2023-06

International Photonics & Electronics Committee

White Paper on Survey of Optical Modules in Wireless Fronthaul

White Paper on Survey of Optical Modules in Wireless Fronthaul

Version 1.0

June 15, 2023

White Paper created and approved by IPEC

www.ipec-org.org

The International Photonics & Electronics Committee (IPEC) is an international standards organization that is committed to developing open optoelectronic standards and delivering strategic roadmap reports. IPEC focuses on standardizing solutions in optical chips, optical/electrical components, and optical modules. Markets addressed by IPEC include 5G, IoT and AI. The gradual digitalization of these industries and the construction of new infrastructure require standardization. However, current optoelectronic standards are reactive, do not pro-actively motivate strategic investments, and do not address all market segments. Therefore, IPEC will look beyond the work of other standards organizations. IPEC will support the optoelectronic industry for the long term, and address un-met needs of its members.

IPEC is open to any interested party who wishes to join. All members have the opportunity to participate in developing all IPEC standards and reports on a non-discriminatory basis. The process of developing these standards and reports is transparent to all members. IPEC is registered in Switzerland.

White Paper on Survey of Optical Modules in Wireless Fronthaul

Summary

This white paper analyzes application scenarios of the next-generation fronthaul solutions and explores standards for 50G optical modules.

Keywords

Fronthaul, 50G, MPI, Dispersion, Standard

Working Group: **Network Requirements**

TITLE: **White Paper on Survey of Optical Modules in Wireless Fronthaul**

SOURCE: TECHNICAL EDITOR

Name: Feng Jia

Company Name: Huawei Technologies Co., Ltd

Email: fengjia@huawei.com

SOURCE: TECHNICAL EDITOR

Name: Sheng Xia

Company Name: China Telecommunications Corporation

Email: shengx3@chinatelecom.cn

SOURCE: TECHNICAL EDITOR

Name: Li Can

Company Name: Huawei Technologies Co., Ltd

Email: lican32@huawei.com

White Paper on Survey of Optical Modules in Wireless Fronthaul

WORKING GROUP CHAIR

Name: Liu Hao

Company Name: China Telecommunications Corporation

Email: liuhao3@chinatelecom.cn

List of Members

The following companies were members of this project at the release of this specification:

Company	
China Telecommunications Corporation	China Academy of Information and Communications Technology
Huawei Technologies Co., Ltd.	Accelink Technologies Co., Ltd.
HG Genuine Optics Tech Co., Ltd.	Hisense Broadband Multimedia Technologies Co., Ltd.
InnoLight Technology (Suzhou) Ltd.	Sitrus Technology
EXFO Inc.	FiberHome
Source Photonics	Shanghai Jiao Tong University

Document Revision History

Rev	**Date**	**Description**
1.0	2023-06-15	Publication of this White Paper.

Contents

Overview

5G networks have become a critical component of a nation's infrastructure, with many countries already deploying 5G technologies on a large scale. With such mass deployments, there are of course opportunities and challenges. For example, 5G enables enhanced Mobile Broadband (eMBB) applications and Internet of Things (IoT) applications (interconnection between devices). However, to support new applications and ultimate user experience, 5G must meet specific efficiency and performance requirements, deliver higher user-perceived rates, and provide higher bandwidths.

Centralized RAN (CRAN) facilitates quick 5G deployment. New 5G fronthaul solutions can run on CRAN to provide denser connections, less power consumption, and simpler fronthaul architectures. This background can create new wireless access topologies. New fronthaul solutions promote the construction of the next-generation wireless networks and maximize the multiplier effect of wireless networks in various fields.

Next-generation fronthaul solutions are expected to be put into commercial use between 2024 to 2026, and to ensure 6G-oriented evolution, the International Photonics & Electronics Committee (IPEC) has set up the next-generation mobile fronthaul 50G (MFH50) project.

This white paper analyzes application scenarios of the next-generation fronthaul solutions and explores standards for 50G optical modules.

1 Challenges and Opportunities for 5G Fronthaul Optical Modules

1.1 5G Fronthaul Network

5G fronthaul has become an important part of 5G networks. Fronthaul networks are classified into distributed RAN (DRAN) and CRAN. The two types of networks will retain even after an upgrade to the next-generation wireless networks.

To support the rising number of sites and carriers, more optical fiber resources must be available for fronthaul. 5G fronthaul optical modules, which are currently available in many forms, typically run rates of 25G and 10G. Conventional optical modules include dual-fiber bidirectional gray optics, but future solutions will save on optical fiber resources. New solutions include single-fiber bidirectional (BIDI) and passive wavelength division multiplexing (WDM), the latter of which is divided into coarse wavelength division multiplexing (CWDM), LAN wavelength division multiplexing (LWDM), medium wavelength division multiplexing (MWDM), and dense wavelength division multiplexing (DWDM). In addition, semi-active and active WDM solutions are planned for specific scenarios. As a variety of different 25G WDM optical module-based solutions are currently available, it is recommended that next-generation fronthaul optical module solutions be narrowed down, with performance, costs, and industry chain maturity considered.

Due to the increase in the required air interface bandwidth in scenarios where massive MIMO base stations with more channels, U6G base stations, or mmWave base stations are used, future fronthaul networks will require larger bandwidth. It is expected that next-generation 5G fronthaul optical modules will be developed to provide higher rates while retaining the existing number of ports and optical fiber resources.

1.2 Challenges to 5G Fronthaul Optical Modules

The rise of CRAN deployment requires a longer fiber length, fewer backbone optical fibers, and higher rates. Next-generation 5G fronthaul must meet diverse bandwidth, optical module performance, optical link quality (multipath interference penalty or MPI penalty, and dispersion penalty), and power consumption requirements.

- Ambient temperature

  Fronthaul devices work in many complex environments. In DRAN, baseband units (BBUs) are typically deployed indoors (in equipment rooms or cabinets) or outdoors. In CRAN, BBUs are deployed in central equipment rooms and remote radio units (RRUs) / active antenna units (AAUs) are deployed outdoors (on towers, poles, or walls), and as such, optical modules must be able to withstand extreme environmental conditions.
- Power consumption

  Optical modules have specific operating temperature ranges, and their power consumption must meet the requirements of the air-cooling system for the BBU and the natural heat dissipation system for RF modules.
- Link budget

  Although CRAN allows data to be transmitted over greater fiber distances, the challenge arises in keeping costs low and yield rates high. The TX optical power and receiver sensitivity of optical modules must be considered during link power budget. Compared with 25 Gb/s non-return zero (NRZ), 50 Gb/s four-level pulse-amplitude modulation (PAM4) requires higher receiver sensitivity. Given the same link budget, the TX optical power of 50G optical modules must be increased.
- Optical fiber quality

Increasing fronthaul rates and using PAM4 typically cause an increase in dispersion and MPI penalty on fiber links. CWDM is the mainstream solution used in CRAN in China. The dispersion penalty can be large for optical modules with a wavelength of 1351 nm or 1371 nm. One way to overcome this challenge is to apply dispersion compensation through optical digital signal processor (oDSP) or other innovative methods. In wireless fronthaul links, engineering deployments cannot meet the high cleanliness (low reflectance) requirement defined by IEEE, and designs of 50G optical modules must balance TX optical power, RX sensitivity, and dispersion and MPI penalty.

- Multi-rate

  In 5G, different split solutions require varying rates. For example, SFP 25G optical modules need to support two rates, 24.33 Gbit/s (CPRI) and 25.78 Gbit/s (eCPRI), while enhanced models, such as SFP 50G optical modules, need to support 50.13504 Gbit/s (CPRI) and 53.125 Gbit/s (eCPRI). To suit the fronthaul interface of the existing BBUs/RF modules, SFP 50G optical modules must be compatible with the rate of 25G.

- Encapsulation protocol

  To support intelligent operations and maintenance (O&M) features, registers such as those related to signal-to-noise ratio (SNR), power-on duration, and multi-rate compatibility need to be added for wireless fronthaul optical modules. The current encapsulation standard, SFF 8472, cannot meet the current demands, and as such, SFP 50G optical modules must consider the inventory software versions and future evolution requirements.

2 Survey of 5G Fronthaul Optical Networks

This white paper surveys wireless fronthaul scenarios and summarizes MFH50, including its requirements, specifications and suggestions of each work group. The survey data includes the inventory information about optical modules (mostly on networks using LTE/NR base stations) of certain offices of three tier-1 Chinese operators and statistics on related fronthaul links. The survey data relates to hundreds of thousands of links and nearly one million optical modules in provinces in China.

