# Real-Time 7-Core SDM Transmission System Using Commercial 400 Gbit/s OTN Transceivers and Network Management System

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**Abstract:** Space-division multiplexing (SDM) utilizing uncoupled multi-core fibers (MCF) is considered a promising candidate for next-generation high-speed optical transmission systems due to its huge capacity and low inter-core crosstalk. In this paper, we demonstrate a real-time high-speed SDM transmission system over a field-deployed 7-core MCF cable using commercial 400 Gbit/s backbone optical transport network (OTN) transceivers and a network management system. The transceivers employ a high noise-tolerant quadrature phase shift keying (QPSK) modulation format with a 130 Gbaud rate, enabled by optoelectronic multi-chip module (OE-MCM) packaging. The network management system can effectively manage and monitor the performance of the 7-core SDM OTN system and promptly report failure events through alarms. Our field trial demonstrates the compatibility of uncoupled MCF with high-speed OTN transmission equipment and network management systems, supporting its future deployment in next-generation high-speed terrestrial cable transmission networks.

**Keywords:** multi-core fiber; real-time transmission; optical transport network; field trial; network management system

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## 1 Introduction

With the continuous development of emerging network services and digital economy, the bandwidth requirements of optical transmission networks are experiencing explosive growth, which promotes the research and implementation of various optical multiplexed transmission techniques such as wavelength-division multiplexing (WDM) and polarization-division multiplexing (PDM)[1]. However, due to the inevitable nonlinear effects of single-mode fibers (SMF), the transmission capacity of a single SMF has approached its Shannon nonlinear limit[2]. In order to meet the explosive growing demand for network traffic, SMF-based optical transmission networks have to constantly deploy new optical fibers, which is cost-inefficient and will occupy considerable space resources. Recently, space-division multiplexing (SDM) transmission techniques utilizing multi-core fibers (MCF), few-mode fibers (FMF), or multi-mode fibers (MMF) have attracted great research interest as a promising candidate for next-generation high-speed optical transmission systems[3–4]. The contained multiple fiber cores or fiber modes of a single SDM fiber can serve as communication channels for signal transmission, which can effectively break the capacity bottleneck of a single fiber and find multiple applications in optical transport networks (OTN), passive optical networks (PON), and high-speed short-reach optical interconnections[5–7].

In terms of field implementation, the SDM approach based on uncoupled MCFs shows great potential due to its low inter-channel crosstalk, high transmission stability, and facilitated mode conversion between MCFs and SMFs. Besides, the uncoupled MCF-based transmission system can be directly compatible with existing single-mode (SM) optical modules through fan-in/fan-out (FIFO) devices, which makes it easy to be applied to various optical transmission scenarios[8–11]. Thanks to the inherent advantages of MCFs, high-speed optical transmission systems and effective maintenance techniques based on uncoupled MCFs have been widely investigated over a decade, and multiple key solutions for low-crosstalk MCFs, high-performance FIFO devices, and ultra-low-loss connection approaches have been proposed and demonstrated[12–14]. Besides, experimental demonstrations of two critical SDM configurations have validated the feasibility of MCF-based SDM optical transmission systems for next-generation high-speed long-haul transmission: 1) real-time high-speed transmission utilizing probability constellation shaping 16-array quadrature amplitude modulation (PCS-16QAM) 400 Gbit/s OTN transceivers over 7-core fiber, and 2) ultra-long-haul SDM transmission employing integrated multi-core erbium doped fiber amplifier (MC-EDFA) over 4-core fiber[15–16]. With the maturity of MCF-based SDM transmission technology, uncoupled MCFs have reached the field pilot stage, and field trials on deployed 4-core and 7-core MCF cables have also been reported[17–18]. Field-investigating the compatibility of MCFs with high-speed optical transceivers and network management systems is critical to advancing their field implementation.

In this paper, we demonstrate a real-time high-speed SDM transmission system over a field-deployed 7-core MCF cable, using commercial 130 Gbaud 400 Gbit/s backbone OTN transceivers and a network management system. Thanks to the high modulation rate enabled by optoelectronic multi-chip module (OE-MCM) packaging technology, the 400 Gbit/s OTN transceivers adopt a high noise-tolerant dual-polarization quadrature phase shift keying (DP-QPSK) modulation format and are suitable for long-haul or unrepeated long-span transmission. The network management system can manage and monitor the performance of the 7-core OTN transmission system in real time, and promptly report failure events through alarms. Our work shows a complete MCF-based OTN transmission and management system and can further promote the application of MCFs in optical transmission networks.

