, and the ideal optical bandwidth of the 80-wavelength system is about 12THz. Actually, in terms of system architecture compatibility and evolution feasibility, if a multi-band discrete networking architecture shown in Figure 2.4 is used, optical signals of optical transport systems at different bands are amplified and crossed independently in parallel, and an optical module, OA and WSS are used at each band. On the one hand, the current C-band system can be compatible at a relatively low cost. On the other hand, because more bands such as S and U can be multiplexed, the system can evolve to the transport with larger capacity and more bands in the future.

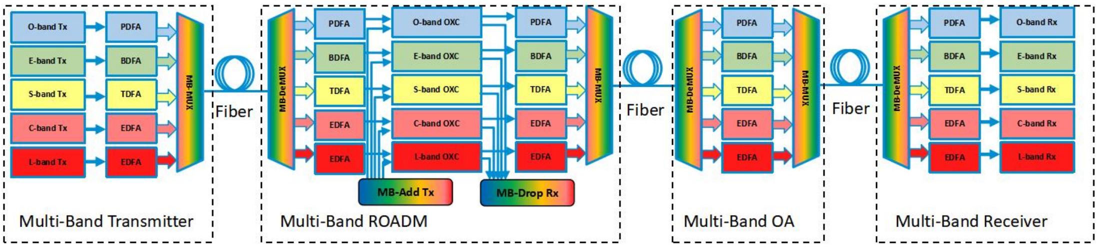


Figure 2.4. Multi-Band Optical Transport System Architecture (Discrete)

However, bandwidth/band expansion and architecture upgrade also contribute to a series of new challenges. 1) In a discrete system architecture, optical system components need to be added almost exponentially, which increase system complexity and costs. The protection interval between bands lowers spectral efficiency, a larger range of wavelengths are actually occupied to make it more difficult to manufacture optical components. An insertion loss introduced by band multiplexing or demultiplexing also deteriorates system performance. 2) The stimulated Raman scattering effect (SRS) of optical fibers in the wide-band system is significantly enhanced, and the optical power is obviously transferred from the short wavelength to the long wavelength. The system needs to design a more powerful automatic optical power management/adjustment algorithm to support fast system debugging and reliable recovery. 3) The multi-band complex optical system is accompanied by the strong SRS effect, which makes it difficult to evaluate and optimize the transport performance. The performance consistency of different wavelengths in the wider band needs to be guaranteed by special design. 4) The new band requires new components, such as the L-band coherent optical module (modulator, receiver, and ITLA), L-band OA, L-band WSS, C/L multiplexer/demultiplexer, and L-band OPM. Because the L6T band is wider than the traditional L one for a L-band OA, mainly an EDFA, the erbium fiber efficiency in the EDFA decreases more obviously than that in the C band, and is more sensitive to temperature. The gain of the long wavelength drops sharply, so a new doping process and EDFA design are needed to overcome this problem.

3. Key Technologies of LH 400G Optical Transport

The challenges to the multi-band introduction in Section 2.4 are mainly solved in the following ways: The problem of the discrete architecture in the 1) will be overcome through continuous architecture upgrade and evolution. For example, if the C+L integrated architecture is used, all wavelengths can be supported by a broad-spectrum optical module, OA, and WSS. The external interfaces of the system still keep the same integrated adding/dropping, scheduling and cross-connection as the traditional C-band, which will be discussed in the transport system architecture in Section 3.2.2. For the problem caused by the SRS in the 2), the fill-wavelength technology and the automatic optical power optimization algorithm (APO) are used to manage the optical power of the C+L system so as to ensure fast debugging and reliable recovery, corresponding to Section 3.2.1 and 3.2.3. The problems of difficult system performance evaluation in the 3) will be reflected and solved in Section 3.2.4. The capabilities and progress of the L-band optical components in the 4) will be described in Section 3.2.1. To meet the above challenges, it is required to fundamentally master the key technologies of LH 400G optical transport, such as high-speed coherent optical modules (including DSP algorithm and optical components), and C+L-band system architecture (including key optical path components, fill-wavelength and OXC solutions, and optical power management and performance evaluation algorithms).

3.1. High-Speed Coherent Optical Module

The coherent optical module is the core of the LH transport OTN system, so its function and features determine the transport capability of the system. To ensure transport performance, the 400G LH coherent optical module should have the following capabilities: a) The highest baud rate is 130Gbd or higher, and has multiple levels or even is continuously adjustable. b) Line rates and modulation patterns are adjustable, including common modulation modes such as 200G QPSK, 400G 16QAM, 400G PS16QAM, 400G QPSK, 800G PS16QAM, and 800G 16QAM. c) The output optical power of the module is at least -9dBm, and the working band covers the extended C (C6T) band and L (L6T). d) The back-to-back OSNR tolerance of the 400G QPSK is at least 1dB better than the current 90Gbd scheme. These performance and features are guaranteed by advanced DSP algorithms, chips, and high-speed coherent optical components.

3.1.1. Advanced DSP and Algorithm

A coherent DSP is composed of a hard IP and a soft IP. The soft IP includes algorithms such as forward error correction (FEC), coherent modulation and demodulation, and constellation shaping, and integrates the Framer function. The hard IP includes DA/AD and high-speed SERDES. For the 130Gbd system, the sampling rate of DA/AD is up to 170Gsa/s. The multi-channel multiplexing or time interleaving technology architecture needs to be used to improve the bandwidth, and the 5nm CMOS process to reduce power consumption. A maximum of 16 channels of SERDES are required, among which at least 12 ones support 106/112G PAM4.

Obviously, the coherent DSP technology is the core of coherent optical modules and even the OTN system. To effectively focus on applications, the DSP is divided into two types: high performance and low power consumption. A low-power-consumption DSP integrates standard FEC, simplifies balancing algorithms for line-side interconnection and interworking, and deals with network-layer applications that are sensitive to integration and power consumption more effectively. The MAN is its main application scenario. The high-performance DSP can cover all applications from the perspective of performance. However, due to its large size, high power consumption, and high cost, it is mainly applied to ultra-long trunks and large-capacity short-haul scenarios.

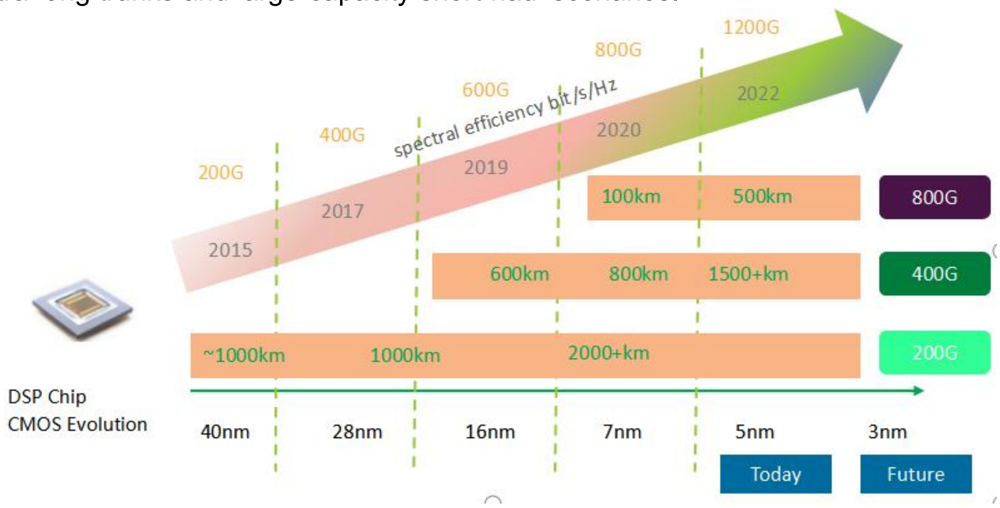


Figure 3.1. Technology Evolution of Coherent DSP

As shown in Figure 3.1, with progress of the CMOS technology, the performance, power consumption and volume of each generation of DSPs are continuously improved, which not only increases the highest operating rate of an optical module and prolongs the transmission distance of an 400G/800G signal, but also dramatically increases the quantity of logic gates that regardless of the limit of a unit area and power consumption as a transistor size decreases, so that some innovative and relatively complex DSP algorithms can be quickly applied. Two typical applications are the hybrid modulation (TDHM) and the probability constellation shaping (PCS). After used for 16nm/7nm coherent DSPs in recent years, they greatly improve the flexibility of an optical module/optical system configuration, and the code pattern and baud rate may be optimized to satisfy the requirements for back-to-back tolerance, ROADM pass-through and transmission distance in different scenarios. For 5nm and 3nm DSPs, some more advanced algorithms such as high-performance private FEC (LDPC, TPC, MLC, etc.), high-dimensional/code modulation, ultra-Nyquist technology (FTN), multi-electronic carrier (DSCM), non-linear compensation algorithms, and neural network algorithms is likely to be gradually employed in high-performance DSPs to further improve 400G/800G transport performance.

