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REVIEW ARTICLE

Spectrally efficient single carrier 400G optical signal transmission

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Abstract In this paper, the recent progress on spectrally efficient single carrier (SC) 400G optical signal transmission was summarized. By using quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16QAM) and 64QAM, we can realize transmission distance over 10000, 6000 and 3000 km, respectively, with large area fiber and all-Raman amplification. To improve the system performance and generate high-order QAM, advanced digital signal processing algorithms such as probabilistic shaping and look-up table pre-distortion are employed to improve the transmission performance.

Keywords coherent detection, digital signal processing, single carrier (SC), probabilistic shaping, OFDM

1 Introduction

Due to the increasing bandwidth requirement of video traffic, cloud computing and mobile data, the bandwidth of optical network grows at a rate of about 2 dB per year [1]. High-speed coherent optical communication [2–6] is a good solution to meet the bandwidth requirement and is developing rapidly [7–9]. In fact, the deployment of single carrier (SC) 100G coherent communication system from the laboratory to the real network spent less than five years [7]. At present, 100G has been widely deployed, and the demand of meeting rapidly increased bandwidth requirement by SC 400G is urgent [10–17]. A lot of high-speed experimental results on SC 1 Tb/s have also been reported [18–23]. Different from the widely employed SC 100G polarization multiplexing quadrature phase shift keying (PM-QPSK) modulation, SC 400G will have a difficult choice because the bandwidth of the current optical and electrical devices is not enough for SC 400G PM-QPSK modulation. If SC 400G also adopts PM-QPSK modulation and coherent detection, its baud rate will reach 128 Gbaud or higher [14]. Current optical and electrical devices at this baud rate are not mature and very expensive. Similarly to 100G system, the spectral efficiency can only reach 2 b/s/Hz, which means that the transmission capacity is not increased [14]. For the SC 400G transmission system, we have to use high-level modulation formats to increase the spectral efficiency and the transmission capacity [12,15,18–26]. In this way, we also reduce the baud rate of the optical signals and thus reduce the required bandwidth of optical and electrical devices. For example, the required baud rate for employing 8 quadrature amplitude modulation (8QAM), 16QAM or 64QAM is reduced to be ~80, 60 and 40 Gbaud, respectively [27]. But the advanced QAM requires a higher optical signal-to-noise ratio (OSNR). For example, 16QAM needs an additional OSNR of 3 dB compared to QPSK signals, which results in a transmission distance of only ~50% of QPSK [28]. So that the transmission distance will be shorter and may not meet the requirement of long-distance transmission. The recently researched geometrical shaping, probabilistic shaping and other advanced digital signal processing (DSP) technologies can greatly extend the transmission distance, and transmission capacity can be closer to the Shannon limit because of the optimized probabilitic or geometric distribution of signal constellation [29–39]. In addition, small-loss large-area fiber and Raman amplification can also be adopted to extend the transmission distance [14,31].

2 High baud rate transmission

Historically, to use high baud rate to increase the signal bit rate of each channel is an effective and popular way [40]. Adopting high baud rate can realize high-speed transmis-