2.1 Fronthaul Networking

Figure 1 shows DRAN and CRAN fronthaul networks. In DRAN, the BBU and RF modules are typically deployed at the same site, leading to a short transmission distance. In certain cases, RF modules are deployed far from the BBU or RF modules are cascaded. As such, gray optics for short-distance transmission are typically used. In CRAN, BBUs are centralized in an equipment room and RF modules are deployed far from the BBUs. This results in a long transmission distance, and long optical fibers have to be used between the BBUs and RF modules. As such, gray optics for long-distance transmission and WDM optical modules are typically used. WDM solutions include passive WDM, active WDM and semi-active WDM. Passive WDM is cost-effective and easy to deploy; active WDM supports high-reliability and proactive O&M and monitoring, but is difficult to deploy; and semi-active WDM uses passive multiplexers on the AAU side to simplify deployment, and active devices on the BBU side to implement O&M. The semi-active WDM solution combines passive WDM and active WDM, to deliver competitive advantages but at a higher price point.

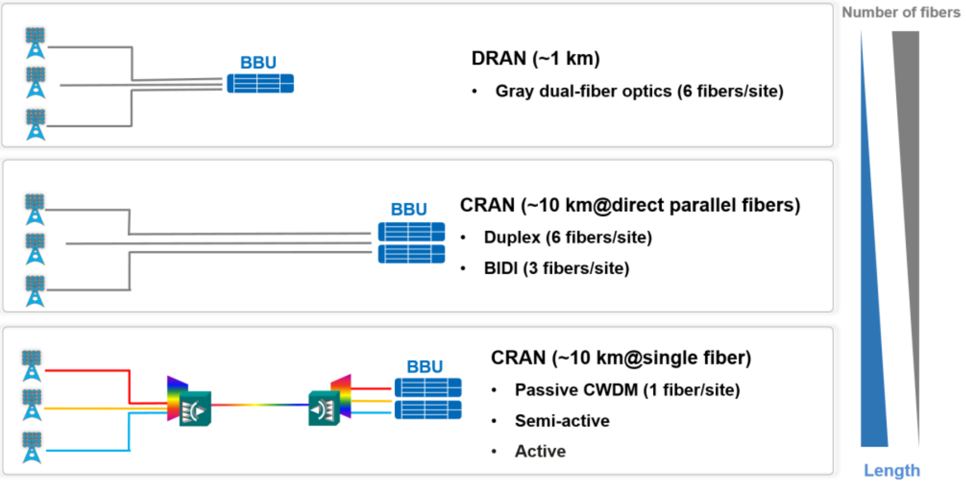

Figure 1 DRAN and CRAN

2.2 Survey of Fronthaul Optical Links

DRAN and CRAN support different optical link distances. The optical link conditions for deploying gray optics and WDM optical modules are also different. For example, long link distances are supported when WDM optical modules are used, with multiplexers and demultiplexers added at remote sites and central equipment rooms. In this case, the link differences between WDM optical modules and gray optics must be considered during optical module design. This white paper analyzes fronthaul optical links, including the transmission distance and link loss, and the influence of MPI penalty and dispersion penalty as they are key factors that affect link budget and optical link quality.

2.2.1 Transmission Distance

The fiber transmission distance can be calculated using transmission delay, though the two factors do not influence the processing capabilities of wireless and transmission equipment.

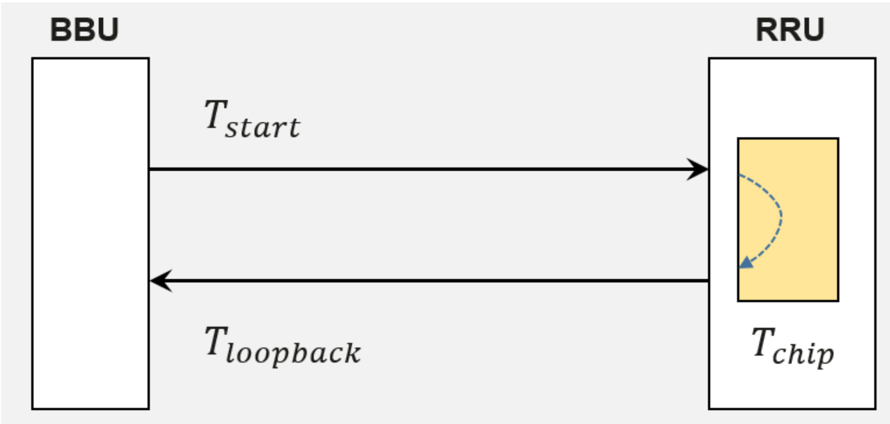

Figure 2 Measurement of the transmission distance of an optical fiber

In Figure 2, a measurement signal is transmitted from the BBU to an RRU over an optical fiber, and then loops back to the BBU. The speed of light over optical links is about 200000 km/s, and the fiber length related to the fronthaul link is measured based on transmission delay as follows:

$$Length = (T_{loopback} - T_{start} - T_{chip}) \times 200000 \div 2$$

T_{start} is the time when the measurement signal is transmitted; T_{chip} is the duration the RRU chip processes the measurement signal; and $T_{loopback}$ is the time when the measurement signal loops back to the BBU.

Figure 3 shows live network statistics about fiber distances at certain offices. Detailed descriptions are as follows:

- In terms of networking, about 70% of all direct fiber links using gray optics do not exceed 2 km. In DRAN, gray optics for short-distance transmission are typically used. By comparison, CRAN typically uses WDM optical modules (with convergence) with fiber link distances of 2 km to 6 km. Such a transmission distance is longer than that when gray optics are used. In certain cases, CRAN uses gray optics for direct fiber links.
- In terms of transmission distances, the fiber link distance is typically within 10 km for fronthaul using gray optics or WDM optical modules, though this can exceed 10 km if needed.

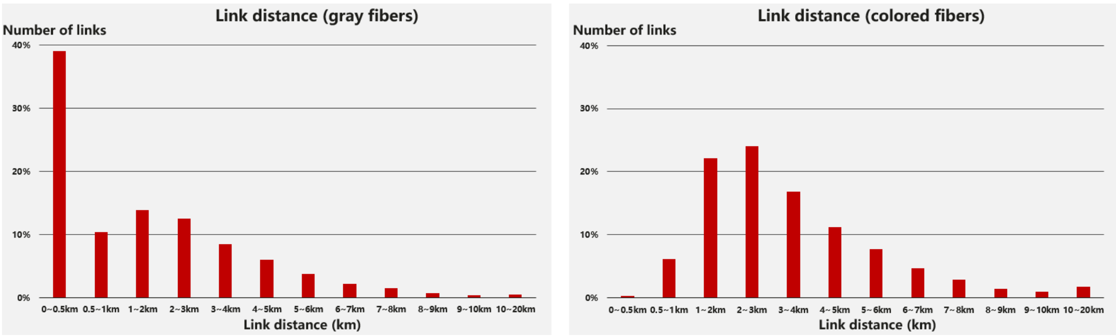

Figure 3 Live network statistics about fiber link distances at certain offices

2.2.2 Link Loss

The main sources of link loss over an optical link are the optical fibers, connectors, maintenance, multiplexers/demultiplexers (present in WDM), dispersion, and MPI (Figure 4). With the rise of fronthaul rates, the dispersion penalty and MPI penalty have an increasing impact on link loss. The link loss can be calculated based on the difference in the TX and RX optical power of optical modules between the BBU and RF modules.

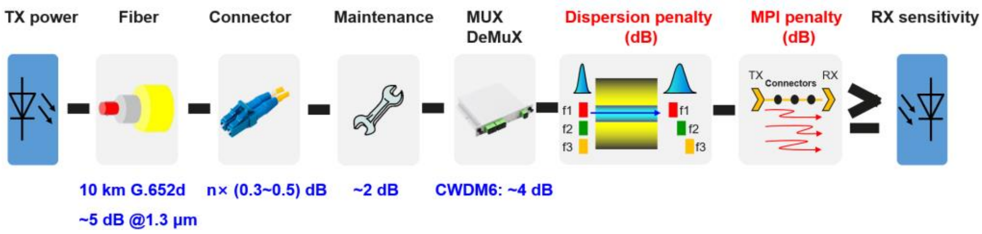

Figure 4 Link budget for CWDM optical modules

Figure 5 and Figure 6 show live network statistics about link loss at certain offices. The main takeaways are as follows:

- Given the same fiber length, the average link loss when WDM optical modules are used is approx. 3 dB greater than that when gray optics are used, due to multiplexers/demultiplexers and connectors on the colored fiber links.
- Gray optics support link distances up to 2 km, with an average link loss of approx. 4 dB, which is relatively low.
- WDM optical modules support link distances of between about 2 km and 6 km, with an average link loss of approx. 10 dB, which is relatively high.