## 2 Field-Deployed MCF Cable

In this section, we introduce the field-deployed MCF cable used in our trial. The cable was deployed in Jinan City, China, with the route shown in Fig. 1a. The entire MCF cable spans 17.69 km between Jinxiu Chuan and Xiying data centers, which was constructed by 11 segments of the MCF cable through fusion splicing (individual segment lengths shown in Fig. 1c). The cable is deployed through a combination of three methods including direct-burial, overhead installation, and pipeline laying. Before this trial, the MCF cable had been damaged and repaired by splicing a spare cable, resulting in a final length of 17.69 km (slightly longer than the initial 17.63 km). The cable contains eight 7-core fibers, whose cross section is shown in Fig. 1b. The seven fiber cores in the MCF are arranged in a regular hexagon with a core-to-core distance of 42 μm, and the diameter of fiber cladding is 150 μm. Fluorine-doped depressed-index trenches are applied around each fiber core to reduce the inter-core crosstalk, achieving an inter-core crosstalk of less than −50 dB per 10 km transmission. A marker core is included in the 7-core fiber to ensure accurate alignment of each fiber core during the fusion splicing process. The coating diameter of the 7-core fibers is 245 μm, which is consistent with that of SMFs and makes it compatible with standard cabling processing. Partial fundamental characteristics of the 7-core fibers after cabling at 1 550 nm are shown in Table 1, which are almost identical to those before cable processing.

In our field trial, as shown in Fig. 1c, we cascaded six of the eight 7-core fibers to form a single-span 106 km MCF link for long-haul transmission testing. This cascading approach allows OTN transceivers to be installed at the same station. The

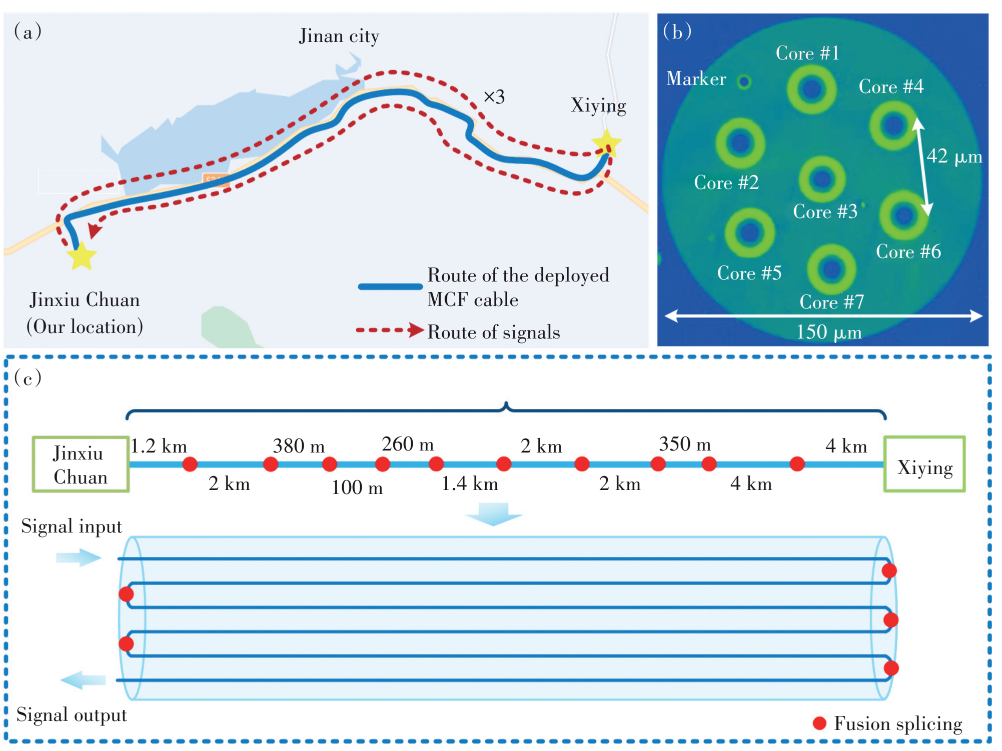



**Figure 1. Field-deployed MCF cable for our trial: (a) the route; (b) cross section of the 7-core fiber in the cable; (c) the length of each cable segment and the schematic diagram of cascading six MCFs for long-span transmission**