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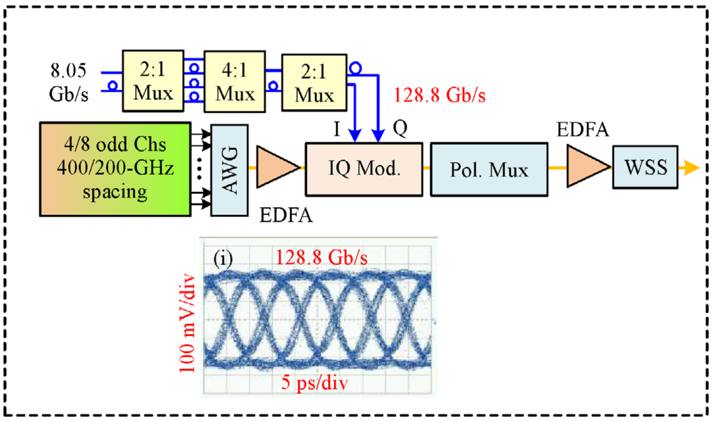
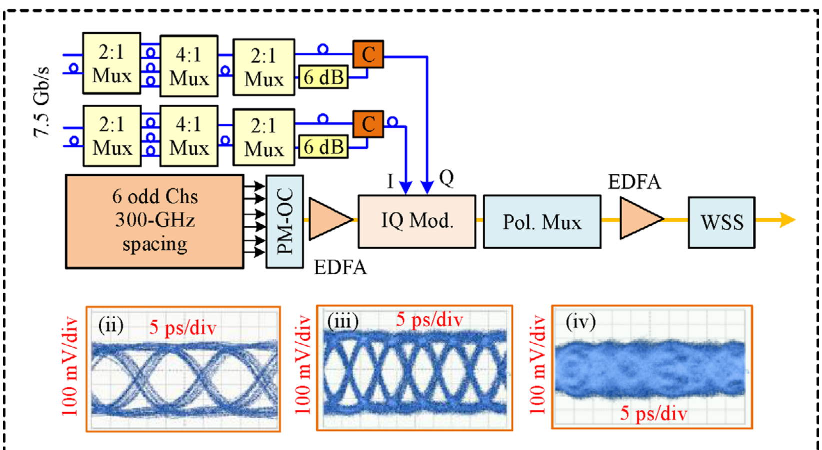
sion for each single channel, thus we can reduce the channel numbers in wavelength division multiplexing (WDM) systems and reduce the maintenance cost of optical transmission networks. To achieve high baud rate signal generation, electrical time division multiplexing (ETDM) technology [11–15] or high-speed sampling rate digital analog converter (DAC) [16–19] can be employed. Thanks to ETDM technology, over 100 Gbaud signal generation and transmission has been realized [11–15]. In our previous work, we demonstrated the generation and over terrestrial distance (tens of thousands of kilometers) optical fiber transmission of 128.8 Gbaud PM-QPSK signal [14]. The experimental setup and eye diagram for 128.8 Gbaud signal is shown in Fig. 1(a). Here we generate two pairs of 128.8-Gbaud in-phase (I) and quadrature (Q) data by three-stage all-ETDM blocks with 2:1, 4:1, and 2:1 electrical multiplexing ratios, from 8.05-Gbaud binary pseudo-random binary sequence (PRBS) signals. We can see the quite clear electrical eye diagram of the 128.8-Gbaud binary signal shown as inset (i) in Fig. 1(a). Recently, we have also reported the wavelength division multiplexing transmission of 120 Gbaud ETDM polarization multiplexing 16QAM optical signal [15]. The experimental setup and eye diagram is shown in Fig. 1(b). The four pairs of 120-Gbaud I and Q 4-level pulse-amplitude-modulation (PAM-4) signals are also produced through three stages of ETDM with a combination of two 120-Gbaud NRZ signals. Like the QPSK signal generation, we first produce the 120-Gbaud binary signals from the 7.5-Gbaud PRBS using the cascade of 2:1, 4:1, and 2:1 electrical multiplexers. Then, we generate the four-level signals by using an electrical combiner on two de-correlated 120-Gb/s binary signals. When combined, one path is first reduced by one half of its amplitude with a 6-dB attenuator. All the signals for ETDM are de-correlated by an applied delay. In these two demonstrations, the employed 4:1 Mux is a 56-Gb/s 4:1 broadband multiplexer module, while the second 2:1 Mux is a 120-Gb/s 2:1 broadband multiplexer module. The obtained output of the 4:1 Mux has the peak-to-peak value V_{pp} of 500 mV and the output of the second 2:1



(a)



(b)

Fig. 1 Transmitter setup of (a) 128.8-Gbaud polarization-division-multiplexing quadrature-phase-shift-keying (PDM-QPSK) signals, and (b) 120-Gbaud PDM-16QAM signals generated by ETDM methods; Mod: modulator, AWG: arrayed waveguide grating, Pol: polarization, Mux: electrical multiplexer; PM-OC: polarization-maintaining optical coupler; WSS: wavelength-selective switch; EDFA: Erbium-doped fiber amplifier

Mux has the V_{pp} of 400 mV, while the 4-level signal has the V_{pp} of ~300 mV. We can see that the electrical eye diagrams of 60- and 120-Gbaud binary signals are still quite clear as insets (ii) and (iii) in Fig. 1(b). However, the eye-diagram quality of generated four-level signal as inset (iv) is very low, which is due to the bandwidth limitation of the combiner. By using a 100 GSa/s DAC, a recorded 100 Gbaud polarization multiplexing 64QAM signal has been generated and transmitted over hundreds of kilometers optical fiber [18]. The bandwidth limitation of electrical multiplexer, DAC or other optical/electrical components can be compensated at the transmitter or receiver by DSP with pre- or post-equalization [41–51]. For high baud rate signal generation based on ETDM, partial response maximum likelihood sequence estimation at the receiver can greatly improve the system performance by eliminating narrow-band filtering effect caused by photoelectric device bandwidth limitations [46,48–51]. Experimental results show that we can employ pre-equalization [46] and look-up-table (LUT) pre-distortion [27] to overcome the nonlinear effects caused by DAC and other optical/electrical devices.