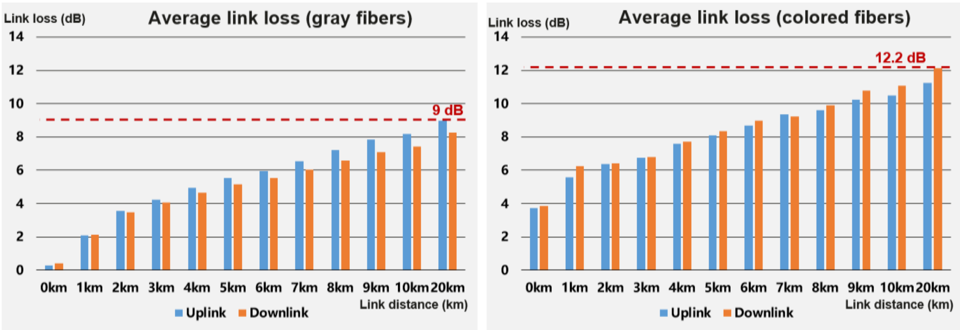

Figure 5 Live network statistics about link loss at certain offices

- According to the distribution of link loss when WDM optical modules are used with link distances of between 2 km and 3 km and between 7 km and 8 km, different links of distances in the same range have varying quality. In the case of a large link loss, an optical link is subject to potential risks even if the RX optical power alarm threshold has not been reached. In this case, it is necessary to rectify any link issues to prevent the link from deteriorating further and impacting services.

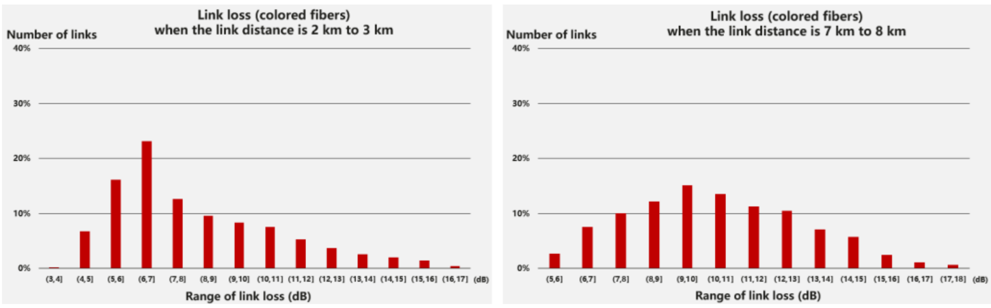

Figure 6 Distribution of link loss with WDM optical modules under different link distance ranges

2.2.3 Optical Fiber MPI

The multiple connection points in an optical link reflect certain optical signals, in which light can be reflected again at a connection point, and as such, an interference signal is generated and transmitted in the same direction as the original signal. At the receive end, the interference signal is superimposed onto the original signal. This propagation means that the receiver receives both wanted and unwanted signals and therefore the SNR is degraded and system transmission performance deteriorates.

MPI occurs when the interference signals generated over multiple paths are superimposed onto the original signals at the receive end. The impact of MPI depends on the strength of the interference signals when they are superimposed onto the original signals and the original signals' tolerance to the interference signals. The main influencing factors include the number and reflectance of connection points, and polarization direction of interference signals, whereby the larger the reflectance, the larger the number of connection points, and the more the alignment between the polarization of the interference and original signals, the greater the MPI impacts. In addition, other factors include phases of interference signals, interference signal loss due to transmission through intermediate connectors, and amplitudes and extinction ratios of the original signals.

The MPI penalty is indicated by the changes in the quality factor of eye pattern at the receive end, the ratio of the total power of all reflected signals to that of the original signals, or the changes in receiver sensitivity under the same bit error rate (BER).

The IEEE 802.3 Ethernet standards state that the reflectance of each connector must be less than –35 dB when there are six connectors. To limit MPI risks, it is recommended that simulations run on general link model to convert the MPI penalty to link loss and apply forward error correction (FEC) to improve tolerance.

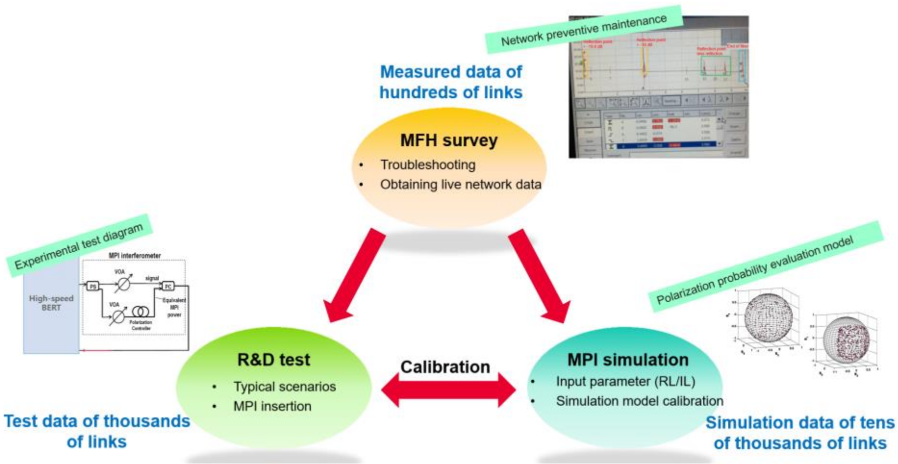

Figure 7 Quantitative analysis of MPI

Figure 7 shows the quantitative analysis of MPI in an optical link from three aspects.

- Data from hundreds of links in an MFH survey, such as the number of connectors, reflectance, and distance, is used as the input for subsequent tests in research and development (R&D) environments and MPI simulations.
- The live network data is used for typical fronthaul scenarios in R&D environments to test the impact of MPI penalty on actual networks and related MPI changes under different conditions.
- Based on the MPI principle, the connector-specific parameters are determined using real-link MPI simulation models to accurately evaluate the link loss due to large reflection events. The R&D test and simulation results can be mutually calibrated to obtain a more accurate link MPI penalty.

A typical 5G fronthaul C-RAN deployment uses six connectors (ODFs and multiplexers/demultiplexers on both sides). According to IEEE 802.3, the reflectance of each connector must be less than –35 dB, but this survey at certain offices finds 32.8% of live-network connectors on high-risk fronthaul links have a reflectance of greater than –35 dB, in addition to 29% greater than –30 dB and 9.8% greater than –20 dB. We can ascertain that for the deteriorated connectors on some fronthaul links, the reflectance is greater than –20 dB, which means the equivalent MPI reflectance is likely greater than –30 dB, causing MPI risks to arise in fronthaul links.

A typical equivalent MPI test on the live network requires a delay fiber, variable optical attenuator (VOA), and polarization controller. The preliminary test result of the survey suggests the maximum equivalent MPI reflectance tolerated by optical modules is approximately –33 dB. Table

1 lists the MPI penalty simulation using fronthaul simulation models. To improve the accuracy of MPI penalty, factors that influence the simulation model like the number of connectors, typical reflectance of connectors, and connector positions will be further calibrated based on live network surveys and lab tests.

Table 1 MPI simulation results

Simulation Configuration	ROP (dBm)	ER (dB)	MPI Penalty (dB)
No MPI	–10.16	3.5	/
6 x (–35 dB)	–10.08	3.5	0.08
6 x (–33 dB)	–10.04	3.5	0.12
6 x (–29 dB)	–9.76	3.5	0.40
6 x (–26 dB)	–8.99	3.5	1.17
Note: Simulation OMA and ROP parameter settings at 2E-4 BER			

2.2.4 Transmission Fiber Dispersion

Dispersion is a common issue in fronthaul links. It mainly comes in the form of material dispersion but also in waveguide dispersion. Fiber dispersion causes pulse broadening, lower peak power to signals in the time domain, and a decrease in extinction ratio and SNR. The zero-dispersion point of G.652 fibers is near the 1310 nm wavelength region. Table 2 lists the dispersion in a typical fronthaul application scenario (10 km). For the 6-wavelength CWDM, the 1371 nm wavelength records the highest dispersion (36 ps/nm to 66.2 ps/nm) for a 10-km fiber.

Table 2 Typical fronthaul dispersion (for a 10-km fiber)

Dispersion	6-wavelength CWDM					
	1271 nm	1291 nm	1311 nm	1331 nm	1351 nm	1371 nm
Minimum 10-km dispersion (ps/nm)	–59.4	–38.5	–18.5	0.5	18.6	36.0
Maximum 10-km dispersion (ps/nm)	–21.5	–2.3	16.0	33.4	50.2	66.2

Table 3 lists the mainstream dispersion compensation solutions. The dispersion fiber/grating solution is difficult to implement because it requires prior measurements of the dispersion of the fronthaul link, and its parameters such as the length of the dispersion fiber/grating need to be tailored for a site and further configured for the optical modules. The digital signal processor (DSP) compensation solution can compensate for electrical dispersion, but the compensation capability varies between vendors and requires prior tests and surveys. Generally, the 50G CWDM optical module employs a directly modulated laser (DML), and therefore the external modulation solution (EML/MZM) can be used to reduce the chirp effect of lasers and subsequently the dispersion penalty. Another solution, the micro-ring dispersion compensation solution, provides a theoretical compensation of 720 ps/nm, though this research is still incomplete.