**Table 1. Partial fundamental characteristics of the 7-core fiber after cabling**

| Diameter of Cladding/μm | Core-to-Core Distance/μm | Mode Field Diameter/μm | Dispersion Coefficient/(ps·nm$^{-1}$·km$^{-1}$) | Attenuation Coefficient/(dB/km) | Inter-Core Crosstalk/(dB/10 km) | Bending Loss with $R$=30 mm/(dB/100 turns) |
|---|---|---|---|---|---|---|
| 150 | 42 | 9.0 | ≤22 | ≤0.22 | ≤-50 | <0.1 |

106 km MCF link has 65 multicore fusion splices, corresponding to 455 (7×65) single-core fusion splices. We measured each single-core splice loss through an optical time-domain reflectometer (OTDR) and FIFO device at 1 550 nm, and the average single-core splice loss was no more than 0.2 dB. The span loss and total inter-core crosstalk of the 106 km 7-core core-division multiplexed (CDM) link are summarized in Table 2. The CDM link contains the 106 km 7-core fiber and a pair of FIFO devices. The total inter-core crosstalk is defined as the cumulative crosstalk from all other fiber cores to the tested core. We can find that the span loss of each fiber core is no more than 37 dB, and the inter-core crosstalk is all lower than −40 dB. The span loss is higher than that of an SMF link of the same length, primarily due to the higher splice loss of MCF. Notably, Core 3 has the minimum span loss, as it is the central core and has the lowest splice loss for easily achieving precise alignment.

**Table 2. Span loss and total inter-core crosstalk of the 106 km 7-core CDM link (Unit: dB)**

| Parameter | Core 1 | Core 2 | Core 3 | Core 4 | Core 5 | Core 6 | Core 7 |
|---|---|---|---|---|---|---|---|
| Span loss | 37.0 | 35.7 | 29.6 | 34.6 | 36.0 | 35.0 | 35.4 |
| Inter-core crosstalk | −41.5 | −43.3 | −40.5 | −43.0 | −44.0 | −42.9 | −42.0 |

CDM: core-division multiplexed

## 3 System Setup and 400 Gbit/s Backbone OTN System

The system setup of the real-time 106 km CDM field trial, using commercial 400 Gbit/s OTN transceivers and a network management system, is shown in Fig. 2. At the transmitter station, a pair of C-band and L-band 400 Gbit/s optical transponder units (OTUs) are used to transmit modulated optical signals to each fiber core. The central frequencies of the C-band and L-band OTUs are tunable within the range from 190.75 THz (1 571.65 nm) to 196.6 THz (1 524.89 nm) and 184.4 THz (1 625.77 nm) to 190.25 THz (1 575.78 nm), respectively, at 150 GHz channel spacing. Each fiber core can support 80-wavelength C+L band WDM transmission. To simulate 80-wavelength fully-loaded WDM transmission, dummy light (DL) generated by C-band and L-band amplifier spontaneous emission (ASE) noise sources is used to fill the remaining wavelength channels of the C+L band. The 400 Gbit/s modulated signals and DL of the two bands are multiplexed through a C+L band integrated wavelength selection switch (WSS), and then C-band and L-band EDFAs are utilized to amplify the signals of the two bands, respectively. The amplified C-band and L-band signals are combined through an optical band multiplexer (OBM) and coupled to a fiber core of the 7-core MCF via a FIFO device. After single-span 106 km