3 High-level QAM modulation

High speed signal transmission can be achieved by adopting high baud rate and high-level QAM modulation [9,28]. The advantage of using high-level QAM modulation is to reduce baud rate and improve spectral efficiency. However, high-level QAM requires more complex DSP at the coherent receiver. In addition, high-level QAM requires higher OSNR, narrower laser linewidth and better linearity of optoelectronic devices [24]. The nonlinearity caused by optical and electrical devices and optical fibers can also be compensated by means of DSP. In Ref. [24], we first realized the generation and coherent detection of the SC 400G polarization multiplexing 256QAM signal. Figure 2 shows the experimental setup for the SC PM-256QAM signal generation. The transmitter includes an external cavity laser (ECL) with a narrow linewidth of 400 Hz, an optical I/Q modulator with bandwidth of 30 GHz, two parallel 30-GHz electrical drivers, an 80-GSa/s DAC with analog bandwidth of around 20 GHz, and an optical polarization multiplexer. The receiver consists of an integrated coherent receiver (ICR) with 40-GHz balanced photo-detectors and a 160-GSa/s ADC. The inset in Fig. 2 shows a measured eye diagram of the generated 30-GBd PAM-16 (I-path) at the DAC output. The DSP at the receiver includes front-end correction, squaring time recovery, a fast-converging polarization-tracking $T/2$-spaced equalizer, carry phase recovery using blind phase search (BPS) algorithm with 64 divided phases, a T-spaced decision-directed least mean square (DD-LMS) post equalizer, and LUT generation for nonlinear pre- and post-compensation [14].

In the DSP part, a fast-converging polarization-blind equalizer is updated in two steps as illustrated in Fig. 3. The error function of the first tracking decision-directed constant modulus algorithm (DD-CMA) step is governed by both CMA and DD-LMS algorithm inside the same loop, enabling faster convergence speed and lower mean square error (MSE) than those with standalone CMA/MMA/DD-LMS algorithms, while the second step uses enhanced DD-LMS to minimize the MSE. The insets (a) and (b) in Fig. 3 display the x-pol constellation diagrams of the 30-GBd PM-256QAM signal with 35-dB ONSR after the 1st and 2nd steps of the $T/2$-spaced equalization. In addition, as illustrated in Fig. 2, an estimated inverse channel response for pre-equalization at the Tx can be derived from the above mentioned $T/2$-spaced equalization. A subsequent T-spaced post DD-LMS equalizer was used to precisely match the channel response within the Nyquist band to provide valuable processing gain. To overcome the nonlinearity-induced pattern-dependent