In general, the DSP compensation solution may provide the most competitive advantages.

Table 3 Mainstream dispersion compensation solutions

Solution	Dispersion fiber/grating	oDSP compensation	Chirp-free external modulation	Micro-ring dispersion compensation
Compensation Amount	Customized compensation amount	appr. 10 ps/nm (evaluated based on vendor-specific tests)	appr. 15 ps/nm	appr. 720 ps/nm
Size	Large	Medium (integrated into oDSP)	Small	Small
Optical Insertion Loss	1.X to 3 dB	None	appr. 1 dB	appr. 1 dB
Maturity	Mature	Mature	The 50 Gb/s MZM solution supports mass production.	Under research

2.3 Survey on Optical Modules for Fronthaul

To understand the evolution trends of next-generation fronthaul optical modules, this survey focuses on the optical module type and temperature, with further market analysis used for the different types of optical modules. The optical module temperature is a key indicator in design of optical modules, as it influences power consumption, cost, and base station hardware compatibility.

2.3.1 Optical Module Types

Current optical modules are tailored for various 5G fronthaul setups. The evolution trends of next-generation fronthaul optical modules are still under research. Figure 8 shows the statistics about the types of optical modules on the live network for an operator in the China region.

- The survey data covers a period starting from before 2019 to the present day where 5G is now deployed on a large scale. Statistics indicate that gray optics are the mainstream type of optical modules for fronthaul, owing to their strengths in flexibility and easy deployment, and are expected to be a mainstay in the next-gen high-speed 50G fronthaul market.
- The WDM solution is available for organizations to overcome insufficient CRAN fiber resources. Currently, 25G CWDM optical modules account for a large share in the WDM market. A small number of 10G CWDM optical modules will be used in small-bandwidth scenarios. It is estimated that CWDM optical modules will account for a large share in the 50G WDM market. Other WDM solutions are under exploration.

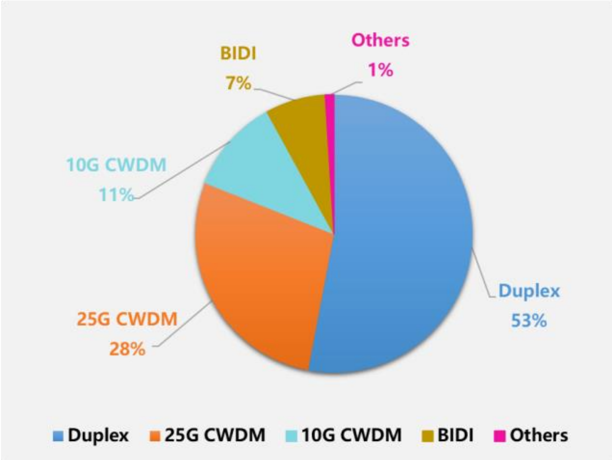

Figure 8 Distribution of optical module types for an operator in the China region

2.3.2 Optical Module Temperatures

Fronthaul optical modules are deployed in complex and diversified environments. The temperatures of optical modules vary greatly with regions, seasons, and time intervals. This temperature difference further affects power consumption and performance. The operating and startup temperatures of optical modules must meet industrial-grade specifications, and therefore a long-term survey and analysis on optical module temperatures is required.

1. **Operating temperatures of optical modules**

   The operating temperatures of optical modules are sensitive to their environments. Usually, high operating temperatures result in poor performance and even fronthaul link faults, affecting services. Figure 9 shows the live network statistics about operating temperatures of optical modules from two offices in September 2022.

   - Optical modules have an operating temperature range between 0°C to 85°C, and normally 20°C to 50°C, meeting the requirements of industrial-grade optical modules.
   - The operating temperatures of optical modules on the BBU side are generally lower than those on the RF side. The ambient temperatures of optical modules on the BBU side are determined by equipment room environments and the fan speed policies of the cabinets, while those on the RF side are determined by the outdoor environments and the power consumption of RF modules.
   - The operating temperatures of optical modules at southern offices generally differ from those at northern offices in China, due to geographical regions and seasons.

   Currently, optical module temperatures are surveyed at certain offices in China. In future studies, more offices across a wide range will be selected to obtain more complete and long-term data statistics regarding the operating temperatures.

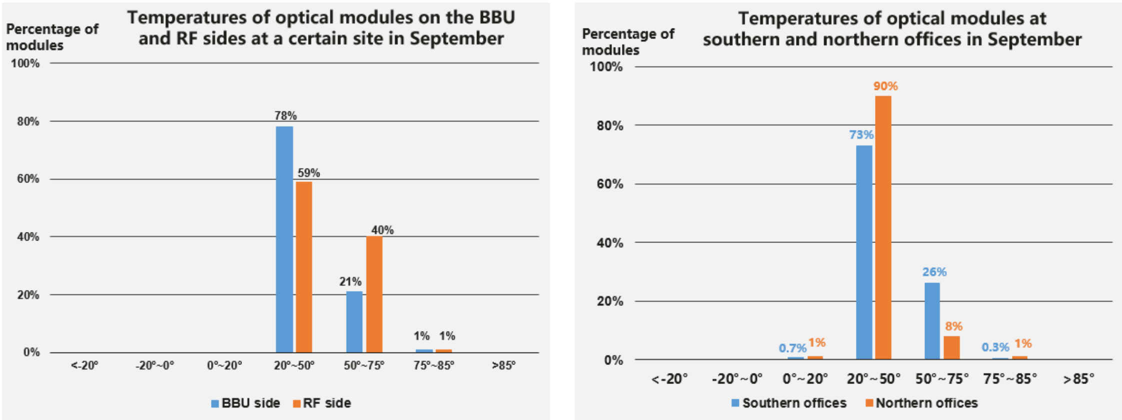

Figure 9 Live network statistics about operating temperatures of optical modules at certain offices in September 2022

2. **Startup temperatures of optical modules**

The startup temperatures of optical modules are also a key indicator in extreme, low-temperature environments. Especially, optical modules need to be restarted multiple times in such environments to save energy for base stations. The startup temperatures of optical modules will be further investigated and analyzed.

2.4 Survey on Industry Standards

2.4.1 IPEC Standard Evolution of 50G Fronthaul Optical Modules

In September 2021, the IPEC initiated the MFH50 standard project, focusing on single-channel 50G optical links in mobile fronthaul technologies. The IPEC MFH50 research project focuses on optoelectronic components and engineering deployment. The research works on optoelectronic components include optoelectronic parameters of optical modules, optical parameters of passive multiplexers and demultiplexers, low power consumption technology of optical modules, and O&M features of optical modules and fronthaul links. The research works on engineering deployment include the fronthaul link quality and optimized fronthaul link engineering solutions. Big data analysis on the existing fronthaul optical link parameters and operating temperatures of optical modules is expected to enable faster and higher-quality deployment of MFH50 optical modules.

The draft of the standards for 50G SFP gray optics (including BIDI) was completed in April 2023, with those for CWDM 6-based 50G fronthaul optical modules set to be improved and released in the future. Other WDM solutions are under exploration.

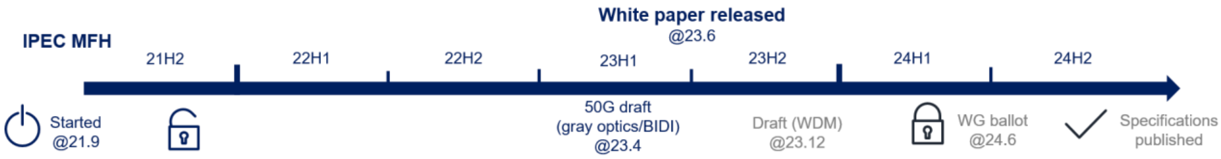

Figure 10 Roadmap of the IPEC MFH50 project

2.4.2 Current State and Evolution of Standards for 50G Fronthaul Optical Modules in China

2.4.2.1 Current State

China Communications Standards Association (CCSA) is the standards body in China. In 2020 and 2021, CCSA released the technical specifications for 50G dual- and single-fiber bidirectional gray optics, namely, *50Gb/s PAM4 Modulation Pluggable Transceiver* (YD/T 3713-2020) (0.1 km/2 km/10 km/40 km) and *Single Fiber Bi-Directional (BIDI) Optical Transceiver Module-Part3: 50Gb/s* (YD/T 2759.3-2021) (10 km/20 km) (https://www.ccsa.org.cn/english/standard).