By virtue of its excellent supply chain management and technological innovation capabilities, ZTE makes full use of advanced DSPs, from 28nm and 16nm to 7nm and 5nm, to grow together with upstream and downstream partners in the industry, continuously reducing the power consumption of modules, boards and devices to make optical transport faster, more intensive and greener. The 130Gbd 400G LH optical transport solution to be launched will adopt the industry-leading 5nm process. Compared with the industry's average, it improves the performance by 40% and reduces power consumption by 30%. It continuously practices the industry's development ideas of speed increase and price reduction and green dual-carbon. The core capabilities of in-house chips are also continuously enhanced. 100G chips have been successfully verified. 400G chips are being developed, and 800G chips and algorithms are being pre-researched. Oriented to the future, the application of super-strong DSP algorithm, 3nm process, and in-house chip capability will bring greater improvement and differentiated competition points to the high-speed optical system, which is worth expecting.

3.1.2. High-Speed Coherent Optical Components

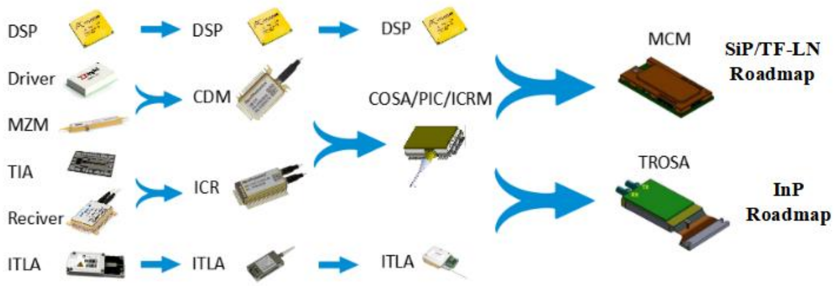


Figure 3.2. Technology Evolution of Coherent Optical Components

As coherent optical modules develop towards miniaturization and low power consumption, coherent optical components must be more integrated. As shown in Figure 2, two technical routes are currently used to continuously facilitate miniaturization and integration of components. One is the silicon photonics technology, which encapsulates modulation, receiving, and driving into the ICRM, and even DSP die into the MCM. In this way, optical transceiving modules can be formed only by adding external light sources and amplification. The MCM Packaging not only makes the device miniaturized, but also shortens the high-speed signal wiring and increases the component bandwidth by more than 10%, which compensates for the bandwidth upper limit of the SiP technology while cutting the Packaging cost. The 64Gbd silicon photonics MCM has been widely put into commercial use, and the 130Gbd MCM will be mature soon and is estimated to be commercially available within 1-2 years. When the baud rate continuously rises to 192Gbd or even 256Gbd, the problem of insufficient SiP modulation bandwidth is expected to be exposed. The transmitting end needs to use the TF-LN technology. Currently, there are some TF-LN-based modulation chips or CDM samples with a bandwidth of up to 110GHz, demonstrating the great application potential. The material properties also show that the TF-LN is not only partially compatible with the SiP process, but also expected to continue non-air-tight Packaging, further increasing its commercial opportunities. The other is the InP technology, which adopts III-V compound materials for modulation and receiving components. It takes advantage of the on-chip integration of the active component, and makes it easier to enable light sources and SOA amplification than the SiP. Therefore, the TROSA that integrates ITLA + modulation and receiving can be finally offered, and the coherent transceiving function can be implemented together with the external chip. Theoretically, the bandwidth of the InP modulator is higher than that of the SiP, the output optical power of the module is higher, and the transport capability is stronger. However, in the 400G era, especially when the 130Gbd is available, the performance of the module depends not only on the component bandwidth, but also on the compensation and cooperation of the DSP algorithm. It is also very important to design and optimize the coordination between the optical component and the electrical chip. This accelerates the vertical integration of the optical chip, components, electrical chip, and DSP industry chain.

ZTE released the 400G pluggable coherent optical module based on MCM and TROSA in 2021, which supports the compact CFP2 Packaging. The coherent optical modules for the 130G baud rate will also continue exploring the two mainstream technologies of SiP MCM and InP, and optimize performance, power, and costs. The application of the new TF-LN material system, processing platform, and advanced Packaging technology can improve the component bandwidth and reduce the component size and cost. It is widely used in LH 400G and future B400G optical transport systems, and ZTE and its industry partners is actively promoting its R&D.

3.2. C+L-Band Optical System

The demand for single-wavelength rate rise and capacity multiplication has forced the optical system bandwidth to expand, which has become an industry consensus. Since the 200G LH solution has been put into commercial use, the traditional C-band bandwidth has to be extended from 4.8THz to C++-band 6THz. In the Real 400G era (QPSK), the C6T band is no longer enough to multiply the capacity of a single fiber (remaining 80 wavelengths), and there is a need to extend the spectrum resources to the C+L band. First, C6T and C+L-band systems can be compared on the whole. As shown in Table 3.1, they are obviously different in both system architecture and transport capability. Key technologies of the C+L system are described in detail subsequently, such as L-band wavelength allocation, optical component maturity, transport system architecture, power management algorithm, and transport performance evaluation.

Table 3.1. Comparison Analysis of Extended C-Band and C+L-Band Systems

Comparison item	C6T band	C+L band
Available optical spectrum bandwidth	6THz	12THz
Transport performance (compared with C4.8T system)	Performance degradation is 0.5dB~1dB. After optimization, the degradation is expected to be lower than 0.5dB.	After optimization, performance degradation is expected to be around 1.5dB.
Optical layer architecture	1	It is possible to be made into one set according to the device form.
Optical transceiver	1	Two sets, supporting band C and L respectively. It is expected to evolve to one set of C+L system in the long term.
O&M Complexity	Equivalent to the C4.8T	Slightly more complicated than the C4.8T

3.2.1. L-Band Wavelength Allocation

The working wavelength range is a problem that must be solved preferentially in the optical system. Otherwise, the supply chain will be distributed and the R&D cost will go up. In terms of the wavelength range of the extended band, the wavelength range of the C6T band has been unified in the industry: The edge wavelength range is 1524.3nm-1572.27nm, as shown in Figure 3.3. The wavelength range of the L band is still under planning and discussion. The international tendency is the extension to C4.8T+L4.8T. In China, the L4.8THz bandwidth is not enough, and the C6T is overlapped, so it is expected to extend the L-band on the basis of the C6T. At present, the L-band 5THz technology has basically matured, but the bandwidth is still inefficient to the LH 400G application, so it is expected to further extend to the L-band 6THz. The main controversy over the L-band 6THz lies in whether the protection interval between C6T and L6T is 2.9nm or 2.1nm, that is, Type I or Type II in Figure 3.3. Considering the supply chain situation in the industry and the crosstalk between C and L bands to be compressed as much as possible, the industry prefers to converge the wavelength range of the extended L band to 1576.16nm to 1626.43nm, that is, the Type I solution.

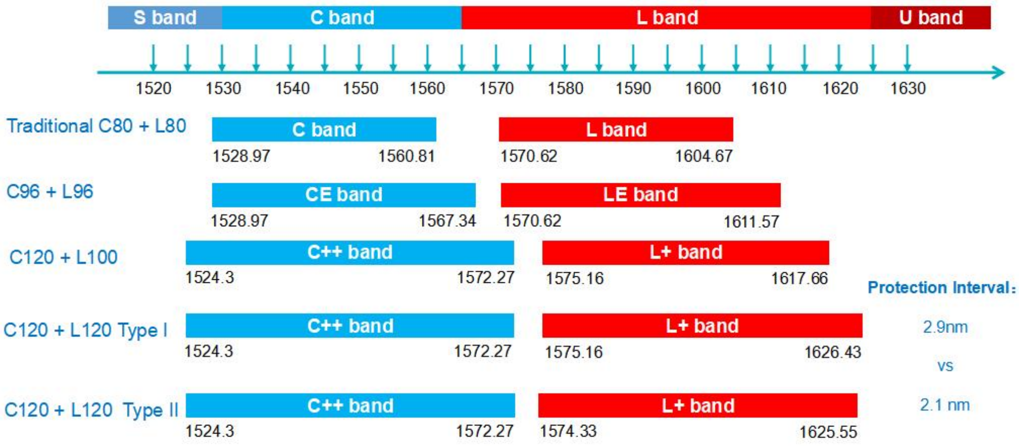


Figure 3.3 Extended Spectrum Wavelength Range of the WDM System

3.2.2. L-Band Optical Components

To commercialize the band extension technology, the industry is actively promoting the evolution from C4T to C6T+L6T. Table 3.2 shows the development of the C6T and L6T industry chains. The L6T optoelectronic components and assemblies basically have samples. The main difficulty lies in the optimization of the gain and noise coefficient of the L6T-band EDFA. The 400G C6T +L6T system will start the commercial use at the end of 2023. This will lay a solid foundation for the application of LH single-wavelength 400G and metro single-wavelength 800Gb/s and higher-rate transport systems.