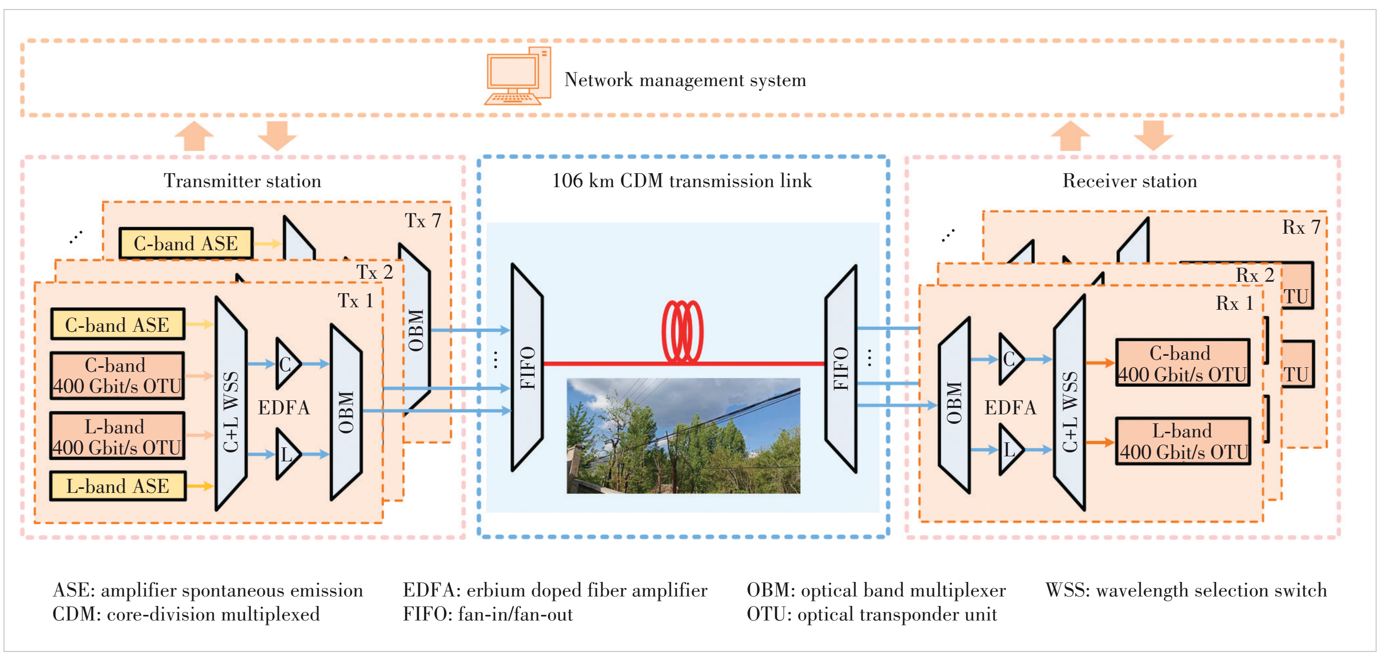



**Figure 2. System setup of the real-time 106 km CDM field trial using commercial 400 Gbit/s OTN transceivers and a network management system**

CDM transmission, the received CDM signals of the 7-core fiber are demultiplexed through another FIFO device at the receiver station, and then amplified by a pair of C-band and L-band EDFAs. The separation of the two-band received signals is also achieved through the OBM. The C-band and L-band modulated signals are demultiplexed by another C+L band WSS, and finally sent back to the corresponding 400 Gbit/s OTUs for coherent detection and real-time bit error rate (BER) calculation. The real-time digital signal processing (DSP) application-specific integrated circuit (ASIC) mainly consists of six function blocks, in the order of chromatic dispersion (CD) compensation, clock recovery, polarization demultiplexing, phase and frequency recovery, whitening filter, and equalizer. A proprietary low-density parity-check (LDPC) coding technique is utilized, achieving a soft-decision forward error correction (SD-FEC) limit up to $3.3\times10^{-2}$. Notably, we utilize each fiber core of the MCF as a transmission channel to transmit high-speed signals and employ a set of the above-mentioned OTN transceivers for each fiber core to perform the real-time CDM field trial. This system setup can test the performance of each fiber core and is closer to the structure for the field implementation of MCF.

In our field trial, the 400 Gbit/s backbone OTUs had a modulation rate up to 130 Gbaud, enabling the adoption of highly noise-tolerant DP-QPSK modulation format and making them suitable for long-haul or unrepeated long-span transmission. The high baud rate was enabled by the OE-MCM packaging technique. In this packaging technique, the driver was directly mounted on the photonic integrated circuits (PIC) through flip-chip welding, while the DSP die and PIC were packaged on the same substrate, enabling the hybrid packaging of optical and electronic chips. This packaging approach can minimize high-speed signal transmission distance, ensuring enough modulation bandwidth of the device. The C+L band integrated WSS was achieved by improving the resolution of liquid crystal on silicon (LCoS), and enabled the integrated 12 THz dispatching capability for optical signals over the C+L band. As shown in Fig. 2, the 400 Gbit/s OTN modules are connected to the network management system, which realizes real-time monitoring of the 7-core OTN system performance and can promptly report system failures through alarms. The network management system monitors the OTN transmission system by tracking real-time performance metrics such as BER, optical signal to noise ratio (OSNR), and optical power, while also analyzing OTN-specific frame overhead bytes including section monitoring (SM), path monitoring (PM), and tandem connection monitoring (TCM) for error detection. It triggers alarms for anomalies, monitors path integrity via trail trace identifiers (TTI), and evaluates latency/jitter using performance counters, enabling proactive maintenance and optimization through visualized network status and automated reporting. The adjustment of device parameters and acquisition of BERs before SD-FEC are also performed through the network management system. The 400 Gbit/s backbone OTUs utilized in the field trial are part of the ZTE S3F-E series optical transmission equipment, and specifically hosted on the LB4TF model optical line board. The OTN equipment is installed on the ZXONE 19700 platform, and the network management system is the ZTE ElasticNet UME system.

