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Real-time 10-λ×800-Gb/s Sub-carrier-multiplexing 95-GBd DP-64QAM-PCS Transmission over 2018-km G.654.E Fibre with Pure Backward Distributed Raman Amplification

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Abstract *With the help of pure backward distributed Raman amplification and ultra-low-loss G.654.E fibre, for the first time, a record 2018-km transmission with OSNR margin of 3.39 dB can be achieved by 10-λ×800-Gb/s sub-carrier-multiplexing 95-GBd DP-64QAM-PCS signals at 112.5-GHz grid. ©2022 The Author(s)*

Introduction

With the rapid growth of data-hungry applications, e.g. short-form user videos like TikTok and webinars due to the limitation of global Covid-19 pandemic [1], long-haul backbone transport networks are expected to carry more dataflows efficiently. As arteries of communications worldwide, long-haul backbone transport networks traditionally play the role of consuming a large portion of energy. Now that major regimes around the world have released their plans of carbon dioxide emission cutting and neutrality [2-3], the power consumption of new long-haul transport technique will be a factor as important as transmission performance. 100G and 200G long-haul transmission systems have been massively deployed worldwide [4]. 400G techniques have already been able to reduce optical module numbers needed per 100G by two to four times with sufficient transmission performance over both G.652.D and G.654.E. According to multiple network operator's news, it is expected that 400G may start its backbone network deployment in around 2023. Hence, it is necessary to investigate the performance of the more environment-friendly 800G approaches for next generation backbone network.

There have been some discussions and reports on 800G long-haul transmission [5-7]. In 2020, Infinera reported its 800G DSP ASIC design using probabilistic constellation shaping (PCS) and digital sub-carrier multiplexing (SCM), based on which 2×800-Gb/s 95.6-GBd dual polarization 64 quadrature amplitude modulation (DP-64QAM) real-time transmission over 1000-km G.654.E has been achieved [5]. After one year, they furtherly enhanced the transmission distance to 1600-km by 100.4-GBd DP-64QAM-PCS and G.654.E [6]. Another real-time 12-λ×800-Gb/s single-carrier 90.5-GBd DP-64QAM-PCS transmission over 1122-km G.654.E has also been reported [7]. We can see that, with the help of low-noise hybrid amplification of erbium doped fibre amplifier (EDFA) and Raman amplifier for all three demonstrations, 800G techniques can surpass 1000-km transmission distance with their extreme abilities. However, for 100G and 400G, they can easily transmit more than 2000-km, which is still not achieved by 800G techniques. Therefore, we would like to see the extreme transmission ability of real-time 800G based on about 90-GBd symbol rate.

In this paper, we demonstrate a SCM 800-Gb/s wavelength-division-multiplexing (WDM) ultra-long-haul transmission systems based on pure backward distributed Raman amplifiers (BDRAs) and ultra-low-loss large-effective-area G.654.E. links. The BDRAs can effectively provide a lower noise figure than hybrid amplification consisting of EDFA and RA. Though The gain of BDRA will drop about 30% on G.654.E due to the lower nonlinearity coefficient, it still can fully compensate the span loss of 16 dB. Furthermore, the introduction of BDRA also eliminates wavelength selective switches (WSSs) used as gain control, which inversely helps the slowing down of optical signal-to-noise ratio (OSNR). With all above efforts, a real-time error-free 10-λ×800-Gb/s SCM 95-GBd DP-64QAM-PCS transmission over 2018 km is successfully demonstrated for the first time. OSNR margin of 3.39 dB is achieved. Experimental results show that longer distance can be achieved under the same architecture and configuration.

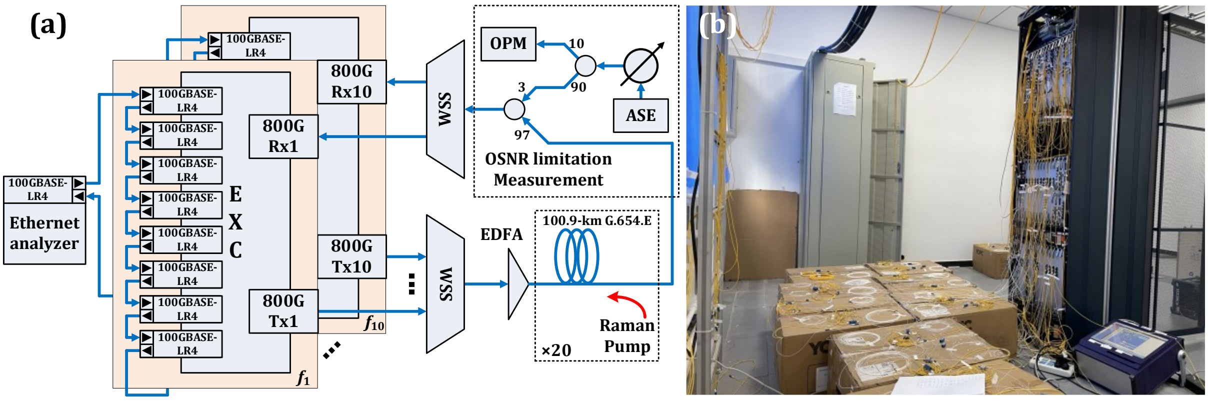

Fig. 1: (a) Schematic experimental setup of the 10-λ×800-Gb/s SCM DP-64QAM-PCS coherent transmission; (b) photograph of the built real-time test bed.