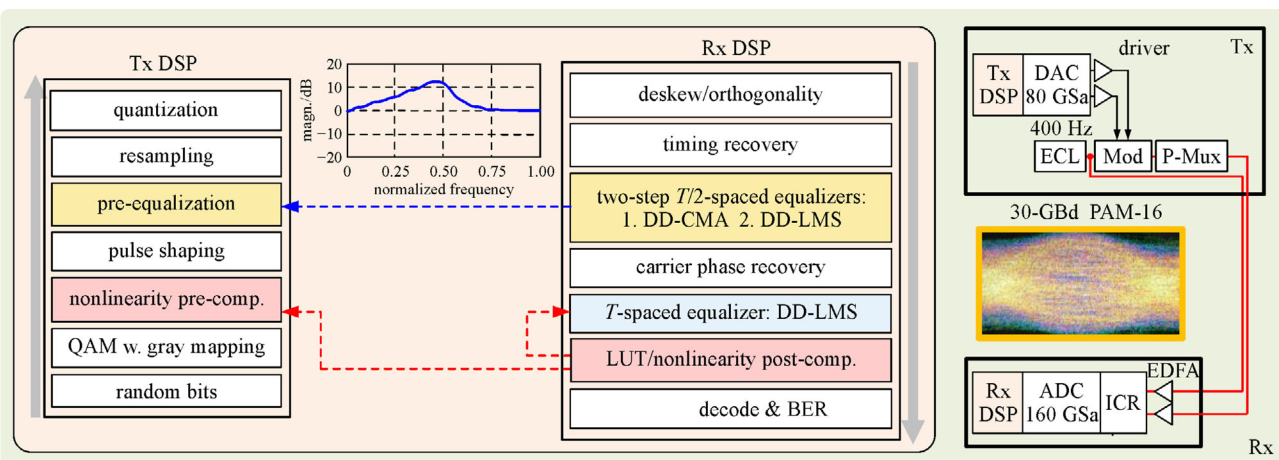


Fig. 2 Experimental setup for the proposed PM-256QAM SC-400G generation, and key enabling Tx and Rx DSP algorithms

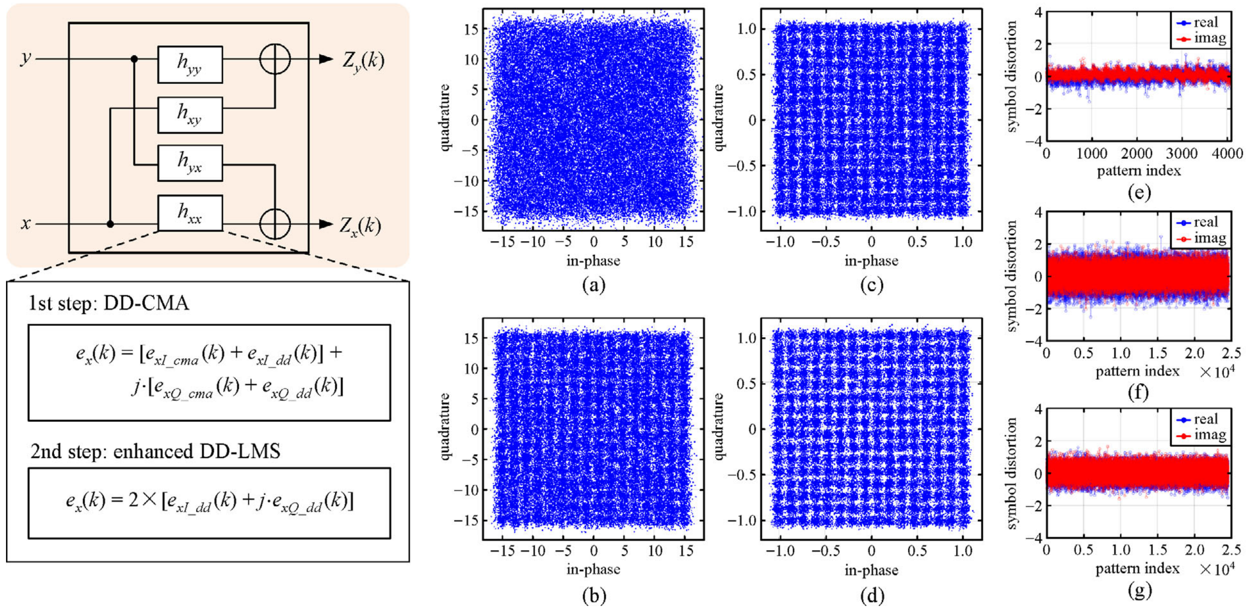


Fig. 3 Conceptual diagram of a two-step polarization-tracking blind equalizer, and the received constellations and LUT

symbol distortion, LUT with various memory lengths are established for the incoming I and Q symbols in each polarization, respectively, and can be used for DPD at the Tx [2]. The insets (e) and (f) in Fig. 3 shows the obtained x-pol LUTs with memory lengths of 3 and 13 symbols, respectively, which were trained by 295k symbols obtained at the output of the T-spaced post equalizer.

At present, transmission of 4096QAM, the highest-order QAM adopted, has been demonstrated although the bit rate is only ~80 Gbit/s [52].