Table 3.2. Industrial Chain Progress of Key Components of the C+L-Band WDM System

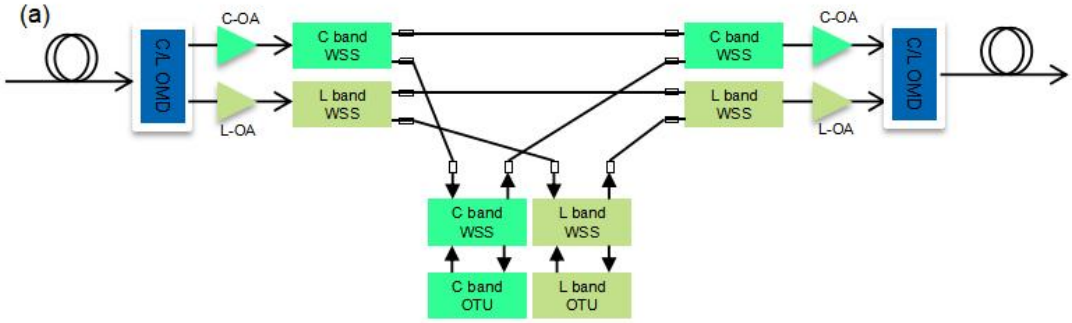
	C6T	L6T	Technical Difficulties
ITLA	Already commercially available	The sample is available.	Redesign the gain area and frequency-selective optical cavity.
Optical modulation receiver	Basically the same as C4T	Basically the same as C6T	Pay attention to the correlation between the offset point and the response wavelength.
oDSP	Same as C4T	Almost the same as C6T	The dispersion of band L is slightly large, and the components at different bands are different in compensation.
EDFA	Already commercially available	L5T products are produced, L6T samples are available, whose performance is being optimized.	Optimize the erbium fiber doping ratio to improve the gain bandwidth, improve saturated power and noise figure, and control the dimensions and power consumption of the EDFA module.

DRA	Already commercially available	Add a long-wavelength pump laser	Resolve the wavelength conflict with the OTDR.
WSS	Already commercially available	Samples are available, and the technical difficulty is low. The C+L 10THz is productized.	Change the design of diffraction gratings and spatial optical paths, and design high-isolation ports.
AWG	Already commercially available	The difficulty is low, and the technology is ready.	None
OPM	Already commercially available	The difficulty is low, and the technology is ready.	None
OTDR/OSC	Same as C4T	The difficulty is low, and the technology is ready. The wavelength is to be determined.	None

3.2.3. C+L Optical Transport System Architecture

To overcome the challenges brought by band extension, the C+L optical transport system requires a new architecture, power management algorithms, and performance evaluation methods. The system architecture is obviously a key. Theoretically, the C+L system is divided into two categories: discrete and integrated, as shown in the following figure. The discrete architecture means that signals at C and L bands are generated, amplified, and routed independently. The integrated architecture is divided into two types according to whether the OA supports C+L wide spectrum amplification. One is that OA is independent and WSS and OTU are integrated, and the other is a fully integrated architecture including OAs. Obviously, the latter is ideal, and its deployment and O&M are almost the same as those of the traditional C band. The equipment cost and integration are expected to be greatly improved. However, the feasibility and deployment time depend on the maturity and commercialization time of key components.

(a)



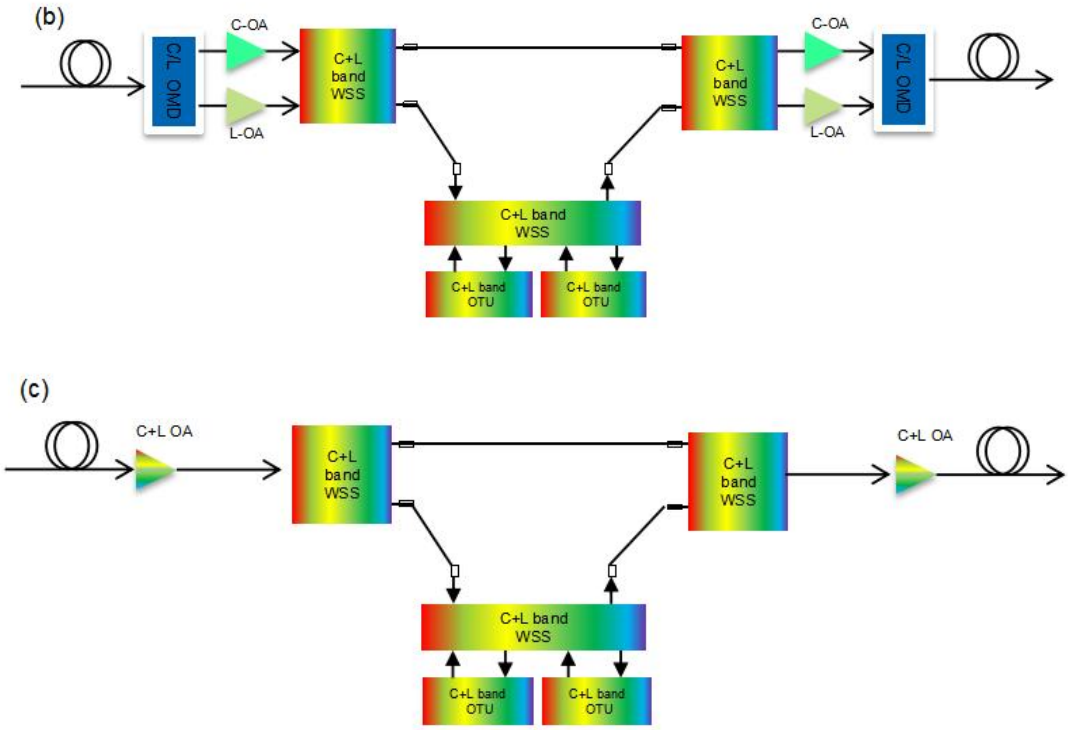


Figure 3.4. C+L Optical Transport System Architecture: (a) Discrete, (b) Integrated-Discrete OA, (c) Integrated-Wide-Spectrum OA

Table 3.3. summarizes the comparison of different aspects of the three system architectures. Currently, the discrete C+L system architecture is the most mature, and will be able to be put into commercial use for the earliest time. It can also support the smooth evolution from C to C+L in the existing network (through the reconstruction of a few sites). However, the main problem lies in the low integration and high cost of THE equipment. Basically, one set of C device and one set of L device are needed, and the operation dimension is more complicated. Whether the integrated architecture with the discrete OA can be put into commercial use depends on the technical maturity and productization time of the integrated WSS and OTU. Theoretically, there are corresponding solutions for the WSS and OTU to work within 1524-1626nm. However, the product may face challenges in the implementation, for example, the integrated WSS requires higher-resolution LCoS chips as well as grating with larger dispersion capability. A wide spectrum ITLA may need two chips and an optical switch, which increases power consumption, volume and costs. Coherent optical devices can operate in a wide 100nm range and have material and design requirements. For example, if the silicon-optic/TF-LN technology is used, the MMI design should be noticed to reduce the wavelength correlation of device insertion loss. The integrated architecture with the wide-spectrum OA integrates C/L amplifiers on the basis of the integrated architecture with the discrete OA to further improve the integration. However, the technical challenges are also great. Although the C+L EDFA amplification technology has been researched in the academic field in recent years, the specific

technical routes are not clear, so its performance competitiveness is not strong. Thanks to its outstanding advantages in transport performance, performance costs, wavelength route scheduling, O&M complexity, and equipment integration, the wide-spectrum OA has great technical challenges in the long term, but the fully integrated C+L system architecture is worth expecting.

