Real-time Demonstration of 12-λ×800-Gb/s Single-carrier 90.5-GBd DP-64QAM-PCS Coherent Transmission over 1122-km Ultra-low-loss G.654.E Fiber

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Abstract *A record real-time error-free coherent transmission of 12-λ×800-Gb/s single-carrier 90.5-GBd DP-64QAM-PCS signals with a spectral efficiency of 8.0 bit/s/Hz over 1122-km ultra-low-loss large-effective-area G.654.E fiber is experimentally demonstrated for the first time.*

Introduction

Driven by the rapid development of 5G applications, gigabit broadband services and cloud-oriented network, long-haul optical transport networks are facing great challenges on enhancing system capacity. For example, the compound annual growth rate (CAGR) of global IP traffic is up to 24%[1]. In the past few decades, the single-channel rate of long-haul optical transmission systems have been increased from 10 Gb/s, 40 Gb/s, to 100 Gb/s. By using coherent techniques to overcome the limitations, such as chromatic dispersion, 100-Gb/s long-haul transmission systems have been achieved and widely deployed in the world[2-3]. To pursue large capacity, 200-Gb/s transmission techniques are being deployed regionally. With a combination of advanced modulation formats and G.654.E fiber, the field-trial transmission distance of single-carrier 200-Gb/s and 400-Gb/s has been significantly improved to 1000-km and 600-km respectively with an optical signal-to-noise ratio (OSNR) margin of more than 5 dB[4-5]. As single-carrier 400-Gb/s long-haul transmission will potentially be available in the next few years, 800-Gb/s long-haul transmission is becoming a hot topic[6-8]. 10×800-Gb/s off-line transmission using single-carrier dual polarization 256 quadrature amplitude modulation with probabilistic constellation shaping (DP-256QAM-PCS) and 100-GHz grid over 400-km has been reported[6]. Net 800-Gb/s off-line transmission over 605-km using single-carrier 99.5-GBd DP-64QAM has also been achieved[7]. Moreover, an impressive experimental result of 2×800-Gb/s 95.6-GBd DP-64QAM real-time transmission over 1000-km with over 101.62-GHz bandwidth has been achieved based on digital sub-carrier multiplexing recently[8]. We can see that different kinds of modulation formats and baud rates have been proposed for 800-Gb/s system, there are still some controversies on future choice that is crucial to the system and devices design of the whole industry. More efforts should be made to further increase 800-Gb/s system's transmission distance by comprehensively considering modulation format, baud rate, fiber type and amplification. For service providers, with relatively lower cost and complexity, single-carrier approaches might be more attractive than sub-carrier approaches if they could meet the requirement of long-haul transmission. However, to the best of our knowledge, there is still no report on real-time single-carrier 800-Gb/s approach to achieve transmission distance over 1000 km. Therefore, we would like to explore the feasibility of real-time single-carrier 800-Gb/s approach for 1000-km above transmission, and provide reference for both industry and academia.

In this paper, we propose and demonstrate a single-carrier 800-Gb/s 100-GHz-spacing wavelength division multiplexing (WDM) long-haul transmission system based on a novel functional structure of real-time coherent receiver. Here, a turbo equalizer consisting of an iterated combination of inter-symbol interference (ISI) equalizer and forward error correction (FEC) decoder can effectively compensate the ISI penalty and reduce the filtering penalty of passing 100-GHz gird. By using this coherent receiver, single-carrier 90.5-GBd 800-Gb/s DP-64QAM-PCS signal can fit into 100-GHz standard WDM grid for long-haul transmission. Furthermore, with the aid of G.654.E fiber having an attenuation coefficient of 0.156-dB/km, real-time error-free 12-λ×800-Gb/s DP-64QAM-PCS coherent

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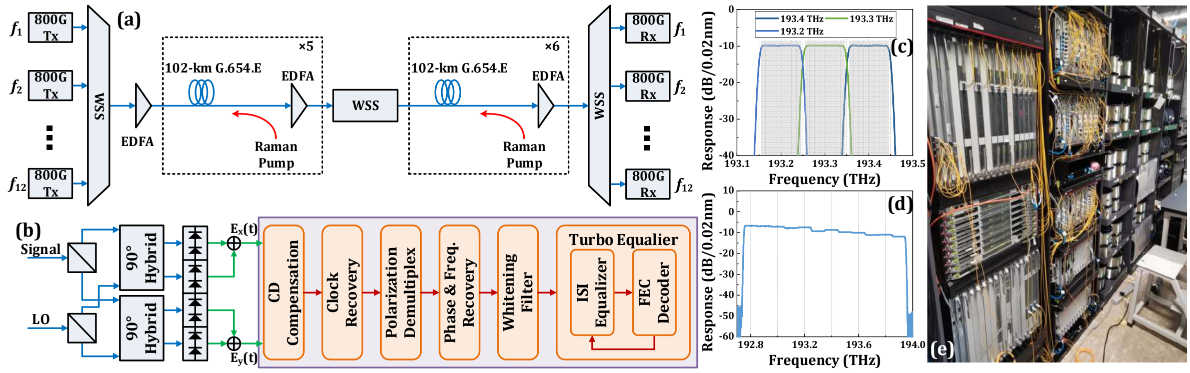