In wireless fronthaul scenarios, main wireless equipment can be upgraded by replacement of 25G NRZ optical modules with 50G PAM4 optical modules. However, the current standards for 50G optical modules are incompatible with those for 25G optical modules in terms of data rate, transmission distance, wavelength range, transmit/receive optical power, receiver sensitivity, and link budget. This incompatibility affects the 50G optical module solution. Currently, CCSA has not defined the standards for fronthaul 50G optical modules, which cannot be used in fronthaul scenarios. In this background, the current standards for fronthaul 50G optical modules must be customized to suit the fronthaul application scenarios.

In December 2022, CCSA began research into 50G optical modules for fronthaul, with the standard for SFP gray (including BIDI) optics currently under revision and that for WDM optical modules in development for technical solutions. Research on the evolution of 25G solutions (such as previous-generation CWDM) for WDM optical modules will continue, with consensus from operators across the industry chain. The research report is expected to be officially released in 2023 or 2024.

Research into fronthaul 50G optical modules will focus on WDM optical modules, dual small form-factor pluggable (DSFP), management enhancement, and test standards. In the research, a survey on fronthaul optical modules and links as well as channel penalty analysis will be conducted, and WDM optical module solutions will be proposed. In the fronthaul link survey, the transmit optical power and receiver sensitivity which have impacts on link budgets must be studied and re-defined to ensure compatibility between optical module standards. In addition, attentions should be paid to the encapsulation and electrical parameters of optical modules, and the power supply to optical modules from devices as well as heat dissipation should match to reduce compatibility risks. Further, the optical module management interface must support optical module diagnosis, rate switching, and optical link detection. Performance tests and platforms from different vendors must use a consistent framework to ensure standardization.

2.4.2.2 Evolution

Optical module technologies are gradually developing towards higher rates and higher integration. In fronthaul networks, the optical module rate has evolved from 10 Gb/s (4G CPRI ports) to 25 Gb/s (5G eCPRI port), and will continue to increase to 50G or higher. Currently, the following standards have been released:

10G – Duplex/BIDI/CWDM 6: SFP/SFP+ optical transceiver module between BBU and RRU for base station interconnecting (YD/T 3131-2016)

25G – Duplex: Enhanced SFP transceiver (SFP+) used in communication. Part 2: 25 Gbit/s (YD/T 3125.2-2019)

25G – BIDI: (Single fiber bidirectional optical transceiver module Part 2: 25Gb/s) (YD/T 2759.2-2020)

25G – CWDM: (25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 1: CWDM) (YD/T 4019.1-2022)

25G – LWDM: (25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 2: LWDM) (YD/T 4019.2-2022)

25G – DWDM: (25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 3: DWDM) (YD/T 4019.3-2022)

25G – MWDM: (25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 4: MWDM) (YD/T 4019.4-2022)

50G – Duplex: (50Gb/s PAM4 modulated optical transceiver module) (YD/T 3713-2020)

50G – BIDI: (Single fiber first optical transceiver module 3 parts: 50Gb/s) (YD/T 2759.3-2021)

The 10G/25G-to-50G optical module evolution causes key performance parameters to change, especially in the transmit and receive optical power ranges, OMA receiver sensitivity, and link budget. Existing standards suggest a link budget of 6.9 dB, 11.2 dB, and 10 dB for 50G, 10G, and 25G duplex and BIDI modules, respectively. A 50G optical module has higher channel loss and reflection penalty during signal transmission than a 25G optical module, and therefore must have a higher link budget to support application scenarios of 25G optical modules. However, the link budget of the existing 50G standard cannot meet requirements.

The link budget is determined by the transmit optical power and OMA receiver sensitivity. The new standard will increase the link budget by adjusting the transmit optical power. In addition, 50G optical modules must be compatible with previous-generation modules in terms of wavelength range, transmission distance, rate, and temperature. Moreover, revisions must be made to the CWDM multiplexer/demultiplexer standard, dual-channel extended application scope, and module color label specifications to extend applications of the new 50G optical module standards. Currently, Chinese operators adopt the CWDM solution for the mainstream fronthaul optical modules in their 5G CRAN deployment. IPEC MFH50 explores the compatibility of lasers and passive components like multiplexer/demultiplexer modules with previous-generation solutions.

To conclude, the performance indicator and component specifications of 50G optical modules need to be supplemented and revised during the formulation of 50G fronthaul standards.

2.4.3 MOPA Standard Progress of 50G Fronthaul Optical Modules

In June 2021, the Mobile Optical Pluggables Alliance (MOPA, an organization including Ericsson, Nokia, Coherent, Lumentum, and Sumitomo Electric) released Technical Paper-Version 1.0, which provided 10G/25G blueprints. In March 2022, Technical Paper-Version 1.1 was released to cover the 50G blueprint. In the applicable blueprint tables, references to existing optical layer interface standards were included. This was further updated to Version 2.1 (Papers and Presentations | MOPA Alliance (mopa-alliance.org)) in March 2023, which adds a framework for 2 km and 10 km RU-DU direct parallel fibers, dual and BIDI fiber blueprints in section 7.2 "DRAN Optical Blueprints". As specified in the blueprints, the standards for 50G duplex and BIDI optical modules (2 km/10 km) are IEEE 802.3-2022, Clauses 139 & 160 (IEEE SA - The IEEE Standards Association - Home) and ITU-T G.9806 (Amend 2) (https://www.itu.int/rec/T-REC-G.9806). This document describes the optical and electrical specifications, test standards, and test methods for 50G optical modules (5 km/10 km/40 km).

Also, Technical Paper-Version 2.1 indicates that 50G fronthaul WDM solutions and technologies will evolve continuously, including LWDM and DWDM. These solutions can support long-distance transmission and mitigate dispersion, but are currently expensive and incompatible with the mainstream SFP 25G CWDM optics of Chinese operators, hindering its uptake in global deployments. Such conversion also requires a new industry chain, which means significant investment and expertise. In addition, the specifications of 50G fronthaul optical modules in IEEE 802.3-2022, such as the wavelength range and transmission distance, are different from those in China. Therefore, new standards need to be formulated for new scenarios.

2.4.4 Summary of 50G Fronthaul Optical Module Standard Evolution

The current standards for mainstream 50G fronthaul optical modules in the industry still lack the rationality of performance parameters and compatibility between generations, and these standards need to be further optimized to cover wider application scope and consistency.

The IPEC MFH50 standard aims to address the preceding problems and will cover technical fields such as single- and dual-fiber bidirectional gray optics and WDM optical modules, and adapt to cost efficiency and evolution trends. MFH50 research is a joint venture by IPEC members including operators, vendors (equipment, optical module, electrical chips), and research institutes. This project will continue to focus on problems and challenges in fronthaul scenarios and promote standardization and innovation in the fronthaul optical module field.

2.5 Survey on the Industry Chain

The industry chain of 50G dual-fiber bidirectional gray optics has taken shape. As for optical chips, 50G optical modules use the PAM4 modulation format, which significantly enhances the non-linear effect of lasers, and this issue can be reduced by increasing the bandwidth or optimizing inband flatness. Multiple chip vendors can supply optical chips in batches, such as Lumentum, Sumitomo, Macom, Mitsubishi, Accelink, and Yuanjie. For electrical chips, two solutions are available, including the DSP and clock and data recovery (CDR). DSP vendors like Marvell, Credo, and Chengke Microelectronics have launched driver-integrated DSP chips for 5G fronthaul. CDR vendors include Semtech and Macom, the former of which has launched driver-integrated CDR chips for 5G fronthaul, while the latter's processors are under development. By April 2023, mainstream Chinese optical module vendors produced samples for fronthaul-oriented 50G dual-fiber bidirectional optical modules, which have passed the preliminary performance test and verification.

Table 4 50G dual-fiber bidirectional gray optics solution

Form Factor	Operating Distance	Center Wavelength	Modulation Format	Electrical Interface	Optical Chip	Electrical Chip
SFP56	10 km	1310 nm	PAM4	1 x 50G PAM4	DFB+PIN	CDR/DSP

Like the 25G BIDI optical modules, 50G BIDI optical modules also use the 1270 nm/1330 nm WDM solution. 50G BIDI optical modules save on optical fiber resources and deliver desirable latency symmetry while sharing the industry chain of 50G dual-fiber bidirectional optical modules. Currently, 50G BIDI optical modules are developed based on the 50G dual-fiber bidirectional optical module solution, but with slower development.