Table 3.3. Comparison Between Different C+L System Architectures

	Discrete C+L	**Integrated - Discrete OA**	**Integrated - Wide-Spectrum OA**
Technical feasibility	High	Medium	Not clear temporarily
Maturity	High	Low	Relatively low
Core components	L6T OA	Integrated WSS and OTU	Integrated wide-spectrum OA
Transport performance	Medium	Medium	High
System cost	>2x C-band system	1.x C-band system	Equivalent to band C
Wavelength route	Independent configuration and scheduling of band C and L	Integrated scheduling of band C and L	Integrated scheduling of band C and L
O&M	Two optical layers, complex	Close to one optical layer, medium	The same as band C, simple
Slot occupation/integration	Two times C-band system, low	1.x C-band system, medium	The same as band C, high
Compatibility	Compatible with the existing C-band system	Not compatible	Not compatible

3.2.3.1. dummy light

The C+L system occupies the spectrum bandwidth of over 12THz. The problem of power transfer from short wavelengths to long wavelengths caused by the strong SRS effect in optical fibers cannot be ignored. Additionally, if dynamic wavelength adding/dropping and frequent increase/decrease of wavelength channels are considered in the C+L system, strong power/OSNR fluctuation is generated due to the fiber SRS effect on service signals, resulting in performance degradation and even service interruption. As shown in Figure 3.5, when the C+L is in a full configuration state, the OSNR in the system is shown by a blue line in the following figure in a stable state of a

5-span G.652 optical fiber transport (75km at each span) (It is assumed that C-band single-wavelength average power is ~6.5dBm and L-band single-wavelength average power ~4.8dBm, the noise coefficients of C and L-band EDFAs are both 6dB). When the minimum wavelengths of band C are reduced by 5 wavelengths, 10 wavelengths, and 15 wavelengths respectively, the OSNR degradation values at the maximum wavelengths of band L are respectively 1.7dB, 3.5dB, and 5.2dB, which obviously exceeds the system OSNR margin and may cause service interruption.

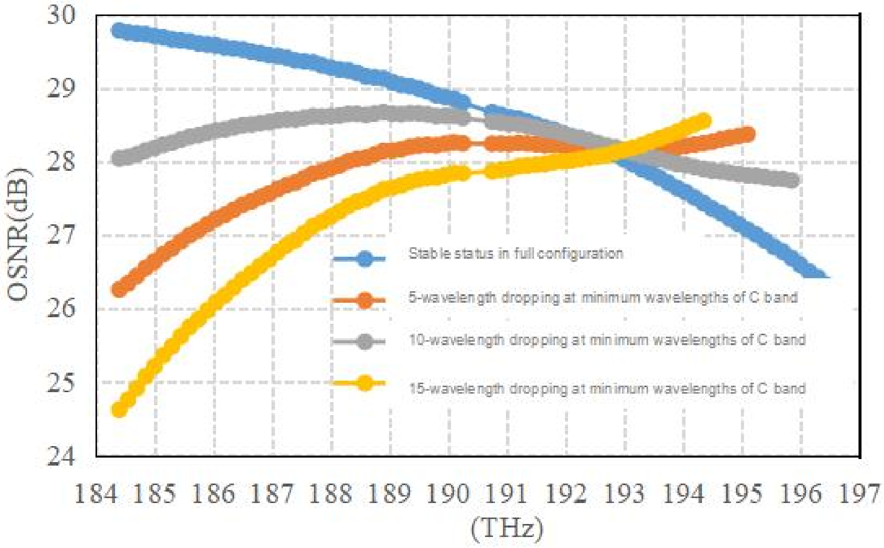


Figure 3.5. C Performance Verification in the C+L Wavelength Reduction Scenario

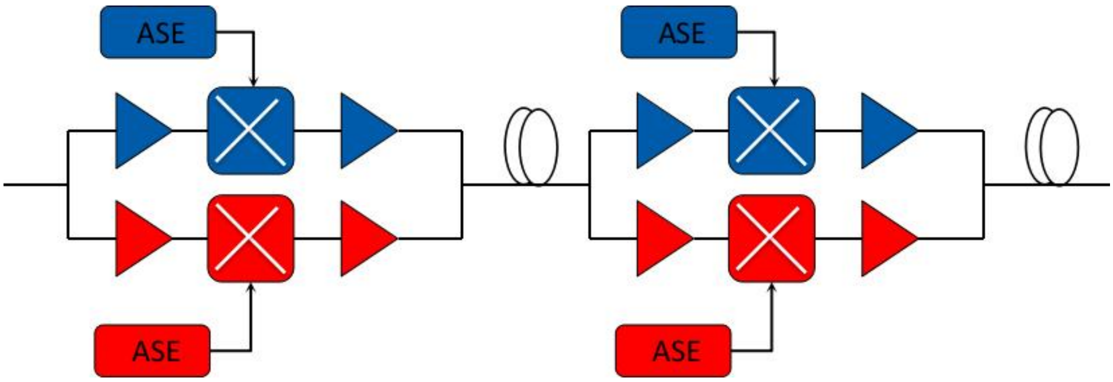


Figure 3.6. C+L dummy light

To overcome the above impact, theoretically the number and position of added and subtracted wavelengths can be automatically detected, the power slope change caused by SRS can be accurately calculated, and the OA gain and slope can be dynamically adjusted to balance the power and OSNR of each channel to avoid service loss. However, this imposes strict requirements on the OA configuration response speed, and may cause the system to be in dynamic adjustment status for a long time, thereby endangering system stability. As an alternative solution, the idea of “replacing true wavelengths with false ones” in the C+L system is proposed. That is, the dummy light channel is used as the false one to keep the system in full configuration status. In the commissioning, the system power in full configuration is adjusted to the target status through the power management algorithm. When a service wavelength channel is created or deleted, it is controlled only at the ROADM/OXC station to exchange the "true wavelength" and "false wavelength" for power stability and performance balance between wavelength channels. It avoids frequent power adjustment at MS and channels level during dynamic wavelength increase/decrease, so that the system can reach stability faster. It should be noted that the dummy light in the C+L system may be offered in different manners, such as, the wide-spectrum ASE noise generated by EDFAs or other types of OAs is used together with WSSs for wavelength channel modeling & cutting and wavelength selection (as shown in Figure 3.6), and the DC tunable laser or laser array filling is used as the dummy light. To introduce the dummy light in the C+L system, it is necessary to pay attention to its influence (crosstalk/nonlinearity) on the service channel performance, and adopt the corresponding solution to suppress it. In addition to keeping the system stable based on power balance and adjustment, the dummy light has other detection functions, for example, detecting the end-to-end optical layer performance of the link as an optical probe.

3.2.3.2. OXC

The introduction and control of the dummy light depends on the ROADM/OXC site whose function is critical. The traditional ROADM employs components such as WSS, OA, and Coupler/optical switch/OTDR/OPM, and its site can be flexibly constructed as required in the mode of building blocks. As the degrees rise, the number of connection fibers in the ROADM site increases rapidly, causing great pressure on provisioning and O&M. To settle the problem of the traditional ROADM, the OXC device emerges, which adopts the all-optical backplane for complicated internal fiber connections. Meanwhile, highly integrated boards combine multiple functions. One board represents one direction, and board insertion means fiber connection, greatly improving ease of use. Obviously, the C+L system generally needs to support large-capacity transport and cross-connection. As the cross-connection degrees are more than 20, so the OXC is indispensable. Due to component limitations, the current C+L OXC uses a discrete architecture, that is, C6T band and L6T band have a set of OXC devices/subracks respectively, and works with the OBM for C/L-band multiplexing and demultiplexing. See Figure 3.7. As the integrated WSS and integrated/miniaturized OA mature, one board may support C and L bands, namely, the C+L-band optical cross-connect function can be fulfilled in one OXC subrack to increase equipment integration.