## 4 Experimental Results

In this section, we show our experimental results of the real-time single-span 106 km 400 Gbit/s OTN transmission and management system over the field-deployed 7-core fiber cable.

### 4.1 Results of 400 Gbit/s OTN Transmission System

The performance of the 400 Gbit/s CDM transmission system is evaluated utilizing the setup shown in Fig. 2. We first measured the BER performance under different single-wavelength input powers of the 7-core CDM system by adjusting the gain of the C-band and L-band EDFAs at the transmitter station. The input power of C-band signals was set 2 dBm higher than that of the L-band signals to mitigate the impact of stimulated Raman scattering (SRS). The results at 1 549.72 nm and 1 589.57 nm of the 7-fiber core channels after 106 km CDM transmission are shown in Figs. 3a and 3b, respectively.

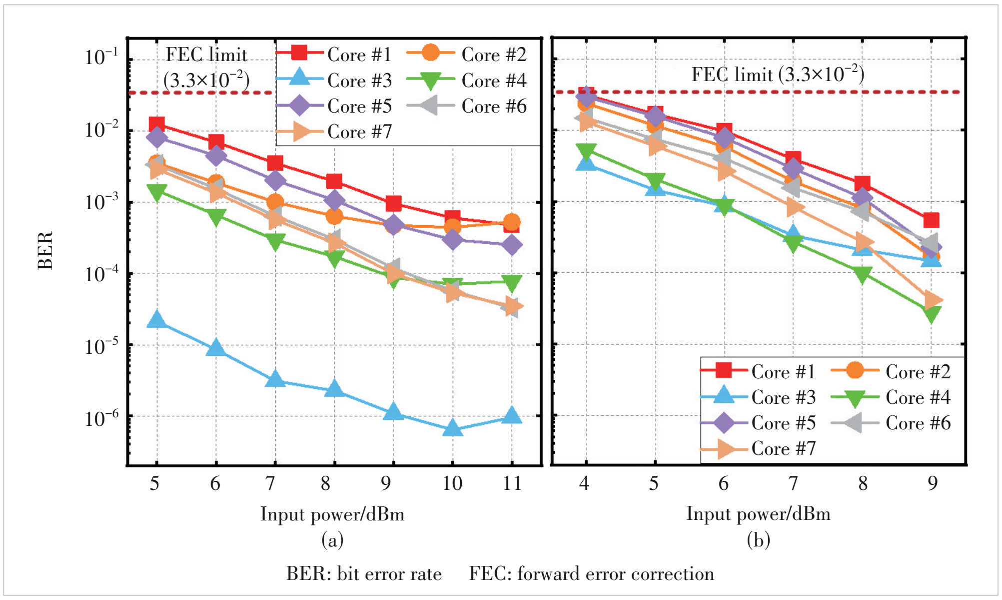
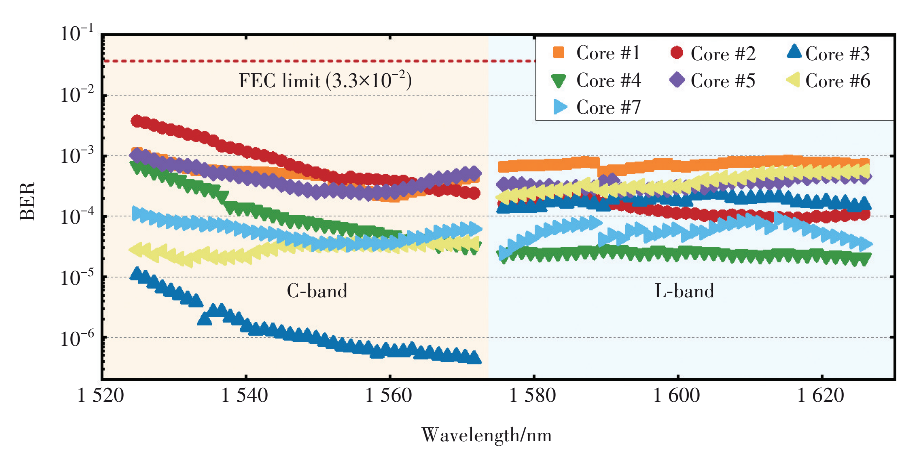