4 New fiber and amplification technology

The transmission performance of optical signals in optical fiber is mainly affected by loss, dispersion and nonlinearity. Optical fiber dispersion can be effectively compensated by DSP in coherent optical communication system. The loss of the C-band signal in the standard single-mode fiber is about 0.2 dB/km, and the total loss is 20 dB after 100 km fiber transmission [14]. To reduce loss and improve OSNR after transmission, new ultra-low-loss fiber has been introduced. Now the minimum loss of optical fiber can be about 0.14 dB/km, and the loss accumulated after 100 km fiber transmission is only about 13 dB, which reduces 6 dB loss compared with standard single-mode fiber. In addition, by increasing the area of the optical fiber and reducing the optical power per unit area, the nonlinear effect in the optical fiber is also reduced. The current optical fiber effective area can be greater than 150 μm^2. For nonlinear effects such as self-phase modulation, cross-phase modulation, and four-wave mixing in optical fibers, we can use decentralized optical amplification, such as Raman amplification. Unlike Erbium doped fiber amplifier (EDFA) which adopts lumped optical amplification, the optical power of the signal in the fiber (close to the EDFA) can be reduced to mitigate the nonlinear effect. At present, long-distance transmission records are basically realized on Raman amplification. If the digital signal processing algorithm is adopted at the receiving end, the influence of the nonlinear effect in the optical fiber can be further reduced [24,53–58]. But the current algorithm is complex and cannot be practically realized, and thus further research is required.

5 Advanced DSP

Signal shaping, which can be divided into geometrical shaping (GS) and probabilistic shaping (PS) [30–39], has become the most popular DSP in the past few years. Since the birth of the information theory, decreasing the gap between the capacity of communication systems and the Shannon limit has become an eternal topic [37]. As a typical modulation format optimization technique, GS technique aims to shape the position distribution of the constellation points of the modulation format, which uses a non-uniformly spaced constellation to obtain a larger minimum Euclidean distance and thereby makes the transmission capacity closer to the Shannon limit. In the PS technique, however, a power-efficient probability distribution is used on the uniformly spaced constellation points [37]. PS is a very important method in additive white Gaussian noise (AWGN) channels, which can reduce the transmission power by matching the symbols with lower amplitude to a greater probability than those with higher amplitude. Although this non-uniform probability distribution will reduce the source entropy of the transmitter, i.e., the average bits each symbol is mapped to, the power saving is enough to compensate for the bit rate loss. In addition, the resistance to noise can be improved by increasing the Euclidean distance at a fixed power.

The advantage of PS over GS is that it does not require a change in the modulator structure, so it is easier to be implemented in terms of practicality. This is especially important for optical communication systems because the optical modulator and DAC operate at very high frequencies and it is really difficult to generate non-uniform constellation points in the complex plane due to limited linearity or effective number of bits (ENoB) in DAC. What's more, the results of the AWGN channel cannot be directly used in optical communication systems because nonlinear interference depends on the power and distribution of the input signal in optical fiber links which limits the maximum achievable signal to noise ratio for the channel. In thus, rather than systems with fixed noise power and signal power, we prefer to focus on distribution of the optical constellation and the transmission power that can enable maximum mutual information for a fixed transmission distance. In the long-distance coherent optical fiber links, noise accumulation and crosstalk caused by nonlinearity are the main issues to be considered. Not only accumulated in all optical devices and fiber spans, nonlinearity noise can also be caused by crosstalk between polarizations and adjacent channels in the transmission links. The principle of PS is to transmit signals with different amplitude using non-uniform probabilities, which means the low-level signals with lower power are delivered more often than those high-level signals with higher power.

For a fixed transmission entropy, the optimal distribution to minimize the average transmission energy is to make the constellation points subject to the Maxwell Boltzmann distribution, which can achieve the maximum information rate in an AWGN channel. In general, when the constellation points obey the Maxwell Boltzmann distribution, a shaping gain (or sensitivity gain) of 1.53 dB can be achieved in each dimension [35,39]. Non-uniform signal generation mechanisms can be implemented by mapping a simple variable-length prefix to the constellation [59,60].

Figure 4 shows graphical illustration of probabilities for PS-64-QAM. The histogram height represents the probability of modulation symbols. With the help of low-density parity-check code (LDPC) which can correct mapping and channel error, shaped constellation shows better performance than regular constellation. With the same effective bit rate, the system transmission distance can be increased by 7% (16QAM). At the transmitter, the ECL uses Nyquist shaping symbol modulation, and the transmitted sequence uses Huffman coding to achieve probabilistic shaping. After transmitted through the noise channel, optical signals are received by the standard coherent optical receiver, and then the electrical signal is sampled by an ADC. The latter DSP include standard synchronization algorithms (blind equalization and data assisted phase recovery) and error-correction-magnitude (EVM) estimation. The system design is very flexible and does not require additional implementation complexity. The most critical step is to introduce a distribution matcher (DM) that generates non-uniformly distributed modulation symbol streams from the data stream.

