Record 46.2Pbit·km/s real-time optical transmission over 1050-km G.652.D SSMF utilizing 400-Gbit/s transponder with a symbol rate of 91.6-GBaud

Anxu Zhang
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
zhanganx@chinatelecom.cn

Yuyang Liu
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
liuyy26@chinatelecom.cn

Lipeng Feng
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
fenglp@chinatelecom.cn

Kai Lv
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
lvkai@chinatelecom.cn

Huan Chen
WDM system design department of wireline product R&D institute
ZTE Corporation
Wuhan, China
chen.huan6@zte.com.cn

Yuting Du
WDM system design department of wireline product R&D institute
ZTE Corporation
Wuhan, China
du.yuting@zte.com.cn

Guangnan Su
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
sugn@chinatelecom.cn

Xiaoli Huo
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
huoxl@chinatelecom.cn

Junjie Li
China Telecom Research Institute
State Key Laboratory of Optical Fiber and Cable Manufacture Technology
Beijing, China
lijj28@chinatelecom.cn

***Abstract*—We experimentally demonstrated a 110-channel 44-Tbit/s real-time wavelength division multiplexing (WDM) transmission over 1050-km G.652.D single-mode fiber (SMF) utilizing 400-Gbit/s transponders with a symbol rate of 91.6-GBaud and 11-THz commercial C+L band Erbium-doped fiber amplifiers (EDFAs). To the best of our knowledge, this is a record capacity distance product (46.2-Pbit·km/s) in the real-time optical transmission systems.**

Keywords—Real-time, optical fiber transmission, 400-Gbit/s, wavelength division multiplexing, C+L

I. Introduction

With the rapid development of bandwidth-intensive services such as the 5th-generation mobile communication technology (5G), cloud computing, mobile internet, and ultra-high-definition video, network traffic will continue to maintain rapid growth. The compound annual growth rate (CAGR) of global IP data traffic has been as high as 26% from 2017-2022, and will continue to grow with such high rate [1]. At the same time, Internet users' requirements for network access bandwidth have also been further improved. It is expected that the global fixed access rate and the mobile access rate will maintain a CAGR growth rate of 20% and 27%, respectively, between 2018 and 2023 [2]. Undoubtedly, as the carrier of information and traffic, the optical communication infrastructure will face tremendous pressure in terms of bandwidth expansion and the single-wavelength rate increase [3,4].

The speed of optical transmission per wavelength has evolved from 100-Gbit/s to 800-Gbit/s and will be even 1.6-Tbit/s in the future [5, 6]. Real-time transmissions of high speed per wavelength have been frequently demonstrated. Field trial of 400-Gbit/s transmission over 1910-km has been demonstrated, with widened C-band amplifiers, capacity of 24-Tbit/s has been achieved [5]. Real-time 2×800G has been transmitted over 1600-km single-mode fiber (SMF) with C-band amplifiers [7]. Although high-speed coherent module with higher-order modulation is benefit to simplify the network design, planning, and management, the transmission distance is also limited. In long-distance transmission, the use of electrical relay stations should be minimized and modules designed for longer distance are required. Recently, 400-Gbit/s has become one of the most potential candidates for the next generation ultra-long haul backbone network. To further increase the transmission capacity, another way is to use wider bandwidth. Several real-time C+L band transmission has been performed. For instance, a 63.2-Tb/s throughput in a 5-span 440-km SMF link employing real-time 400-Gbit/s polarization division multiplexing-16-ary quadrature amplitude modulation (PDM-16QAM) transponders is demonstrated and show a feasible future of the 400-Gbit/s transmission [9]. In [10], C+L band wavelength division multiplexing (WDM) PDM-quadrature phase shift keying (PDM-QPSK) transmission has also been proven. Nevertheless, there are still two main challenges to be overcome to perform multi-band system, one is the stimulated Raman scattering (SRS) induced power transferring, and the other is the wider band amplifier technology [11].

In this paper, we have experimentally demonstrated a real-time WDM transmission with high performance 400-Gbit/s coherent transponders and bandwidth widened 11-THz Erbium-doped optical fiber amplifiers (EDFAs). The 400-Gbit/s signal is generated using probabilistic constellation shaped (PCS) PDM-16QAM modulation format with a symbol rate of 91.6-GBaud, and placed in a 100-GHz frequency grid. The optical back-to-back (B2B) performance of the transponder is measured and shows an