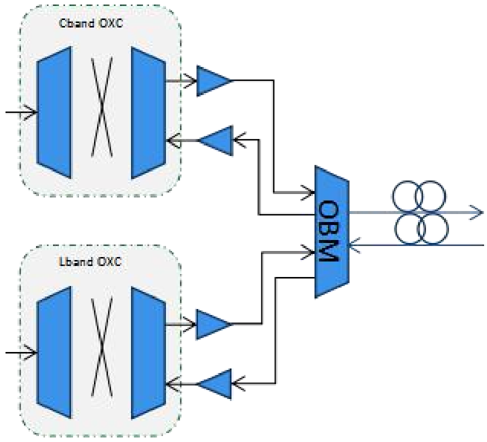


Figure 3.7. Existing Discrete C+L-Band OXC Device

3.2.4. C+L Optical Power Management

It has been mentioned many times that a strong SRS effect exists in a wide-spectrum C+L system (12THz), and optical power is significantly transferred from a short wavelength to a long one. And SRS transfer has an accumulative effect. After transport across multiple spans, the power at a short wavelength at a receiving end is much lower than that at a long wavelength, and OSNR flatness is remarkably degraded, which is difficult to meet system application. In particular, a short wavelength at a C band becomes a bottleneck of system performance. The following uses the power evolution simulation of a single OMS section (containing five G652 fiber spans) as an example. The system wavelength channel is configured to 80x150GHz. Assume that band C and L have the incident power of single-wavelength 5.5dBm, the fiber span loss is about 22dB, and the EDFA operates with the default gain and slope. The blue curve in Figure 3.8 shows the power distribution after one OMS. After being extended to the L6T band, the power distribution at the receiving end of the system is very uneven due to the strong SRS power transfer effect. 1) From the perspective of different bands, the power of band C is transferred to L, so the average power of band L is obviously higher than that of C. 2) From the perspective of one band, band C has a greater impact, whose power non-flatness is 18.5dB, and the power non-flatness of band L is about 3dB.

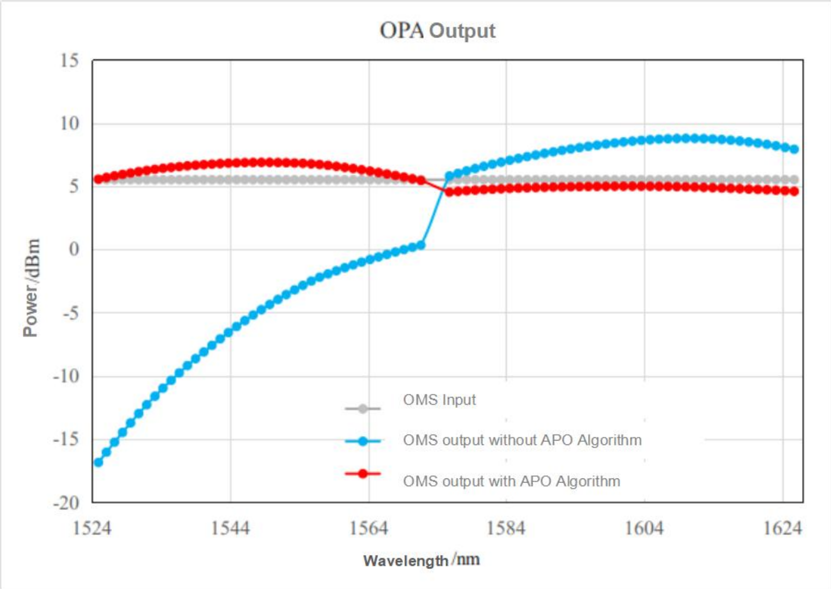


Figure 3.8. Power Distribution of C+L System after One OMS with and without Power Adjustment

Therefore, to suppress the SRS effect and balance the performance between wavelength channels, an intelligent power management algorithm is necessary. Based on the dummy light configuration and "true and false wavelength replacement" principles in the C+L system, the automatic power optimization (APO) algorithm is designed to ensure that the C+L system commissioning and debugging are faster and the steady-state performance is better. The APO algorithm contains:

OMS-level power adjustment: 1) Compensate the uneven power between bands, and iteratively adjust the OA gain of band C and L. 2) Compensate uneven power in the band, and iteratively adjust the OA slope of band C and L as well as channel-level power. 3) Compensate the residual uneven power, and adjusts the WSS channel attenuation of band C and L.

After the adjustment with the APO algorithm, the OMS output power is shown in the red curve in Figure 3.8. After the system power is effectively managed with the APO algorithm, the power flatness is greatly improved, the C-band power non-flatness is about 1.5dB, and the L-band power non-flatness is about 0.5dB.

3.2.5. 400G C+L Optical Transport Performance Evaluation and Comparison

This section is used to evaluate, analyze, and compare the transport performance of PS16QAM and QPSK with different channel intervals and spectrum widths in the C+L system. The transport performance evaluation principles are as follows:

Non-linear cost principle: Optimize the maximum transmission distance of the incident power of a single wavelength at each band when the OSNR margin and the 1dB non-linear cost are met.

Margin principle: Net margin = average OSNR - non-flatness - non-linear cost - filtering cost. The net margin should be greater than 2dB, and the power between band C and L is optimized to make the net margin of band C basically equal to that of band L after transport.

It can be learned that performance evaluation in the single-wavelength 400G C+L-band optical transport system mainly includes evaluation of non-linear costs of different code patterns, link average OSNR evaluation, OSNR non-flatness evaluation, filtering cost evaluation, and the like. The link average OSNR evaluation, OSNR non-flatness evaluation, filtering cost evaluation are similar to those of the C-band system. When calculating the link OSNR, pay attention to the L-band OA noise factor, gain fluctuation, and the additional loss of the C+L system caused by the SRS effect under different actual incident optical powers. The difference from the C+L-band nonlinear cost evaluation lies in two points. First, considering the probabilistic shaping and the modulation pattern of multiple electronic carriers, the PAPR-related coefficient and the integral range of nonlinear interference terms in the EGN model need to be reconstructed. Second, the equivalent attenuation coefficient and effective distance of each channel are calculated based on the influence of the SRS in the C+L wide-spectrum system. A series of papers have been published in the CIOP meeting for theoretical analysis and experimental verification. The non-linear cost estimation precision of the 400G and 800G C+L system is better than 0.3dB.

Under the guidance of the above evaluation principles and methods, the simulation is employed to evaluate the transmission distance limit that can be reached actually for 400G transport solutions with different code patterns and baud rates at different spectrum widths and channel intervals. In the simulation, the basic parameter settings are as follows. The back-to-back OSNR tolerance of each code pattern is the typical value of the actual module. The EDFA noise coefficient (NF) of the C6T band is equivalent to that of the C4.8T band. The EDFA NF of the L6T band deteriorates by 1.6dB than the C6T NF and by 0.9dB than the L4.8T. Each multiplexing section (OMS) includes 5-7 fiber spans. The optical fiber is the conventional G652 one. Each span is 75km, and the loss is 22dB. During the evaluation, the EDFA gain non-flatness feature and the actual automatic power equalization adjustment algorithm are considered, that is, APO. For the C6T band, only gain adjustment is considered. For the C+L system, both gain and gain slope adjustment are considered.

Table 3.4. Transport Performance Comparison Between Different 400G Technical Solutions

Modulation format	Channel quantity	Channel interval (GHz)	System band	Best incident optical power / lambda (C/L) (dBm)	Maximum transmission distance G652 optical fiber (km)	Single-fiber capacity (Tb/s)
64Gbd QPSK	80	75	C6T	3.5	34*75=2550	16
128Gbd QPSK	40	150	C6T	5.8	37*75=2775	16
128Gbd QPSK	80	150	C6T+L6T	6.6/4.2	24*75=1800	32
107Gbd PS16QAM	80	125	C5T+L5T	5.2/3.4	19*75=1425	32
95Gbd PS16QAM	80	112.5	C4.8T+L4.8T	5.1/3.6	17*75=1275	32
91.6Gbd PS16QAM	120	100	C6T+L6T	5.5/2.3	11*75=825	48

Note: The 64Gbd QPSK is a single-wavelength 200G one, which is used as a comparison reference here.

For the transport performance simulation results of different 400G technical solutions, refer to Table 3.4. The C6T-band 200G QPSK solution is used as the reference for comparison. The following conclusions can be drawn:

1. Compared with the 200G QPSK, the C6T-band single-wavelength 400G QPSK solution improve the transport capability by about 10% because of lower filter cost.
2. Compared with the C6T band, the C6T +L6T system reduces the transmission distance by around 37% mainly because the SRS affects the short-wavelength OSNR of the C band.
3. As G652 fibers and EDFA amplify the actual fiber link, the 400G QPSK working with C6T+L6T is the best solution for 1500+km LH transport and the only one. Compared with the 95Gbd PS16QAM, the C4.8T+L4.8T system with a 112.5GHz interval increases the transmission distance by about 40%. Compared with the 107Gbd PS16QAM, the system with a 125GHz interval increases the transmission distance by about 26%.
4. Together with the 100GHz-interval C6T+L6T optical system, the 91.6Gbd PS16QAM has higher spectral efficiency and can be used as a cost-effective solution for 400G metro transport. The capacity can be increased by 50%, but the filtering cost may limit the number of ROADM pass-through sites.