Table 5 50G BIDI optical module solution

Form Factor	Operating Distance	Center Wavelength	Modulation Format	Electrical Interface	Optical Chip	Electrical Chip
SFP56	10 km	1270/1330 nm	PAM4	1 x 50G PAM4	DFB+PIN	CDR/DSP

Research into 25G xWDM optical modules is the catalyst for new industry solutions that provide WDM optical modules with higher rates. The research on 50G 6-wavelength CWDM optical modules has progressed the most. The same wavelength scheme applies to both 50G and 25G 6-wavelength CWDM optical modules. In terms of optical chips, 50G CWDM optical modules can reuse the lasers of their 25G counterparts. However, due to the use of PAM4, the required link budget increases, posing higher requirements on the transmit optical power of lasers. As such, the transmit optical efficiency and yield rate of lasers need to be further optimized. In terms of electrical chips, the CDR or DSP, which is used in 50G gray optics, can also be used in 50G CWDM optical modules. Dispersion penalties vary with wavelengths. Given that CWDM optical modules have a wide wavelength span, the industry has begun to explore the possibility of coexistence of the two solutions to achieve the optimal cost-effectiveness. The technical evaluation result as of April 2023 shows that oDSP has performance advantages in the CWDM optical module solution. In addition, the silicon photonics solution is also used for 50G CWDM optical modules, with leading dispersion specifications indicated by the test data.

To date, the industry chain of different types of 50G optical modules is mature, and will harness the development of 50G fronthaul technologies. For its part, IPEC will work with industry partners to develop a consensus on the future optics field, and promote standardization and industrialization that solve the challenges of fronthaul scenarios.

3 Recommendations to Achieve Standardization of Next-Generation Fronthaul Optical Modules

3.1 Wireless Fronthaul Rate Evolution and MFH50 Application Scenarios

The 5G radio frequency bands are classified into mid-band (sub-6 GHz) and high-band (above 6 GHz). In the China region, the 2.6 GHz (160 MHz bandwidth) and 3.5 GHz (200 MHz bandwidth) frequency bands are typically deployed. With eCPRI split, the 50 Gb/s bandwidth is required for wireless fronthaul.

Assume that three AAUs are deployed for a site, as shown in Figure 11. If 25G SFP optical modules are used, then two groups of CWDM optical modules (six in total) and two CWDM multiplexer/demultiplexer modules are separately required on the RF and BBU sides, and two feeder fibers are required for BBU-RF connection. The deployment using 50G SFP optical modules uses half the required optical modules and optical fibers, and reuses legacy multiplexer/demultiplexer modules.

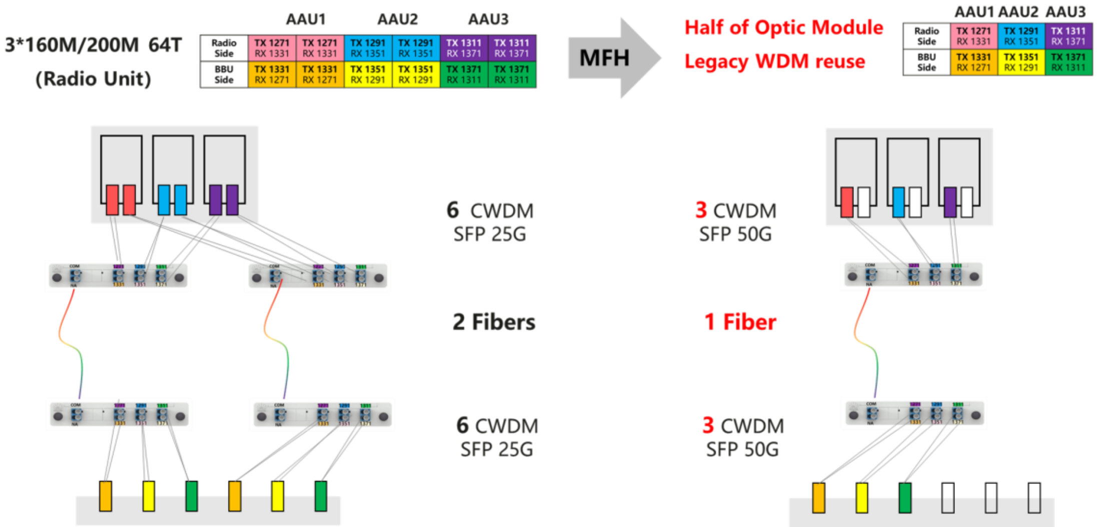

Figure 11 Wireless fronthaul evolution solution

50G RF modules need to support both CPRI and eCPRI rates. Considering PCS encoding and FEC type selection, 50G SFP optical modules need to be compatible with the rates listed in Table 6.

Table 6 Rates that need to be supported by 50G SFP optical modules

Standard Rate	Protocol	PCS encoding: 257/256, 66/64 FEC encoding: KP = 544/514, KR = 528/514
53.1G	**eCPRI**	**50G** x 257/256 x **544/514** = 53.125 Gb/s
50.1G	**CPRI**	**96** x 491.52M x 257/256 x **544/514** = 50.13504 Gb/s
25.78G	**eCPRI**	**25G** x 257/256 x **528/514** = 25.78125 Gb/s
24.33G	**CPRI**	**48** x 491.52M x 66/64 = 24.33024 Gb/s

3.2 Recommendations for MFH50 Optical Module Standardization

The IPEC initiated the research on MFH50 standards in September 2021, and has completed the draft of the SFP gray optics (duplex & BIDI) standards by April 2023. The optical parameters, management interfaces, and test methods of 50G gray optics (duplex & BIDI) have been discussed and approved by the IPEC. Future discussions will cover the link budget, MPI, and dispersion of 50G gray optics (duplex & BIDI), the fiber optic cabling model, EMC and safety regulations, as well as WDM optical modules. Related drafts *50 Gb/s Duplex BIDI PMD Implementation Agreement D2.0* and *MFH50 management interface V0.1* for SFP gray optics (duplex & BIDI) standards are available on the IPEC's official website. For details, register and download at https://www.ipec-std.org/data-download.

This section provides recommendations for standardization of 50G optical modules, including 50 Gb/s gray, BIDI, and CWDM 6 optical modules.

3.2.1 Standards of 50G Dual-Fiber Bidirectional Gray Optics

For details, the MFH50 standard project is developing related standards and specifications.

3.2.2 Standards of 50G Single-Fiber Bidirectional Gray Optics

For details, the MFH50 standard project is developing related standards and specifications.

3.2.3 Standards of 50G CWDM 6 Optical Modules (TBD)

The WDM optical module standards of MFH50 are in research.

3.3 MFH50 Encapsulation Protocol

The new features introduced in 50G SFP optical modules increase the requirements for registers, such as those related to multi-rate compatibility, rate switching time, and optical fiber sensing. Based on SFF-8472 and Common Management Interface Specification (CMIS), new interfaces are added to provide the following functions:

1. Rate set reporting

Fronthaul optical modules need to support different rates. The main device requires that optical modules be capable of rate set reporting, so that the optical modules can be properly configured based on the reported rate set. SFF-8472 provides the Application Select Table function, in which each application is assigned a unique application code, including the protocol name, working rate, and modulation format (NRZ or PAM4). 50G optical modules can be integrated with the Application Select Table function to report the supported rate set.

2. Delivery of the precise rate during switching

   Both 25G and 10G optical modules use the NRZ modulation format. During rate switching, only the SerDes rate of the electrical interface or the working rate of the optical interface needs to be switched. In this way, the optical module can lock the rate and switch to the new rate quickly. 50G optical modules adopt PAM4 and CDR or DSP technology. Both electrical and optical signals have three decision levels, which can be obtained through training and learning. During rate switching, the CDR or DSP chip needs to obtain the accurate working rate and code pattern to facilitate quick training and learning. With the rate set reporting function, the main device delivers the application code to the optical module that contains the accurate working rate and code pattern required for rate switching.

3. Reporting of rate switching setup time

   The rate switching setup time starts when the main device issues a rate switching command to the optical module and ends when the optical module locks the channel and outputs the corresponding signal. The setup time assumes that the signals input into the optical module meet signal quality requirements in the protocol. The setup time includes electrical-optical conversion (egress) channel setup time and optical-electrical conversion (ingress) channel setup time.

   Both 10G and 25G optical modules adopt the NRZ code pattern, in which only one threshold is trained or learned. In this case, the rate switching setup time is short (generally within 1 ms), which is negligible for the main device. In addition, high switching reliability is ensured. The switching setup time is closely related to the code pattern corresponding to the target rate. When the target rate is 50 Gb/s and the PAM4 code pattern is used, the CDR or DSP chip needs to train or learn three thresholds. As a result, the switching setup time may be several or even dozens of seconds, and the switching may fail. In this case, the optical module must proactively report the maximum switching setup time and switching success flag.

   With the switching success flag, the main device obtains the switching state of the optical module (distinguishing between the egress and ingress channels), after which negotiations at the CPRI or eCPRI layer can be performed.

4. Reporting of transmission latency

   For optical modules, optical-to-electrical conversion introduces transmission latency, which is related to factors such as the electrical chip scheme, modulation format, and PCB cabling. For 10G and 25G optical modules, such latency is usually hundreds of picoseconds, which has little impact on fronthaul links. However, the transmission latency introduced by DSP-based 50G optical modules is up to dozens of nanoseconds, which may affect the fronthaul synchronous transmission system. Therefore, a register must be defined in the management interface to claim the transmission latency introduced by the optical module, assisting the main device in analysis.