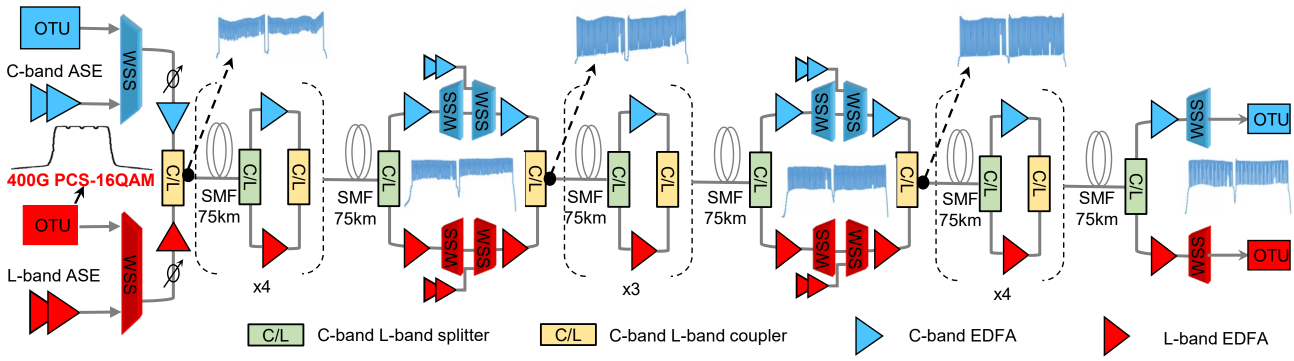

Fig. 1. Experimental setup of 400G real-time transmission system. OTU: Optical transporter unit, SMF: Single mode fiber, WSS: Wavelength selected switch, ASE: Amplifier spontaneous emission.

optical signal-noise ratio (OSNR) tolerance of ~17dB. Bandwidth widened C-band and L-band EDFAs and wavelength selective switches (WSSs) are adopted to realize a total bandwidth of 11-THz and a real-time capacity of 44-Tbit/s. The OSNR performance of different channels are equalized, to weaken the optical power and OSNR uneven caused by the SRS phenomenon. A maximum transmission distance of 1050-km over G.652.D fiber is achieved. To the best of our knowledge, this is a record capacity distance product in the real-time optical transmission system (46.2-Pbit·km/s).

II. Experimental Setup

A. Transmitter side setup

The experimental setup is shown in Fig. 1. The total bandwidth of 11-THz of the system is consisted of 6-THz at C-band and 5-THz at L-band. In the C-band, one testing channel is filled by the PDM-16QAM 400-Gbit/s signal with symbol rate of 91.6-GBaud, which is generated by a real-time optical transporter unit (OTU). The rest of the 59 channels are loading signals of amplifier spontaneous emission (ASE) noise. With two cascading EDFAs and a WSS, the ASE noise of each channel is generated and shaped similar to the spectrum of real-time channels. The 60 channels are multiplexed and amplified by C-band EDFA after passing through a variable optical attenuator (VOA), which is used to control the input power to the fiber link. In the L-band, similar to the C-band, the 50 channels consist of one 400-Gbit/s real-time PDM-16QAM signal and 49 loading ASE noise with 100-GHz channel space. Thus, the total capacity is 44-Tbit/s. It should be noted that the WSS and EDFA in the C-band are widened to support 48nm optical bandwidth, ranging from 1524.4nm to 1572.3nm, and L-band WSS and EDFA can support 43.2nm optical bandwidth, ranging from 1575.2nm to 1618.4nm. Finally, the C-band multiplexed signals and the L-band multiplexed signals are combined by a C-band and L-band WDM coupler and then send to the fiber transmission link.

B. The transmission link

The transmission link is composed of 14-span G.652.D SMF and each span adopts a 75-km SMF and a VOA, realizing a total transmission length of 1050-km. The attenuation value of each VOA is set as 2~3dB for engineering link budget reservation to tolerate the static and dynamic optical impairment in field-deployed fiber links. Limited by the amplifier bandwidth, the signals of the C-band and the L-band need to be de-multiplexed and amplified separately. Generally, the C-band and L-band WDM combiner causes 0.6dB and 0.8dB insertion losses at C-band and L-band, respectively. The average intrinsic link loss, including the fiber, VOA, and WDM couplers, is controlled to 22 dB, while the signals of L-band show about 0.5 dB larger losses than that of the C-band due to the wavelength-dependent loss of the fiber and the WDM couplers. It should be noted that in the practical transmission system, due to the SRS phenomenon, the loss of the C-band signal is larger than that of the L-band. The span 5 and span 9 is composed of 75-km SMF and a dynamic gain equalization (DGE) unit to adjust the optical power flatness to obtain a better transmission performance.

C. Receiver side setup

At the receiver side, the signals are split, and then pre-amplified by the C-band and the L-band EDFAs respectively. After that, the C-band and the L-band signals are selected by corresponding WSSs and detected by the real-time OTU. The optical performances can be measured at the monitor port of the EDFAs, and the bit error rate (BER) and Q-factor can be recorded.