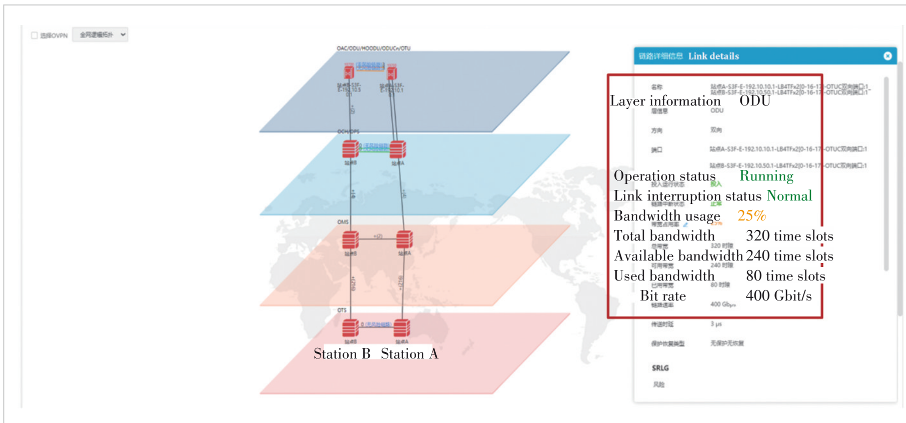

**Figure 3. Measured BER values as a function of single-wavelength input power at (a) 1 549.72 nm and (b) 1 589.57 nm of the 7-core CDM transmission system**

It is evident that each fiber core channel maintains good BER performance across a wide range of single-wavelength input powers for both C-band and L-band signals, which indicates that the CDM transmission system has strong noise tolerance. We can also find that the C-band signal of the third fiber core has the best performance, because the third fiber core has the lowest span loss. The L-band signal of the third fiber core shows no obvious advantage, primarily due to the limited performance of its L-band OTU. We then experimentally investigated the performance of 80 wavelength channels by adjusting the central wavelength of the transmitted signals (Fig. 4). Measurements were performed at single-wavelength input powers of 11 dBm and 9 dBm for C-band and L-band signals, respectively, enhancing OSNR at the receiving end without accumulating significant nonlinear penalties. All BERs across the C+L band were significantly lower than the SD-FEC limit for each core, demonstrating the feasibility of real-time 224 Tbit/s (400 Gbit/s × 80 wavelengths × 7 cores) single-span 106 km transmission over deployed 7-core MCF cable. The corresponding OSNRs of the received 80-wavelength signals for each fiber core channel exceeded 19.5 dB. Compared to the previously measured OSNR threshold (~16 dB) after 106 km CDM transmission, each wavelength and fiber core channel achieves an OSNR margin exceeding 3.5 dB. This margin is also owing to the highly noise-tolerant DP-QPSK modulation format.




BER: bit error rate FEC: forward error correction

**Figure 4. BER performance of the 400 Gbit/s 7-core 80-$\lambda$ transmission system over C+L bands**




ODU: Optical Channel Data Unit

**Figure 5. Interface of the network management system for querying end-to-end multi-layer transmission link details**

## 4.2 Results of Network Management System

We then present the experimental results of the network management system, measured from the third core channel. We first show the query function of end-to-end multi-layer transmission link details, with the system interface shown in Fig. 5. As the system is in Chinese, we translated the key parameters into English (Fig. 5). It can be found that the system can display the layered topology of OTN networks, and comprehensively monitor and present detailed link messages such as the bandwidth usage, the available bandwidth, and the bit rate. To verify its accuracy, we take the bandwidth usage as an example: Since 100GE optical modules are used in this experiment, the bandwidth usage for a single-wavelength 400 Gbit/s transmission system is 25%. When the laser is turned off, signal loss alarms are triggered by the network management system (Fig. 6), which demonstrates that the network management system can monitor the performance of the CDM OTN transmission system in real time and promptly report failure events through alarms.