5. Reporting of support for new functions

   Compared with CDR-based modules, DSP-based 50G optical modules provide new functions such as loopback, SNR detection, and BER detection. The supported new features and functions can be described in the optical module management interface. In addition, the management interface provides registers, through which the detection results can be obtained.

To address the preceding issues, a new management interface should be defined for next-generation 5G fronthaul optical modules. Based on current research, considering the software switching cost and hardware cost of fronthaul optical modules, SFF-8472 is reused and registers are defined for new features to reduce related costs. For details about the MFH50 encapsulation protocol, see *MFH50 management interface V0.1*.

3.4 MFH50 Test Standards

The test methods of optical transceiver modules for optical communication have been released in the industry, involving two parts: *YD/T 2798.1-2015 Optical transceiver module for optical communication test methods - Part 1: Single-wavelength type* and *YD/T 2798.2-2020 Optical transceiver module for optical communication test methods - Part 2: Multi-wavelength type*. In wireless fronthaul scenarios, the test methods will be optimized with reference to MFH50, considering special requirements for dispersion, MPI and the efficiency and accuracy of TDECQ and PAM4 eye pattern tests.

3.4.1 Eye Pattern Test

The eye mask margin commonly used for NRZ signals is not applicable to PAM4. Instead, a new parameter TDECQ is added to represent the performance of PAM4 transmitters, and TDECQ, short for Transmitter Dispersion Eye Closure Quaternary, is the main indicator used to evaluate the communication quality.

Figure 12 shows the IEEE TDECQ test networking. The networking has strict requirements on the polarization state, dispersion, insertion loss, and return loss of the tested optical link, and uses the short stress pattern random quaternary (SSPRQ) as the test pattern. In strict standard tests, optical links need to be set up according to the TDECQ test networking, and due to the difficulty in constructing complex test networks in the manufacturing and engineering environments, it is good practice to optimize the test methods based on the requirements in the manufacturing, verification, and engineering acceptance phases.

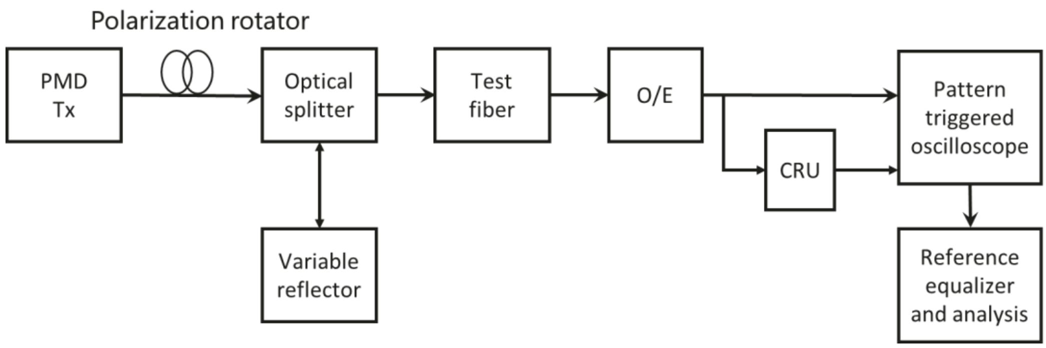

Figure 12 TDECQ test networking (source: IEEE Std 802.3cd™-2018)

3.4.2 Rate Switching Setup Time

The rate switching setup time refers to the time required for an optical module to switch between rates. In the era of 25G optical modules, the setup time for rate switching from 25G to 10G is generally at the millisecond scale. However, in the era of 50G optical modules, the setup time is expected to be several seconds or even dozens of seconds. This is because PAM4 encoding is used, three decision thresholds are set, and chip adaptive equalization takes a certain period of time. Therefore, the rate switching setup time of optical modules must be acknowledged during rate negotiation between wireless devices.

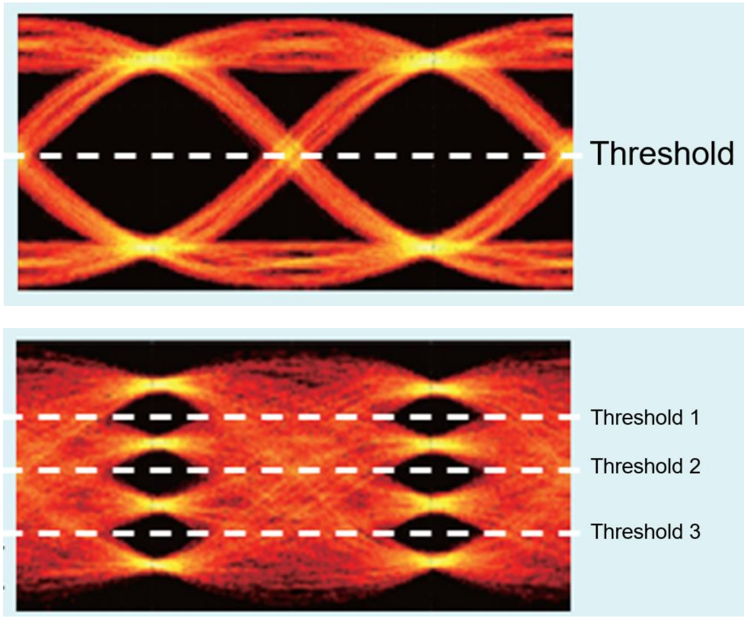

Figure 13 NRZ and PAM4 eye patterns

Definition of setup time:

Electrical-optical channel setup time: The time starts when the I2C issues a rate switching command to the optical module and ends when the module's optical port (point A2) outputs the corresponding optical signal and reports the flag bit over the I2C interface, to indicate that the optical module is locked and working normally. The setup time assumes that the signals at the electrical port (point A1) meet signal quality of the target rate.

Optical-electrical channel setup time: The time starts when the I2C issues a rate switching command to the optical module and ends when the module's electrical port (point B2) outputs the corresponding electrical signal and reports the flag bit over the I2C interface, to indicate that the optical module is locked and working normally. The setup time assumes that the signals at the optical port (point B1) meet signal quality of the target rate.

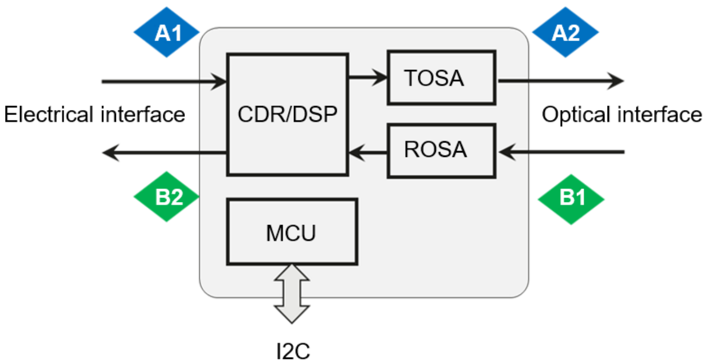

Figure 14 Logical diagram of the rate switching setup time test

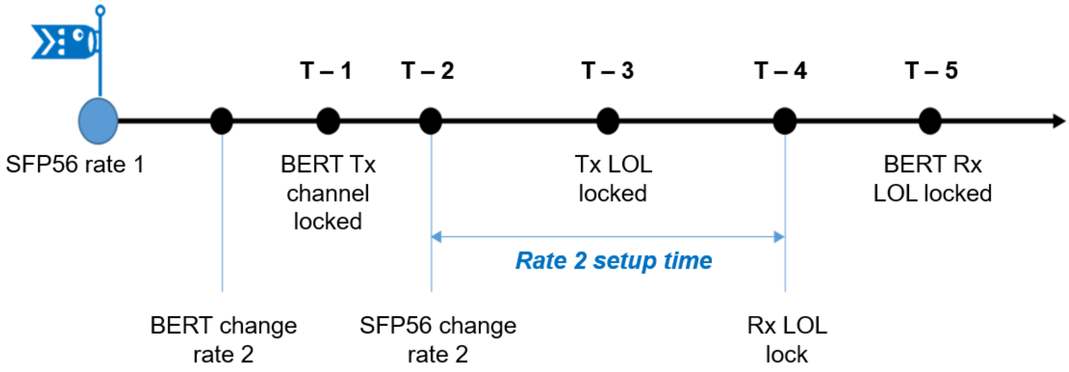

Figure 15 Rate switching setup time test

3.4.3 Latency Test

Generally, 25G SFP optical modules run on the CDR solution, which ensures very short latency for the optical modules. Such latency is negligible for the fronthaul link.