III. Results and Discussions

A. Back-to back case

We first investigate the pre-forward error correction (pre-FEC) BER versus OSNR in optical back-to-back (B2B) case of 400-Gbit/s transponders with 91.6-Gbaud symbol rate

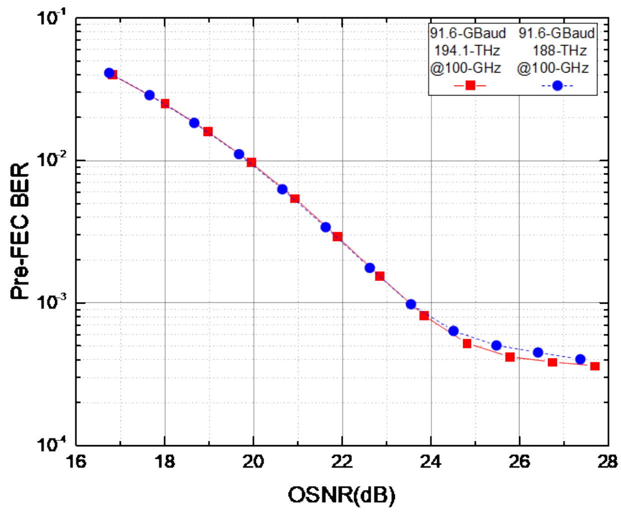

Fig. 2. Pre-FEC BER versus OSNR in B2B case for different symbol rate and C/L wavelength.

operated at C-band and L-band, as shown in Fig. 2. The measured wavelengths are 194.1-THz and 188-THz, respectively. The required OSNR of the 400-Gbit/s transponders with 2×10^{-2} FEC threshold are 16.93dB and 16.88dB at the two wavelengths, respectively, which implies that the performances of the 400-Gbit/s transponders at the C-band and the L-band are almost the same.

The filtering penalty of the 91.6-Gbaud signal placed in 100-GHz channel spacing is also investigated. The 400-Gbit/s signal has been passed through different number of WSSs, the filtering penalty results are plotted in Fig. 3. It can be observed that when sixth WSS is adopted, the filtering penalty is 0.62dB, which shows an acceptable performance degradation.

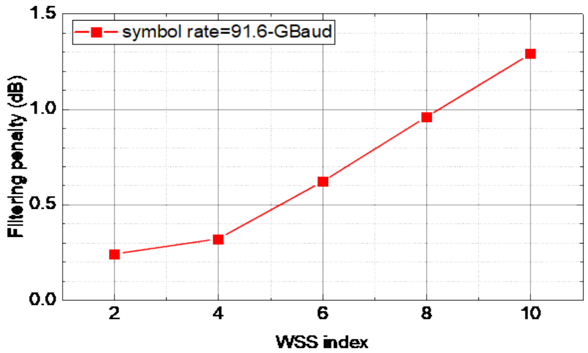

Fig. 3. Filtering penalty of 2nd to 10th WSSs.

B. *G.652.D transmission case*

Due to the power transfer caused by the SRS phenomenon, to equalize the received power and OSNR of all the 110 channels, we utilize an automatic power optimization (APO) procedure to optimize the power profile at the output of each span based on the optical power spectra monitored at the booster, every DGE unit and pre-amplifier. During the APO procedure, the gain and gain tilt of the EDFAs for each band are iteratively adjusted to narrow the gap between the total power of C-band and L-band. In addition, channel-level attenuation adjustment is carried out in the WSS at the transmitter to further enhance the power uniformity. The spectrums are shown in Fig. 1 as insets. The OSNR at the receiver end of all the channels are also measured and shown in Fig. 4. It can be found that the

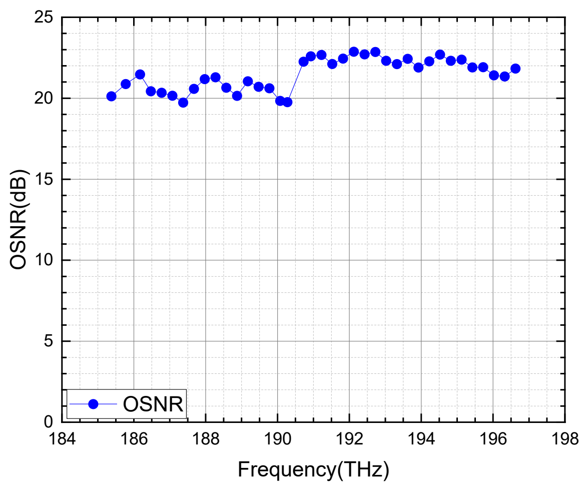

Fig. 4. Frequency (THz) versus the OSNR (dB) after fiber transmission.