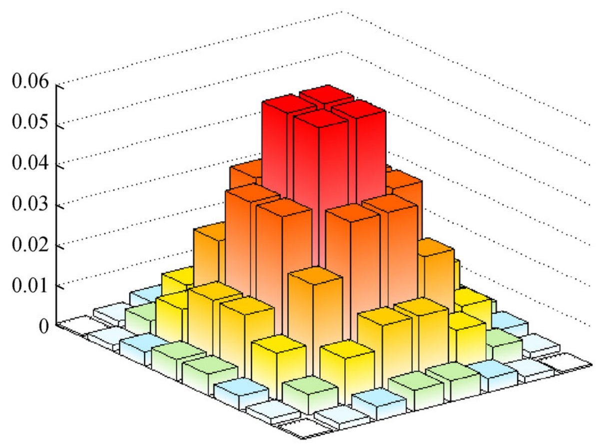


Fig. 4 Graphical illustration of probabilities for PS-64-QAM

The PS mapping and de-mapping is shown in Fig. 5. Based on different OSNR, different probabilities can be assigned to each modulation symbol [59,60]. The key setup is a distribution matcher that converts the data bit stream into non-uniformly distributed constellation symbols. The shaped symbols are represented by binary labels and encoded by a binary forward-error-correction (FEC) encoder, and the system maintains the distribution of the shaped symbols. The output of the FEC encoder is mapped into a QAM complex symbol sequence, which is then input into the optical transmission system and outputs a QAM complex symbol sequence with noise. The demodulator inputs these noisy sequences to the FEC decoder to compute the bit-log-likelihood ratio. The decoded symbols are converted into data bits by a distribution de-matcher.

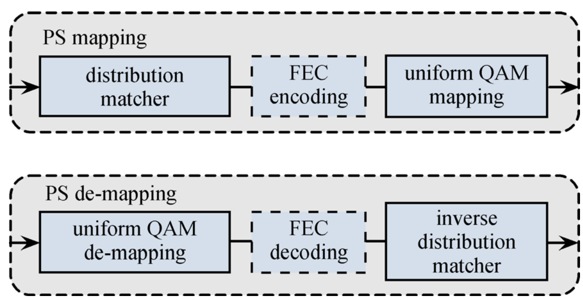


Fig. 5 Diagram of the PS mapping and de-mapping

6 Recorded transmission results

Probabilistic shaping technology can be adopted to enhance the transmission distance greatly. Recently, we have realized a recorded transmission distance of 6000-km by using probabilistic shaped 16QAM modulation [30]. It refreshes the record of the distance of the terrestrial transmission for 400G SC data. A serial of new technologies and new devices, including high-sensitivity probabilistic shaping, pre/post-equalization, low-power small-size high-bandwidth coherent driver modulation module and large-caliber low-attenuation TeraWave™ fiber, are employed in this experiment. The experimental setup is shown in Fig. 6. In the transmission experiment, a 6000 + km transmission of probabilistically shaped single-carrier 506 Gb/s PDM-16QAM signal with 75 GHz channel spacing has been realized. The achieved spectral efficiency is up to 5.3 b/s/Hz. Compared with the case without probabilistic shaping technology, the transmission distance has been increased by 60% after using probabilistic shaping technology.