4. Technical Progress and Application Suggestions on LH 400G

4.1. 400G Related Standards and Industry Chain Progress

International standards related to 400G and beyond coherent optical modules and transport systems are jointly formulated by standards organizations such as ITU-T, IEEE 802.3, and OIF, along with the multi-source agreement (MSA) organization initiated by 800G Pluggable MSA, IPEC, OpenROADM, Open ZR and other vendors. Single-wavelength 400G and 800G optical modules are currently hot research topics in R&D and standardization in the industry. The standardization of high-speed optical transport modules and systems in China is mainly carried out by the China Communications Standards Association (CCSA) Transport Network and Access Network Task Committee (TC6). Most industry standards are based on foreign advanced standards and domestic application requirements. Their overall development speed is basically the same as that of international standards ([10,11]).

In terms of 400G short-haul applications, OIF released the 400ZR implementation protocol as early as March 2020 to define two application scenarios: one is the single-wavelength OA-free point-to-point power budget restriction system with a transmission distance of less than 40km, and the other is the DWDM OA-based point-to-point OSNR restriction system with a transmission distance of less than 120km. This standard specifies the optical layer interworking parameters like DP-16QAM modulation pattern, CFEC with 14.8% overhead and frame structure. IEEE 802.3cw is also developing the 80km DWDM 400Gbit/s standard. The main technical solution is the same as the OIF 400ZR. It is estimated that the parameter of 75GHz channel spacing will be added. On this basis, multiple MSAs in the industry release 400G-related technical standards one after another, such as the 100-400Gbit/s coherent optical module specifications by the OpenROADM/OpenZR+. On the basis of the 400ZR frame structure, modulation modes such as 100/200Gbit/s QPSK and 300Gbit/s 8QAM are added, and oFEC is used to replace CFEC. The optical module can support CFP2-DCO and QSFP-DD/OSFP Packaging, and the transmission distance covers 450km-level metro 400Gbit/s applications. The 15th research group of ITU (ITU-T SG15) researched the physical layer specifications of the 200Gbit/s/400Gbit/s interface to take the 16QAM as the standard code pattern of the 400Gbit/s MAN applications, and promoted the standardization process of the open forward error correction (oFEC) code. For higher single-wavelength rates, the OIF is now discussing the 800G ZR specification, which uses the DP-16QAM pattern, OFEC codes, and 150GHz channel spacing for 80-120km single-span OA-based DWDM links, and even the fixed wavelength coherent solution for shorter 10km 800G interconnection scenarios. The IEEE 802.3 B400G Study Group also followed a warm discussion of the 800G LR/ER standard based on coherent technology.

In China, the formulation of CCSA-related standards includes: The formulation of optical transport and module standards at the rate of 100Gbit/s and below has been completed. The 200Gbit/s draft is submitted for approval to select the 200Gbit/s QPSK, 8QAM and 16QAM. The 400Gbit/s MAN standard essentially adopts the single-wavelength 200Gbit/s dual-carrier solution. Research on standards for higher rate applications such as Technical Requirements for N× 400Gbit/s LH Enhanced Optical Wavelength Division Multiplexing (WDM) System is underway. In terms of band extension, the draft of the extended C-band (C6T) CCSA industry standard has been submitted for review. The 96Gbd PS16QAM is added as an optional solution for the application scenarios within 400G 1000km in the appendix. The topics related to C+L, single-wavelength beyond-400G, and enhanced Nx400G LH transport are under research. It is expected that the industry standard will be initiated within 1-2 years, and new rates and patterns such as 128 Gbd 400G QPSK, 800G 16QAM will be added, followed by the C+L wide-band specifications. On the whole, 400GZR, ZR+ and MAN standards for short-haul interconnection have been released and applied. 400G LH and 800G ZR/ZR+ are still under further research and discussion. And it should be noted that in the future single-wavelength beyond-400G era, there is an obvious trend for the coherent technology to move down to 10km and shorter-haul applications.

In terms of industrial development, all major equipment vendors can deliver 96Gbd 400G PS16QAM and 800G PS64QAM transport capabilities. The 400G C6T and L6T system are commercial available.At the end of 2023, 400G QPSK will be commercially available and compatible with 96Gbd PS16QAM. As the core of the optical system, the OA and wavelength selective switch (WSS) are most critical. The C6T EDFA and WSS have been put into large-scale commercial use, and the bandwidth is 6THz. The L-band 6THz EDFA is also being developed. However, due to the amplification efficiency of erbium fibers at long wavelengths, the noise index of the L-band EDFA is worse than that of the C-band one by 0.5dB, and the module cost and size are larger. The WSS that supports L-band 6THz and even C+L 10THz has been put into commercial use. The next step is to overcome the technical difficulties of the C+L 12THz WSS.

The current situation and standard progress of these industries indicate that the era of 400G and even beyond-400G optical transport is accelerating. High-speed coherent optical modules and new broad-spectrum optical components will continuously improve 400G and beyond LH transport capabilities and boost industrial progress.

4.2. Pilot and Verification of Single-Wavelength 400G LH Transport

In the 400G LH transport field, ZTE has always maintained in-depth cooperation with domestic and overseas operators, and achieved remarkable results. As early as in 2019, by virtue of the industry-leading modulation, powerful FEC algorithm, advanced high-performance DSPs, and unique optical domain equalization, ZTE supports the longest-distance transmission and the most code patterns in China Mobile's existing network test. For the first time, ZTE devices transmit 16QAM, 64QAM, and other single-carrier 400G OTN services in a trunk, with a transmission capacity of 32T. The transmission distance in the existing network exceeded 600km, setting a record for the farthest transmission distance in the existing 400G network in the industry. And they support differentiated rates and code patterns such as 100Gb/s QPSK, 200Gb/s 16QAM, 400Gb/s 16QAM, and 400Gb/s 64QAM, and offers diversified technical solutions for various application scenarios.

In 2021, ZTE and China Mobile Liaoning jointly piloted the industry's first C+L single-wavelength 400G LH 1000km transport in the existing network. As shown in Figure 4.1(a), the Shenyang-Dalian 1300km transport path which selected uses the PS16QAM for large-capacity 400G LH existing network transport without electrical regenerators. The system bandwidth is 11THz, the transmission capacity 32T, and the potential capacity 44T, which highlight the technical progress of ZTE in large bandwidth and LH transport. This innovative application marks that the 400G LH transport solution is being accelerated and perfected. In the same year, ZTE cooperated with China Telecom to actively promote the test of 400G on the existing network. As Figure 4.1(b) shows, the single-wavelength 400G WDM transport is tested on China’s first all-654E terrestrial trunk optical cable in the existing network between Shanghai and Guangzhou, without regenerators transmission distance of over 1,900km. The test results of the existing network show that the G.654E can improve the system OSNR by 3.5dB than the G.652D, which reduces the number of electrical regenerators, saves energy, and provides strong support for the growth and evolution of the single-wavelength beyond-400G high-speed transport system in the future.