Then we investigate the service latency calculation and query ability of the network management system, with the results shown in Fig. 7. The calculated service latency is 664 μs, which is consistent with the 106 km transmission link. We further set the service latency threshold to 400 μs through the "set latency threshold" function (Figs. 7 and 8). As shown in Fig. 8, the system triggers an alarm when latency exceeds the threshold. These results demonstrate that the system can accurately calculate the service latency in real time and effectively monitor the latency, which helps forge low-

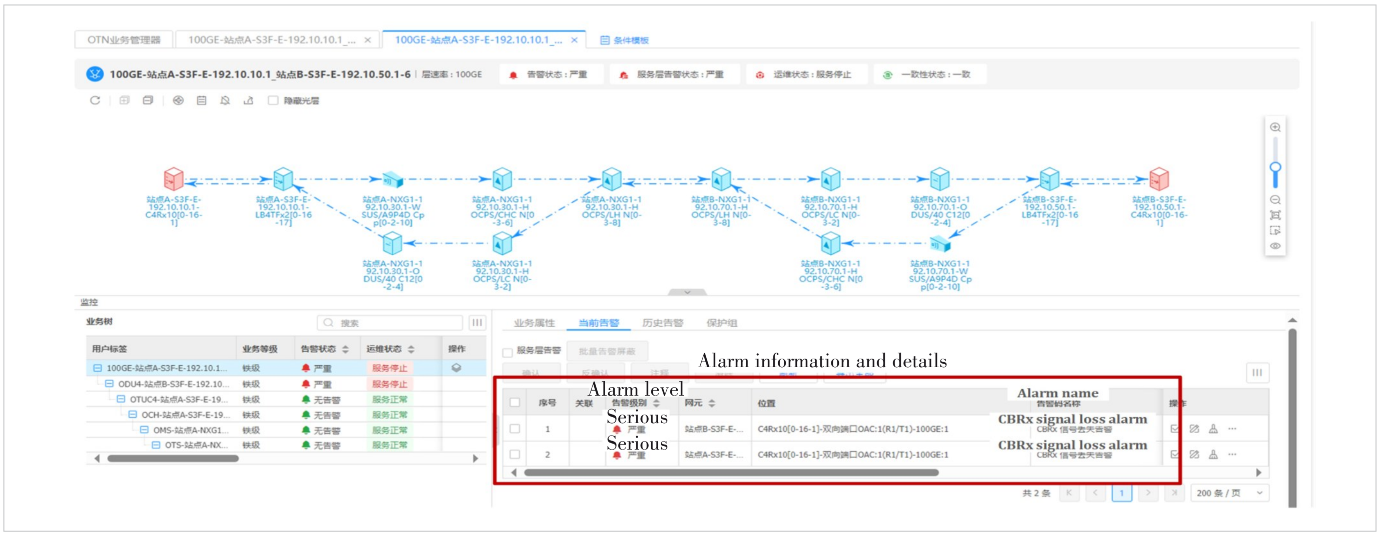



**Figure 6. Interface of the network management system for alarms queries**

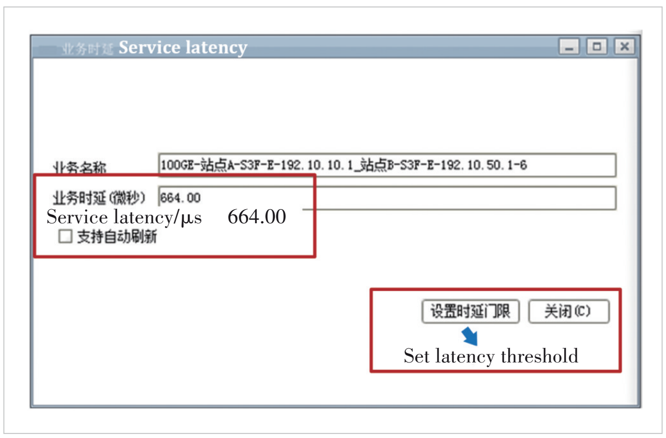



**Figure 7. Interface of the network management system for service latency queries**

latency high-speed optical transmission networks.

Finally, we evaluate the optical health monitoring ability of the network management system. As shown in Fig. 9a, we set the fiber attenuation threshold to 1.5 dBm at the optical network health monitoring configuration interface and artificially added 5 dBm attenuation to the optical link by adjusting the EDFA. The reported sub-health information is illustrated in Fig. 9b. We can observe that the system reports the transmission link is exhibiting a deterioration trend and is in a sub-health status, which demonstrates the network management system can effectively monitor the status of each transmission link and promptly detect sub-health conditions. These results demonstrate that the MCF-based OTN transmission system is directly compatible with existing network management systems, facilitating the field deployment of MCFs.