Fig. 1: (a) Schematic experimental setup of the 12-λ×800-Gb/s DP-64QAM-PCS coherent transmission; (b) Functional structure of the real-time coherent receiver; (c) spectral response of WSSs using as multiplexer/demultiplexer measured at the frequencies of 193.2, 193.3 and 193.4 THz; (d) Measured spectral response of WSS used between Span 5 and Span 6; (e) photo of the built real-time test bed.

transmission over 1122 km is successfully demonstrated for the first time. 24-hour long-time test is also carried out to ensure its stability.

Architecture and Principle

Our schematic experimental setup is shown in Fig. 1(a). As we know, compared with lower-order modulation formats , 800-Gb/s DP-64QAM signal is more sensitive to both OSNR and nonlinearities, such as self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM) and stimulated Raman scattering (SRS), etc. Therefore, ultra-low-loss large-effective-area (A_{eff}) G.654.E fiber is a promising way to mitigate fiber loss and nonlinear impairments. Moreover, backward pumped Raman amplifiers (BPRAs) could be adopted to further improve the OSNR. Due to the larger A_{eff}, the net gain of BPRA would correspondingly decrease, resulting in that pure BPRAs may not be able to fully compensate the span loss. In this way, erbium doped fiber amplifiers (EDFAs) should remain in the link. With the combination of BPRAs and EDFAs, the noise figure is relatively lower than that of the pure EDFA setup and its amplification gain is larger than that of the pure BPRA setup. To obtain similar transmission performance among different channels, a wavelength selective switch (WSS) should also be placed after every few hundred kilometers of transmission to equalize the gain of each channel.

We have also noticed that the 800-Gb/s real-time demonstration reported before has higher baud rate and needs to be placed into a grid larger than 100 GHz[8] to avoid significant ISI, which is incompatible with the standard 100-GHz WDM grid defined by ITU-T G.694.1[9]. To overcome this problem and ensure our system's performance in long-haul scenarios, intensive efforts have been made into the design of the real-time coherent receiver. Figure 1(b) shows the functional structure of the real-time coherent receiver. The real-time digital signal processing (DSP) application specific integrated circuit (ASIC) mainly consists of 6 function blocks, in the order of chromatic dispersion (CD) compensation, clock recovery, polarization demultiplexing, phase and frequency recovery, whitening filter and turbo equalizer. It is well known that when high baud rate signal pass through 100-GHz WDM grid, a large penalty will occur because of ISI. Therefore, an ISI compensating equalizer consisting of a whitening filter and a sequence detection equalizer is used, which can compensate the ISI penalty. Furthermore, we combine the ISI equalizer and the FEC decoder into a turbo equalizer, and use an iteration between the FEC and the equalizer to further compensate the ISI penalty, which greatly reduces the filtering penalty of signal transmission and obtains good transmission performance. As a result, 90.5-GBd 800-Gb/s DP-64QAM-PCS transceiver can be applicable for long-haul 100-GHz WDM transmission.

Experimental Results

The real-time tests are carried out based on the schematic experimental setup shown in Fig. 1(a). The photo of the built test bed is shown in Fig. 1(e). 12 sets of single-carrier 90.5GBd DP-64QAM-PCS transmitters are used for signal generation, whose central frequencies range from 192.8 THz to 193.9 THz with a channel spacing of 100 GHz. The 12-channels optical signals are combined by a WSS and then sent into an EDFA for amplification. In the transmission link, there are 11 spans by using G.654.E fiber and hybrid amplifiers. Here, the average measured attenuation coefficient and the A_{eff} of the G.654.E fiber are 0.156 dB/km and 125 μm^2, respectively. The length of each span is about 102 km and the net gain of BPRA is 11 dB. The spectral response of the WSS used for gain equalization after 5-span transmission is illustrated in Fig. 1(d). After another 6 spans, the 12-channel WDM signals are demultiplexed by another WSS and subsequently launched into