OSNR is measured every 4 wavelengths at 11-THz working bandwidth. The averaged OSNR for C-band is 22.3dB, which is 1.73dB better than that of L-band, mainly due to larger noise figure (NF) in L-band EDFAs. The OSNR flatness of C-band and L-band are 1.74dB and 1.53dB, respectively, and the difference between the maximum OSNR and the minimum OSNR overall 11-THz is 3.1dB.

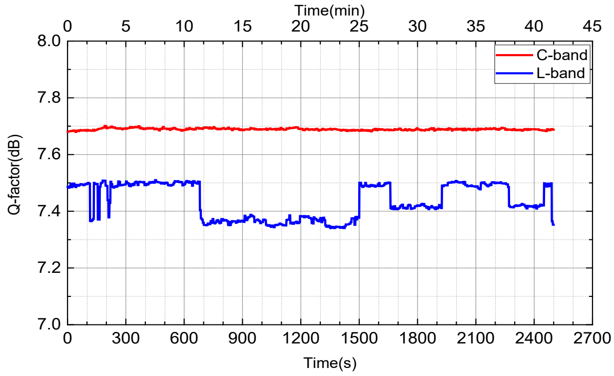

Fig. 5. Long-term Q-factor performances of the C-band (red) and L-band (blue) signals.

Finally, the long-term pre-FEC BER of the C-band and L-band signals after 1050-km G.652.D transmission are recorded, which are captured from the transponder every five seconds. The Q-factor values are calculated from the pre-FEC BER, and the Q-factor curves of the C-band (red) and L-band (blue) signals are shown in Fig. 5. These curves show stable BER and Q-factor monitoring over more than 2000s. A fluctuation of Q-factor within 0.2dB can be observed of L-band signal, but all the Q-factor values are above the limit.

IV. CONCLUSION

In this paper, a record capacity distance product in the real-time optical transmission system (46.2-Pbit·km/s) is demonstrated. A 110-channel 44-Tbit/s real-time WDM transmission over 1050-km G.652.D single mode fiber utilizing 400-Gbit/s transponder with a symbol rate of 91.6-GBaud and 11-THz commercial C+L band EDFAs is experimentally performed.

REFERENCES

[1] Cisco Visual Networking Index: Forecast and Trends, 2017–2022, https://www.cisco.com/c/en/us/about/legal/trademarks.html.

[2] Cisco. Cisco annual internet report (2018-2023), https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf

[3] P. J. Winzer, D. T. Neilson, and A. R. Chraplyvy, "Fiber-optic Transmission and Networking: The Previous 20 and the Next 20 Years [Invited]," in Optics Express, vol. 26, no. 18, pp. 24190–24239, 2018.

[4] K. Zhong et al., "Digital signal processing for short reach optical communications: A review of current technologies and future trends," in Journal of Lightwave Technology, vol. 36, no. 2, pp. 377–400, 2018.

[5] A. Zhang et al., "Field trial of 24-Tb/s (60×400Gb/s) DWDM transmission over a 1910-km G.654.E fiber link with 6-THz-bandwidth C-band EDFAs," Opt. Express 29(26), 43811–43818 (2021).

[6] A. Zhang et al., "32×800Gb/s/carrier DWDM Coherent Transmission over 1050km EDFA amplified G.652 Fiber using OE-MCM Prototype with up to 140GBd Symbol Rate," in proceeding of Asia Communications and Photonics Conference and Exhibition (ACP), paper 1-3, 2022.

[7] R. Maher et al., " Real-Time 100.4 GBd PCS-64QAM Transmission of a 1.6 Tb/s Super-Channel Over 1600 km of G.654.E Fiber," in proceeding of Optical Fiber Communication Conference (OFC), paper Tu6D.2, 2021.

[8] N. Deng, L. Zong, H. Jiang, Y. Duan and K. Zhang, "Challenges and Enabling Technologies for Multi-Band WDM Optical Networks," in Journal of Lightwave Technology, vol. 40, no. 11, pp. 3385-3394, 2022.

[9] D. Le Gac et al., "63.2Tb/s Real-time Transmission Through Discrete Extended C- and L-Band Amplification in a 440km SMF Link," in proceeding of European Conference on Optical Communications (ECOC), paper 1-3, 2021.

[10] H. Kawahara et al., "Simultaneous Nonlinearity Compensation of C+L-band WDM PDM-QPSK Signals using Inter-band Complementary Spectral Inversion," in proceeding of Optoelectronics and Communications Conference (OECC), paper T2B.6, 2021.

[11] S. Okamoto et al., "A Study on the Effect of Ultra-Wide Band WDM on Optical Transmission Systems," in Journal of Lightwave Technology, vol. 38, no. 5, pp. 1061-1070, 2020.