Principles and Experimental Setup

Different from previous 100G and 200G, there are two multiplexing approaches that have been proposed and realized for real-time 800G [5-7]. One is SCM approach, another one is single-carrier approach. When similar symbol rate is adopted, for single-carrier approach, it has better OSNR tolerance, especially with higher order modulation formats. Performance penalties caused by devices, e.g. IQ skew, are relatively smaller compared to SCM. Single-carrier can also deal with faster rotation of state of polarization (RSOP). In addition, the digital signal processing (DSP) structure should be simpler as well. Since it needs no guard band, it has better spectrum efficiency and smaller filtering penalty. While for SCM approach, different modulation formats and orders can be used in different sub-carriers its nonlinear penalty should be relatively smaller with higher order modulation formats. It could also enhance the ability of compensating chromatic dispersion (CD) and polarization mode dispersion (PMD). Owing to lower baud rates of sub-carriers, lower equalization enhanced phase noise (EEPN) can be achieved [5]. Particularly, SCM approach is applicable to P2MP scenario. We can see that SCM and single-carrier have shown advantages and disadvantages in different aspects, and no approach has overwhelming superiority in theory.

One critical requirement for long-haul backbone network is reserving sufficient OSNR margin, e.g. >5 dB in China Mobile, for future link degradation in the length of at least 1000 km. To the best of our knowledge, we have not seen such results. To achieve this goal with OSNR margin as large as possible, we carefully designed the schematic experimental setup as shown in Fig. 1(a). First of all, ultra-low-loss large-effective-area (A_{eff}) G.654.E fiber is essential for the mitigation of nonlinear penalty because of the high sensitivity of 800-Gb/s DP-64QAM-PCS signals in long-haul transmission. In addition, its 0.158-dB/km attenuation coefficient provides a low span loss of 16 dB over a long enough span of 100.9 km that could cover most span length in reality. It also brings another benefit that the gain of BPRA could fully compensate the 16-dB loss, which inversely eliminates EDFAs in the system and reduces ASE noise accumulation. Moreover, the gain flattening can be realized by adjusting the four pumps of the BRPA, in result WSS used as gain control is not necessary as well. Thus, the current system theoretically can achieve better performance with fewer devices. Only one discrete EDFA is employed at the transmitter side as booster.

Experimental Results

As shown in Fig. 1(a), 10 sets of SCM 95-GBd DP-64QAM-PCS transmitters are used for signal generation, whose central frequencies range from 193.3250 THz to 194.3375 THz with a channel spacing of 112.5 GHz. A 100GBASE-LR4 module as well as an ethernet analyser (VIAVI ONT 603) is used for checking whether there is any error symbol after transmission and forward error correction (FEC). The data generated by the ethernet analyser is fed into the client side of the 800G OTN equipment. For each 800G module at the line side, 8 sets of 100GBASE-LR4 modules are plugged for signal convergence, which are cascaded one by one. The client-side modules of different channels are also cascaded. Therefore, the data generated by the ethernet analyser actually transmits 80 loops of the whole link of 2018-km, and monitors all channels simultaneously. There are 20 spans of G.654.E fibre, the average measured attenuation coefficient and the A_{eff} of the G.654.E fibre are 0.158 dB/km and 125 μm^2, respectively. The length of each span is about 100.9 km and the net gain of each BPRA is about 16 dB. After 20 spans of transmission, signals are received by the receivers and fed back to 100GBASE-LR4 modules, and then sent to the ethernet analyser