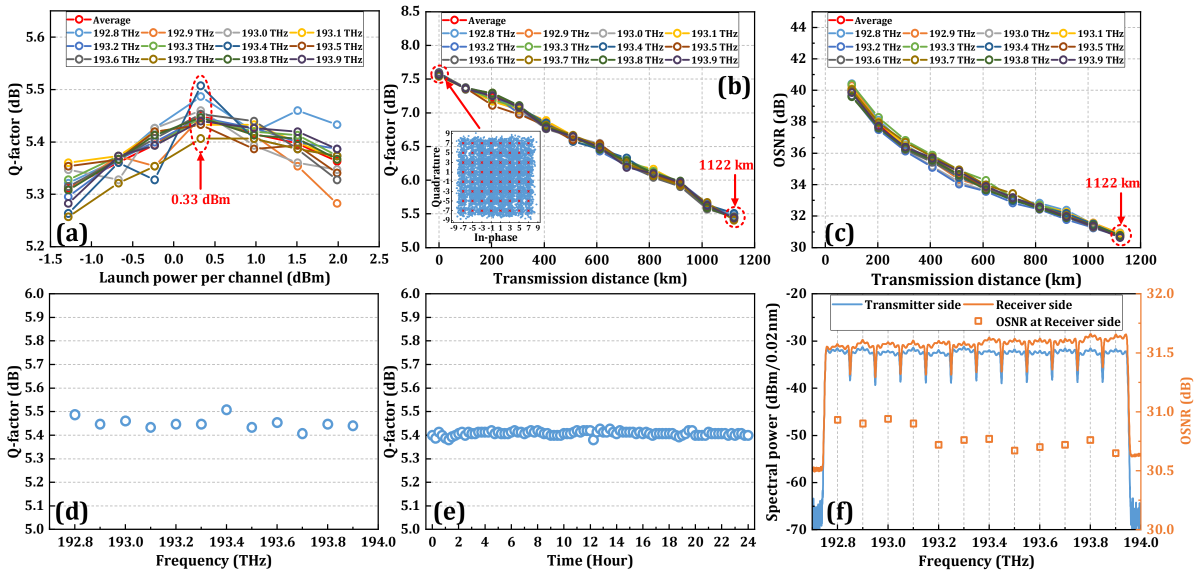

Fig. 2: (a) Measured Q-factor as a function of launch power per channel for all 12 channels after 1122-km transmission; (b) measured Q-factor as a function of transmission distance for all 12 channels, inset: constellation diagram of one polarization of the 90.5GBd DP-64QAM-PCS transmitter; (c) measured OSNR as a function of transmission distance for all 12 channels; (d) measured Q-factors of all 12 channels after 1122-km transmission at the optimal launch power; (e) 24-hour Q-factor of channel 193.7 THz; (f) measured spectra of all 12 channels at the transmitter side and receiver side, respectively, as well as corresponding OSNR after 1122-km transmission.

corresponding receivers for coherent detection. The response of WSSs used in our experiment as multiplexer/demultiplexer is shown in Fig. 1(c) with a commonly-used flat-top shape. It should be noted the transceivers are real-time prototypes.

To obtain the best transmission performance, we firstly sweep the launch power per channel into fiber link by adjusting EDFAs with a step of ~0.50 dB. As shown in Fig. 2(a), the optimal launch power per channel is about 0.33 dBm, then the average Q-factor of all channels after 1122-km transmission reaches its best of 5.45 dB, of which corresponding pre-FEC BER is 3.05×10^{-2}. The Q-factors of all 12 channels after 1122-km transmission are illustrated in Fig. 2(d), distributing between 5.41~5.51 dB. All channels are error-free after low density parity check (LDPC) FEC with 25% overhead (OH). At the optimal launch power, the Q-factor as well as corresponding OSNR of each channel after different transmission distances are measured and shown in Fig. 2(b)-(c), respectively. The constellation diagram of one polarization of the 90.5GBd DP-64QAM-PCS transmitter is also illustrated in the inset of Fig. 2(b). We can see that the average Q-factor gradually deteriorates from 7.57 dB at back to back (BtB) to 5.45 dB after 1122-km transmission. Simultaneously, the average OSNR gradually deteriorates from 39.98 dB after 102-km transmission to 30.79 dB after 1122-km transmission. The optical spectra of all 12 channels at the transmitter side and receiver side measured at the resolution of 0.02 nm are shown in Fig. 2(f), respectively, while corresponding OSNRs after 1122-km transmission are illustrated in the same plot as well. It can be seen that to maintain similar performance between all channels, the WDM channels at short wavelengths have higher optical power than that at long wavelengths. To verify the stability of the single-carrier 800-Gb/s WDM transmission system over 1122 km, we also measure the 24-hour Q-factors of the worst channel 193.7 THz with a time interval of 15 min. As shown in Fig. 2(e), the Q-factor is very stable ranging from 5.38 dB to 5.43 dB, and error-free transmission is also achieved after LDPC-FEC. All experimental results above show that 12-λ×100-GHz-spacing single-carrier DP-64QAM-PCS 800-Gb/s WDM system can reach a long-haul transmission distance of 1122 km. It also can be seen that this 90.5-GBd single-carrier DP-64QAM-PCS signal is able to satisfy long-haul transmission requirement and 100-GHz grid.

Conclusions

In conclusion, a single-carrier 800-Gb/s 100-GHz-spacing WDM long-haul transmission system based on a novel functional structure of real-time coherent receiver is proposed and demonstrated. Furthermore, with the help of 0.156-dB/km G.654.E fiber and Raman amplification, real-time error-free 12-λ×800-Gb/s single-carrier DP-64QAM-PCS coherent transmission over 1122-km distance is successfully demonstrated for the first time, showing that single-carrier 800-Gb/s signal can meet the requirements of long-haul transmission.

Acknowledgements

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