50G optical modules use either of two technical solutions (CDR and oDSP). When the oDSP solution is used, high transmission latency is introduced because the optical module is equipped with the analog-to-digital converter (ADC), DSP, and digital-to-analog converter (DAC). The system design must be compatible with the two hardware solutions. Development for 50G optical modules must set transmission latency thresholds and related test methods.

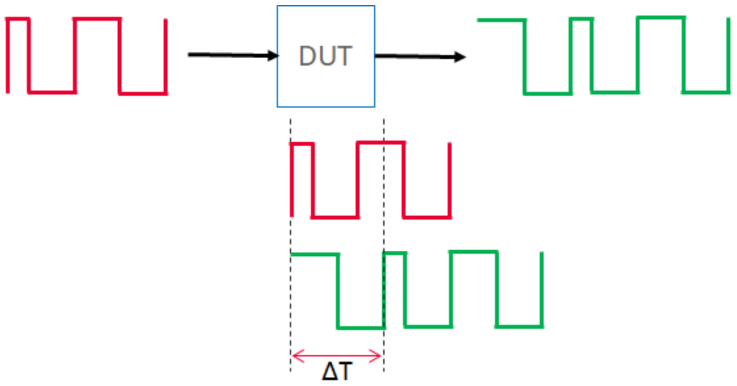

Figure 16 Latency test

3.4.4 Multi-Vendor Test

Through decoupling of optical modules from main devices and unified test standards, it is expected that optical modules can be tested independently, shortening the time to market (TTM), reducing costs, and improving quality of optical modules. To achieve this, equipment vendors, operators, and optical module suppliers must reach an agreement on the optical module test standards.

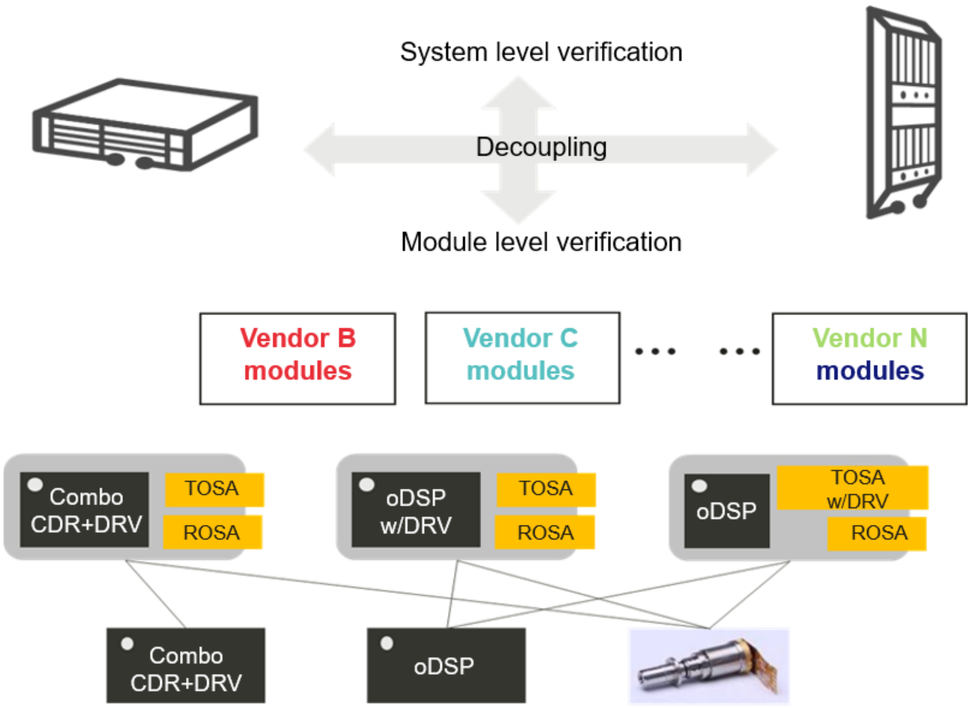

Figure 17 Decoupling of the optical module test from the main device test

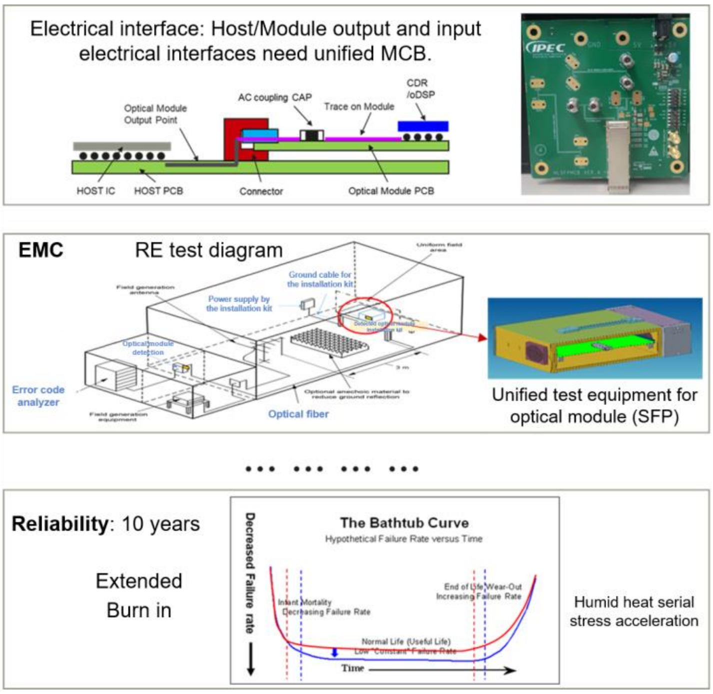

Figure 18 Advantages of test decoupling

4 Summary and Prospect of Wireless Next-Generation Fronthaul Optical Modules

To sum up, the next-generation optical modules for wireless fronthaul will need to cover DRAN and CRAN scenarios as well as live-network standards and wireless device requirements, while achieving optical fiber saving, low power consumption, and high cost-effectiveness. To achieve this, it is recommended that the next-generation optical modules for wireless fronthaul comply with the following key specifications:

- Ambient temperature: Optical modules must be able to tolerate a wide range of climatic conditions, and can work properly in temperatures of –40°C to +85°C (industrial grade) or –20°C to +85°C (extended commercial grade).
- Power consumption of optical modules: It is recommended that the power consumption of 50G gray optics and WDM optical modules be under or equal to 2 W.
- Link budget: It is recommended that the link budget of 50G optical modules be not less than that of 25G optical modules.
- Link performance of optical modules: Optical modules must offer MPI detection and MPI compensation features (specifications to be determined). Dispersion must meet the transmission requirements of CWDM modules that have wavelength of 1371 nm and a transmission distance of 10 km.
- Multi-rate negotiation: The rate of a fronthaul optical module must match the specifications of wireless main devices. It is recommended that 50G optical modules support rate reduction.
- Encapsulation protocol: All of existing wireless fronthaul optical modules (with a rate of 25G, 10G, and lower) comply with SFF-8472. It is recommended that SFP and SFF-8472 be applied to wireless fronthaul 50G optical modules. To meet the requirements of intelligent O&M features, it is recommended that certain registers such as those related to SNR, power-on duration, and multi-rate compatibility be defined with reference to SFF-8472 and CMIS.

For details, see the 50G optical module standard defined by IPEC MFH50.

This white paper will be updated accordingly to include relevant technical research of fronthaul optical modules. With the continuous evolution of wireless fronthaul solutions, IPEC will conduct research on standards of fronthaul optical modules, including those of 100G or higher, which will serve as a catalyst to drive the field towards 5.5G and 6G.

5 Reference

1. Next-Generation 5G Bearer Optical Module White Paper
2. IEEE Std 802.3-2022: IEEE Standard for Ethernet
3. ITU-T G.9806 (Amend 2)
4. YD/T 3713-2020: 50Gb/s PAM4 Modulation Pluggable Transceiver
5. YD/T 2759.3-2021: Single Fiber Bi-Directional (BIDI) Optical Transceiver Module-Part3: 50Gb/s
6. YD/T 3131-2016: SFP/SFP+ optical transceiver module between BBU and RRU for base station interconnecting.
7. YD/T 3125.2-2019: Enhanced SFP transceiver (SFP+) used in communication. Part 2: 25 Gbit/s.
8. YD/T 2759.2-2020: Single fiber bidirectional optical transceiver module Part 2: 25Gb/s.
9. YD/T 4019.1-2022: 25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 1: CWDM.
10. YD/T 4019.2-2022: 25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 2: LWDM
11. YD/T 4019.3-2022: 25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 3: DWDM
12. YD/T 4019.4-2022: 25Gb/s wavelength division multiplexing (WDM) optical transceiver module Part 4: MWDM
13. Mobile Optical Pluggables Alliance (MOPA): Technical paper Version 2.1

E-mail: info@ipec-std.org
Website: http://www.ipec-std.org
COPYRIGHT © 2023 IPEC. All rights reserved.