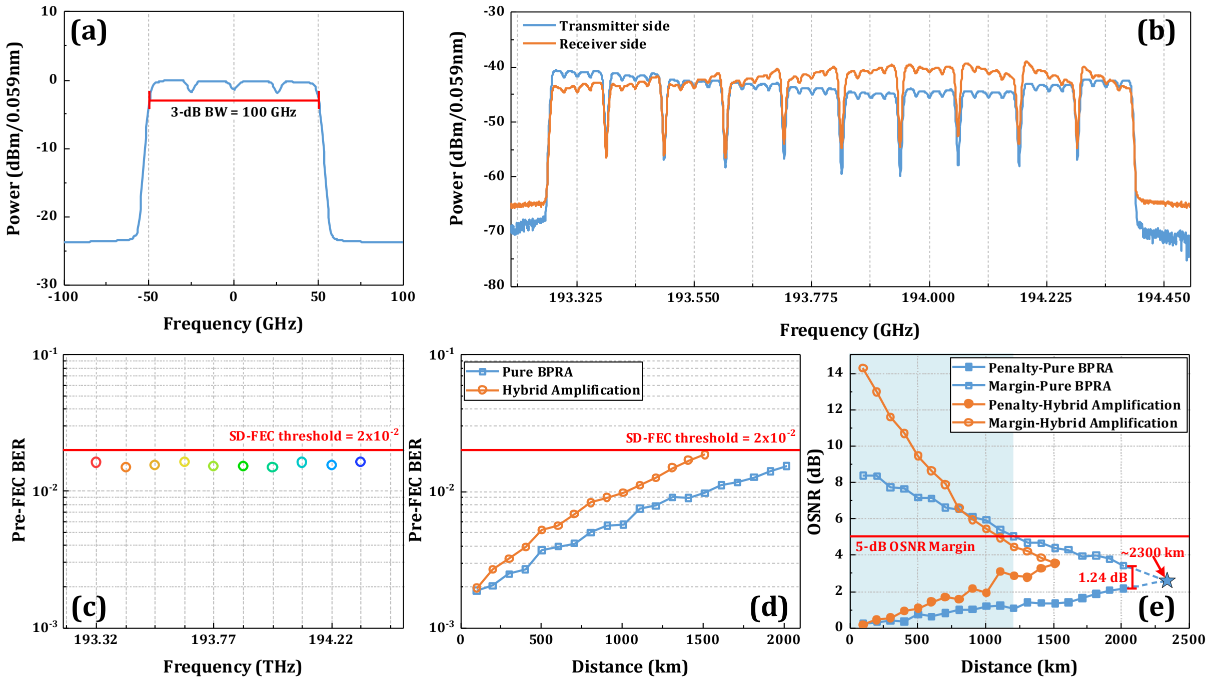

Fig. 2: (a) the spectrum of the SCM 95-GBd DP-64QAM-PCS signal; (b) measured spectra of all 10 channels at the transmitter side and receiver side, respectively; (c) measured pre-FEC BER values of all 10 channels after 2018-km transmission; (d) measured pre-FEC BER value as a function of transmission distance for Channel 193.7750 THz with pure BPRA or hybrid amplification; (e) measured OSNR margin and OSNR penalty as a function of transmission distance for Channel 193.7750 THz with pure BPRA or hybrid amplification.

for post-FEC error detection. We have also measured the results of hybrid amplification by adding one EDFA into each span for comparison.

The optimal average launch power for each channel is about 3 dBm. Because of the slightly gain differences among channels, as shown in Fig. 2(b), the overall spectrum at the transmitter side is tilted a little for performance balance after 2018-km transmission. Fig. 2(a) shows the spectrum of a single SCM 95-GBd DP-64QAM-PCS signal, whose 3-dB bandwidth is about 100 GHz. We can see from Fig. 2(c) that after 2018-km transmission, pre-FEC BER values of the 10 channels are very similar and all below the soft-decision-FEC (SD-FEC) threshold of 2×10^{-2}. The average pre-FEC BER of the 10 channels is 1.57×10^{-2}. The pre-FEC BER values at different transmission distances for Channel 193.7750 THz with both pure BPRA and hybrid amplification were also measured for comparison. For hybrid amplification, when optimal launch power per channel is 6 dBm, the maximum transmission distance is 1513.5 km, and the pre-FEC BER values are always worse than that with pure BPRA at the same distances. To figure out the reason, we measured the OSNR margins and OSNR penalties at different transmission distances for Channel 193.7750 THz with pure BPRA or hybrid amplification as well, all the results are illustrated in Fig.2(e). We can see that though hybrid amplification has larger OSNR margin at the first few hundreds of kilometres, its OSNR margin drops faster than pure BPRA's. It is also worth noting that hybrid amplification case experiences larger OSNR penalty than pure BPRA case, mainly owing to the larger launch power and nonlinearity. At the distance of 1513.5 km, OSNR penalty consumes all OSNR margin for hybrid amplification. While for pure BPRA, at the distance of 2018 km, there is still 1.24 dB left for further transmission. Based on current results, we assume that about 2300-km transmission distance can be achieved with pure BPRA.

Conclusions

In conclusion, a demonstration of SCM 800-Gb/s WDM ultra-long-haul transmission systems based on pure BDRAs and G.654.E is carried out. With fewer devices and better performance than hybrid amplification, a real-time error-free 10-λ×800-Gb/s SCM 95-GBd DP-64QAM-PCS transmission over 2018 km with OSNR margin of 3.39 dB is successfully demonstrated for the first time.

Acknowledgements

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