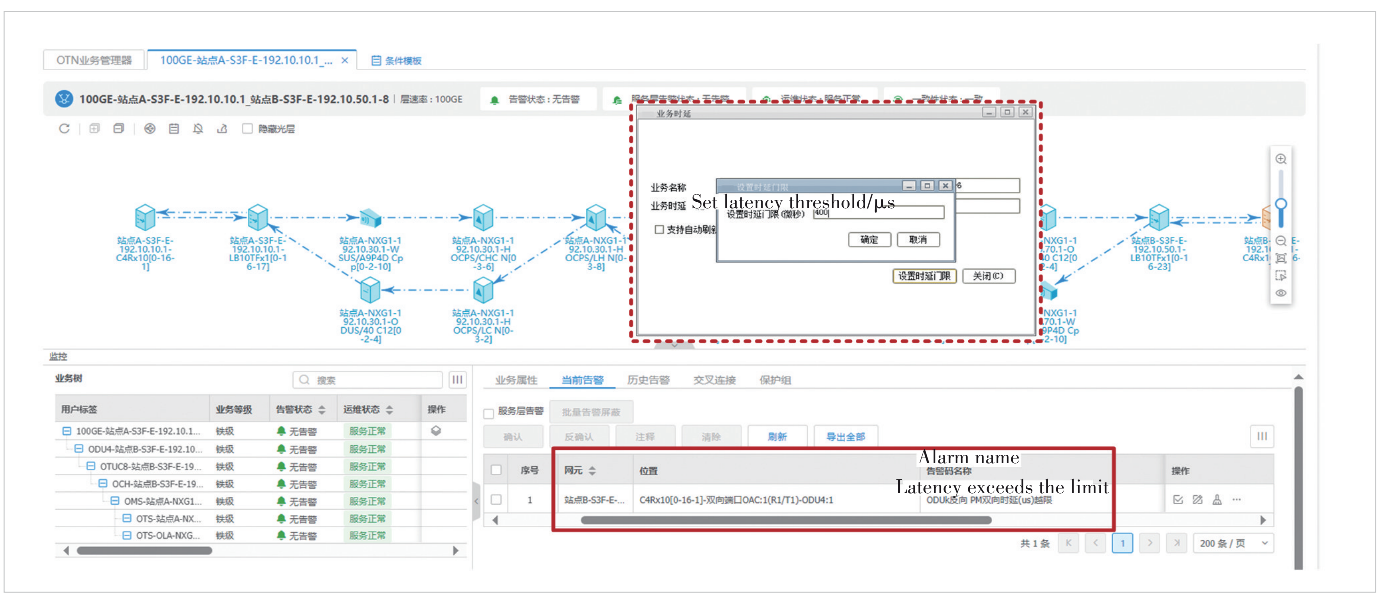



**Figure 8. Interface of the network management system when service latency exceeds the threshold**


**Figure 9. Interfaces of the network management system for (a) optical network health monitoring configuration and (b) sub-health link information**

## 5 Conclusions

In conclusion, we demonstrate a real-time single-span 106 km 7-core 80-wavelength CDM-WDM transmission system over field-deployed MCF cable using commercial 130 Gbaud 400 Gbit/s backbone OTN transceivers and network management system. The system achieves a real-time bit rate of 224 Tbit/s with over 3.5 dB OSNR thanks to the high modulation rate enabled by the OE-MCM packaging technique and high noise-tolerant DP-QPSK modulation format. The network management system effectively manages and monitors the performance of the 7-core OTN transmission system, promptly reporting multiple failure events through alarms. Our work shows a complete real-time MCF-based OTN transmission and management system, and we believe it can further promote the field implementation of uncoupled MCFs in optical transmission networks.

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**YAN Baoluo** has been conducting research at ZTE Corporation for over three years, specializing in optical fiber communication systems and algorithm development. He has published more than 20 papers in peer-reviewed journals and conferences, including the Optical Fiber Communication Conference, European Conference on Optical Communication, and Conference on Lasers and Electro-Optics. Additionally, he serves as a reviewer for several academic journals, such as the *IEEE Journal of Lightwave Technology* and *IEEE Communications Letters*. His research interests focus on optical transmission systems and intelligent algorithms.