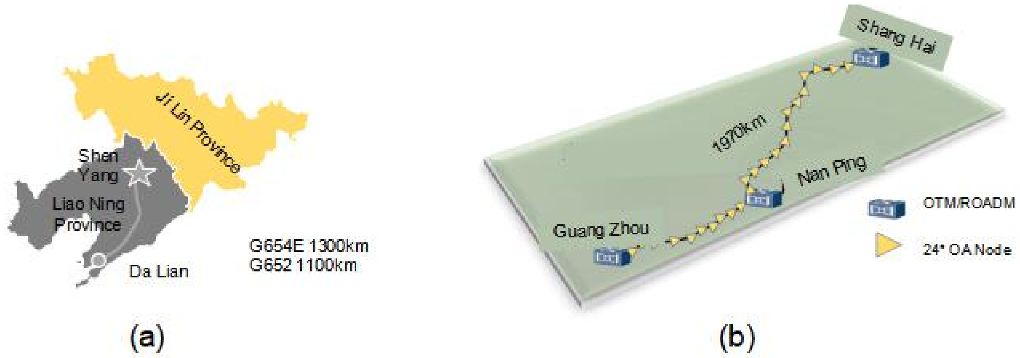
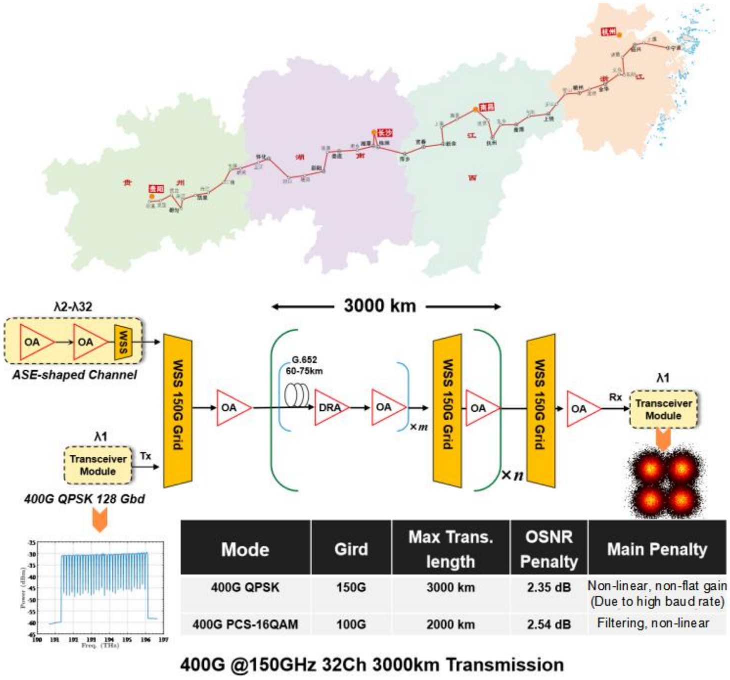


Figure 4.1. 400G Transport Path in the Existing Network: (a) Dalian – Shenyang Path of China Mobile; (b) Guangzhou – Shanghai Path of China Telecom

In 2022, based on 96Gbd PS16QAM and C+L 11THz optical systems, ZTE and China Unicom jointly completed multiple application model research tests of single-wavelength 400G C+L optical transport in the laboratory, laying a foundation for large-scale commercial deployment of 400G and enhancing industry confidence. With the booming development of the digital economy and the initiation of the national "East-to-West Computing Resource Transfer" project, China's computing network infrastructure construction has fully started. Optical networks are the cornerstone of the digital computing era, so broadband-based optical networks have become a consensus of the entire industry, and it is imperative for operators to upgrade their backbone networks to 400G. In July 2022, ZTE worked with China Mobile to simulate the fiber length, loss, and maintenance margin of the existing network in the laboratory, and used a quasi-real-time prototype for 400G QPSK transport verification. The verification result shows that the 128Gbd 400G QPSK optical module encapsulated with the 2.5D/3D optical/electrical chip has a transmission distance of 2018km in the EDFA amplified link due to better back-to-back OSNR tolerance and higher incident optical power. And a new PID gain control algorithm is used to reduce the fluctuation of the system OSNR, and a hybrid Raman amplification technology is adopted on some spans. As shown in Figure 4.2, a 49-span 3038km transmission distance without electrical regeneration in a G.652.D optical fiber can help China Mobile with ULH transport of massive large-bandwidth services, boost its optical network growth, and set a basis for the development of a global digital and intelligent optical network. This project is the world's first 400G QPSK quasi-existing network transport verification, which is of great significance to the entire optical network transport field. It provides an important technical basis for the selection of 400G LH application modulation systems, and proves that the 400G QPSK technology is the best choice for the LH transport of the next-generation backbone network. Overseas, ZTE helps Turkey Turkcell deploy the world's first commercial 12THz ultra-wide-spectrum wavelength division system, offering a powerful OTN platform based on the 1T backplane bandwidth and significantly increasing network transport capacity. Additionally, ZTE presets a C+L-band coupler in the MAN WDM network to support Turkcell's rapid and smooth evolution to multiple bands. Compared with the standard 80-wavelength C-band, the C+L-band coupler can increase system capacity by twice, fully meeting the bandwidth requirements of the future data network. The ultra-large-capacity and ultra-wide-spectrum optical transport system solution will soon usher in the commercial use of 400G and C+L systems.



Mode	Gird	Max Trans. length	OSNR Penalty	Main Penalty
400G QPSK	150G	3000 km	2.35 dB	Non-linear, non-flat gain (Due to high baud rate)
400G PCS-16QAM	100G	2000 km	2.54 dB	Filtering, non-linear

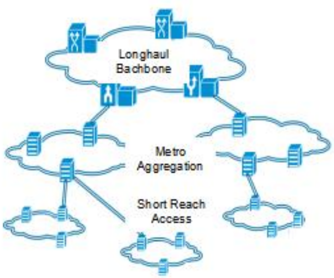
Figure 4.2. 400G QPSK Simulation Verification System in the Lab

To further verify the actual transport performance of the single-wavelength 400G QPSK OTU, ZTE and China Mobile jointly verified the single-wavelength 400G real-time transport in the existing network based on the transport equipment of the commercial system on the Ningbo-Guiyang LH optical network. The network environment includes 45 segments of optical fibers, with the average design loss of 22dB and the unidirectional transmission distance of 2800km. Thanks to the super-strong 5nm DSP and the unique flexshaping 2.0 algorithm family, the existing allows unidirectional 2800km error-free transport on the G652 optical fiber C-band 6THz spectrum, and the OSNR margin is greater than 3dB. To further compress the system margin and challenge the transmission distance limit, the broadband DRA low-noise amplification technology is used to improve link OSNRs and the self-adaptive compensation algorithm to enhance the anti-non-linear impairment capability for 5600km ULH error-free transport. This is the first real-time transport test of the real 400G solution based on the 120+Gbd commercial chip in the industry. The verification result of the existing network not only proves that the 400G QPSK industry chain is gradually mature, but also shows that the QPSK has better transport performance than the PS-16QAM. Undoubtedly, the ultimate transport capability of the 400G QPSK is more suitable for constructing the all-optical base of the computing network with long distance, large capacity, high rate, and low latency.

In addition, ZTE has made good progress in single-wavelength 800G large-capacity and LH real-time transport, coherent DSP algorithm design, optimization, and FPGA verification. Based on the 95Gbd PS64QAM technology, ZTE works with China Telecom for single-wavelength 800G C+L-band G652 optical fiber EDFA amplified link 300km transport in the implementation room, and sets a record of single-fiber real-time transmission capacity 88T. ZTE also joins hands with China Mobile to successfully demonstrate that 800G WDM signals are transmitted on G654E DRA amplified links over 2000km, breaking LH transport records. For the first time in the industry, 140Gbd coherent optical devices are used to enable the quasi-real-time transport on G652 EDFA amplified links over 1050km. These experiments and pilot studies show that the 130Gbd QPSK is the best and the only choice for LH 400G trunk transport. It can utilize the existing G652 optical fiber resources and EDFA sites, and only needs to cooperate with the deployment of L-band equipment and power management algorithm. For single-wavelength 800G LH transport, the 130Gbd 16QAM needs to use the new low-loss large-effective-area G654E optical fiber, low-noise amplification technology, or cross-span loss reduction for 1500km or longer trunk transport.

As a leader in the field of 100G/beyond-100G innovative technologies, ZTE has always been committed to the research of cutting-edge technologies, and has a profound technological accumulation in beyond-100G transport. Over the years, ZTE has published a large number of documents related to beyond-100G in core international journals, and has repeatedly refreshed beyond-100G transport records, contributing to the development of optical network technologies. In the future, ZTE will continue to carry out building stronger core competence, explore optical network technology research and practices, and work with global operators to build digital and intelligent optical networks and promote new development of digital and intelligent economy.

4.3. Typical Application Scenario Analysis and Suggestions



Baud Rate	Modulation Format	Single-wave rate	Channel spacing	Application Scenario
64 Gbd	16QAM	400G	75 GHz	Metro & DCI
90 Gbd	PS16QAM		100 GHz	Metro
130 Gbd	QPSK		150 GHz	Longhaul
90 Gbd	PS64QAM	800G	100 GHz	Short-Reach DCI
130Gbd	PS/16QAM		150 GHz	Metro
130Gbd	PS64QAM	1.2T	150 GHz	Short-Reach DCI

Figure 4.3. 400G and Higher-Speed Optical Transport Modulation Formats and Application

Based on the above analysis and judgment, the transport capabilities and application scenarios of different 400G modulation technologies can be summarized as follows:

For 400G short-haul DCIs, the 64Gbd 16QAM pluggable CFP2 optical module is recommended, which works with the C4.8T or C6T band for 64-/80-wavelength configuration. The 400G metro adopts two technologies. 1) The 64Gbd 16QAM CFP2 optical modules is recommended for a low-performance scenario (less than 600km). The C6T band system can contain 80 wavelengths at a spacing of 75GHz. 2) The 90Gbd PS16QAM MSA or CFP2 optical module is recommended for a high-performance scenario (600 – 1000km). The C6T band can be configured with 60 wavelengths at 100GHz intervals, and the C+L 12THz 120 ones. The 130Gbd QPSK is preferred for a 400G LH trunk transport scenario (1000 – 1500km). Together with the C+L 12THz, it allows 80 wavelengths and 32T capacity. Some new G654E links can also be configured with a maximum of 120-wavelength 90Gbd PS16QAM to raise the spectrum efficiency and cut the cost per bit. In addition, hybrid Raman amplification can also be used in the optical fiber section with large span loss to enhance transport performance.

Only the 90Gbd PS64QAM is now available for the 800G short-haul DCI. However, the current module is large in the MSA Packaging power consumption and size. It is estimated that the 130G CFP2 optical module will mature for commercial use in one or two years. At that time, the 130Gbd 16QAM or 90Gbd PS64QAM can be employed. The 130Gbd PS/16QAM is an appropriate solution for 800G metro <600km transport scenarios, and works with the C+L 12THz for full 80-wavelength configuration. In 600~1000km transport scenarios, the 130Gbd PS/16QAM needs to be used together with new G654E fibers and low-noise Raman OAs. For 800G LH trunk transport, it is recommended that new G654E optical fibers be used to shorten the inter-site distance to control the cross-span loss within 20dB. The 130Gbd can be used to upgrade the 800G. In the future, the 180Gbd or even 256Gbd coherent optical modules can be employed to free from strong dependence on new optical fibers and amplifiers.

For a single-wavelength 1.2T, the current 130Gbd can only support 100km single-span transport for short-haul DCI. However, pluggable modules can be available within 1~2 years, and the estimated power consumption is still challenging.

5. Summary and Outlook

Increasing network traffic drives optical network capacity expansion and single-wavelength acceleration. The LH optical transport system 100G has been put into large-scale commercial use, 200G is deployed in batches, and the 400G era is speeding up. With the maturity of high-bandwidth coherent devices, 2.5D/3D MCMs, advanced DSPs and L6T EDFAs, the 130Gbd 400G QPSK is expected to have commercial capabilities within one year. In terms of performance, it can effectively compensate for the shortcoming of the 90Gbd PS16QAM solution in LH transport and module form power consumption, forming a complete 400G product solution that covers all application scenarios.

The single-wavelength 400G is expected to be a key generation in the optical network evolution, with a life cycle of more than ten years. Continuously optimizing transport performance, improving equipment integration, and reducing costs per bit is the unremitting drive of equipment vendors, and is also the great mission of the overall optical communications industry. To achieve this goal, first, continuous iteration over the 400G C+L system architecture is required. Based on the industry chain and self-developed and innovative capabilities, it is estimated that the C+L system architecture will be available in two to three years, which will significantly improve equipment integration, scheduling efficiency, and maintenance convenience. Second, bottom-layer components and technologies of optical systems should be innovated, such as high-bandwidth and low-insertion-loss TF-LN modulators, small-size and large-bandwidth high-power SOAs, wide-spectrum continuously amplified erbium fibers, and low-cost OPMs, further optimizing system performance. Third, in terms of intelligence, with the improvement of the precision and practicability of the QoT model, rapid acquisition of key parameters of bottom-layer devices, and the introduction of advanced intelligent algorithms of AI and ML, the digital twin optical network will become a reality, forming automatic closed-loop control and performance optimization for evaluation, analysis, decision-making, and execution. Abundant performance monitoring and prediction methods will also greatly improve the reliability of the optical network. For example, the optical cable co-route detection technology based on distributed fiber sensing greatly reduces the risk of active and standby services being interrupted at the same time. The optical probe and GPA algorithm can effectively solve the problems of unknown standby path performance, slow switching and recovery, and long service recovery time in large-scale network scenarios. The optical-layer OAM and optical performance monitoring technologies based on optical labels will help all-optical networks move towards the new phase of more intelligent optical-electrical linkage networking.

As the 400G technology matures and is widely used in the transport market, 800G will be the next important milestone in the evolution of the optical network. ZTE will continuously consolidate the advantages of large-capacity and LH optical transport products and technologies, and vigorously promote the productization of high-performance 800G LH transport solutions, such as 180Gbd and higher-speed coherent optical components, DSPs, and coherent optical modules. And the research on the expansion of the new band will be intensified to explore the application potential of band S and U and overcome the difficulty in the core component technology and system algorithm. For high-value or disruptive cutting-edge technologies, ZTE keeps close attention and actively drives the commercial use of low-complexity fiber non-linear compensation algorithms, hollow core fibers, and meta-surface material.

Oriented to the future, ZTE adheres to core technological innovation from systems and components to chips and materials. ZTE will actively explore, research, and apply various types of new materials, components, and technologies with industry partners, industry chains, universities and competitors, and develop efficient, flexible, compact, reliable, and intelligent optical transport system devices to help global customers with continuous rate increase, capacity expansion, and performance and cost optimization of all-optical bases of computing networks, and to provide sufficient traffic for digital transformation of the industry, making connections and computing power ubiquitous.

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7. Abbreviation

Abbreviation	Term	Description
DSP	Digital signal processing	It is a signal processing chip dedicated for communication, and has a powerful digital signal processing capability.
MCM	Multi-Chip Module	It assembles multiple dies and other components on one multi-layer interconnection substrate and then encapsulates them to form a high-density and high-reliability microelectronic assembly.
ICT	Information and communications technology	The technology covers all communications devices or applications and related services and applications.
DWDM	Dense Wavelength Division Multiplexing	The technology combines a group of optical wavelengths and transmits them through an optical fiber. In a given fiber, the spectral spacing for multiplexing multiple channels of single-fiber carriers is very tight to support higher-bandwidth transport.
DCI	Data Center Interconnect	It refers to the connection communication between two or more data centers.
QPSK	Quadrature Phase Shift Keying	It is a four-phase modulation manner, has a good anti-noise feature and frequency band utilization, and can be applied to a coherent optical communications system.
M-QAM	M-Quadrature Amplitude Modulation	It is also a common modulation mode in a coherent optical communications system.
OTN	Optical transport network	It allows the transport, multiplexing, routing, and monitoring of service signals in the optical domain, and ensures its performance indexes and survivability.
ROADM	Reconfigurable Optical Add-Drop Multiplexer	It is a component or device used in the dense wavelength division multiplexing (DWDM) system. It dynamically adds or

		drops service wavelengths through remote reconfiguration.
MZM	Mach-Zehnder Modulator	It modulates the light through arm interference.
CDM	Coherent Driver Modulator	It is a coherent optical component that integrates a driver and a modulator, and is used to modulate and load a laser signal.
ICR	Integrated Coherent Receiver	It is a coherent optical component integrating a receiver and a transimpedance amplifier which is used to demodulate a coherent optical signal.
ITLA	Integrated Tunable Laser Assembly	It is a wavelength tunable laser used as a coherent optical communication light source.
TROSA	Integrated coherent transmitter and receiver optical subassembly	It is a coherent optical component integrating a tunable laser, a coherent drive modulator, and a coherent receiver for coherent optical communication.
PIC	Photonic integrated circuit	It is an optical waveguide integrated loop in which an optical component is integrated by using a dielectric waveguide as a center.
PCB	Printed Circuit Board	It includes an insulation baseplate, a connection conductor, and a solder pad for assembling and welding an electronic component. It has dual functions of a conductive line and an insulation baseplate, and may replace complex wiring for an electrical connection between components in a circuit.
TEC	Thermo Electric Cooler	It is made of semiconductor materials through the Peltier effect to control the temperature.
TIA	Trans-impedance amplifier	It can effectively suppress amplification of a noise signal and is widely used in coherent optical communication.
PS	Probabilistic constellation shaping	It obtains the shaping gain by changing the probability distribution of each constellation point

GPA	Global Power Algorithm	It is used to calculate the single-wavelength power and OSNR of the working and backup paths. It is a key algorithm for fast and reliable recovery.
MSA	Multi-source agreement	It is a vendor-led standardization organization, and also a fixed Packaging module type.