Moreover, the effectiveness of the probabilistic shaping technology to high-level QAM is more obvious than low-level QAM. We also realized a long-distance transmission of SC 400-G 64-QAM signal by using the probabilistic shaping technology. In the transmission experiment, the transmission of 8-channel (50 GHz channel spacing) 528-Gb/s single-carrier PM-64QAM signal is realized successfully. The I and Q component of the PM-64QAM signals are generated by an integrated high-speed DAC. To generate the I and Q signals, two independent data are first mapped into 64QAM symbols and pre-emphasis and pre-equalization processing are performed. Here pre-emphasis processing is used to mitigate the nonlinear effect of the I/Q modulator. It can properly extend the middle layer in the 64QAM symbols to avoid the signal distortion which is induced by the nonlinear effect of the modulator. Pre-equalization is used to compensate the linear distortion of the modulator by using digital filter. The linear distortion is induced by the high-frequency attenuation effect of the modulator and electrical amplifier. The taps of the digital filter are obtained by inversing the channel response which is measured when the available bandwidth of the signal is up to 62.5 Gbaud at a high OSNR without fiber. The sampling rate of the DAC is set at 80 GSa/s, and the bandwidth of the DAC is 20 GHz. When PS technology is not applied, the baud rate of the generated 64QAM signal is 44 Gbaud and its corresponding data rate is 528 Gb/s. When PS with 5.75 bit/symbol entropy is applied, the raw baud rate of the signal is 46.272 Gbaud, the net baud rate of the signal is 44.344 Gbaud and its corresponding bitrate is 532.128 Gb/s. When PS with 5.5 bit/symbol entropy is applied, the raw baud rate of the signal is 48.125 Gbaud, the net baud rate of the signal is 44.114 Gbaud and its corresponding bitrate is 529.375 Gb/s.

The odd and even channels passed through a WSS and combined again. The frequency interval of odd or even channel before WSS is 100 GHz, and the frequency spacing of odd or even channel after WSS is 50 GHz. Raman amplification (Raman) is used for optical amplification. The fiber loop consists of 4×100 km OFS large effective area fiber (TeraWave SLA +). The effective area of the OFS fiber is about 122 μm^2, and the attenuation coefficient of the fiber is 0.185 dB/km, and the dispersion coefficient of the fiber is 20.0 ps/(nm·km). A 60-GHz tunable optical filter is used to choose the measured channel from the WDM signals. The coherent receiver adopts an ICR with 65-GHz 3-dB bandwidth. The line width of the local oscillator (LO) is less than 100 kHz. The signals after coherent receiver are recorded by 160-GSa/s sampling-rate, 60-GHz 3-dB bandwidth oscilloscope, and then the captured signals are processed by offline digital signal processing. Figure 7 shows the relation between the bit-error ratio (BER) and transmission distance. When the transmitted optical power is set at 8 dBm, it can be found that the performance of the PM-64QAM-PS 5.5 and the PM-64QAM-PS 5.75 are almost the same. They both can achieve a 2400 km transmission with BER below 2.4×10^{-2} and can achieve a 3200 km transmission with BER below 5×10^{-2}. When PS is not applied, the maximum transmission distance is only 2000 km. The PS technology helps to increase the transmission distance by 60%.

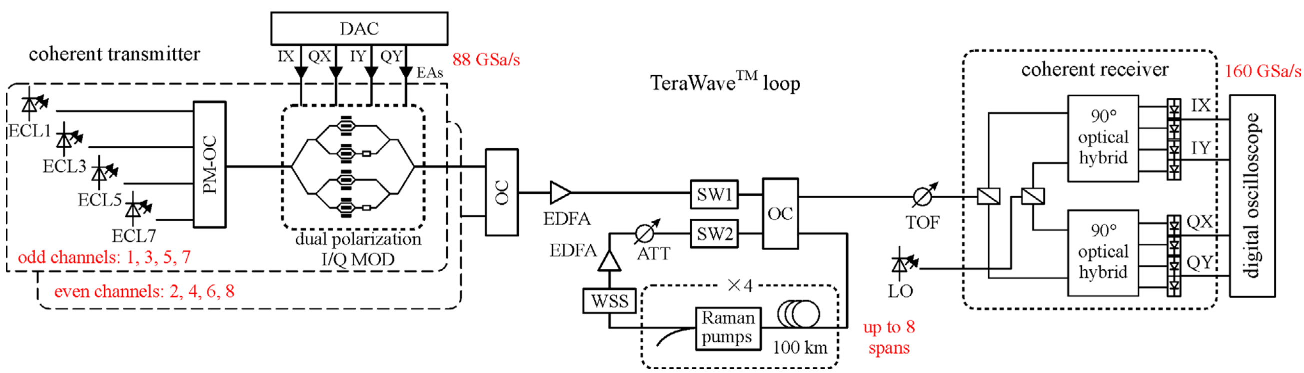


Fig. 6 Experimental setup. ECL: external cavity laser, OC: optical coupler, TOF: tunable optical filter, WSS: wavelength selective switch, DAC: digital to analog convertor, EA: electrical amplifier, ATT: attenuator

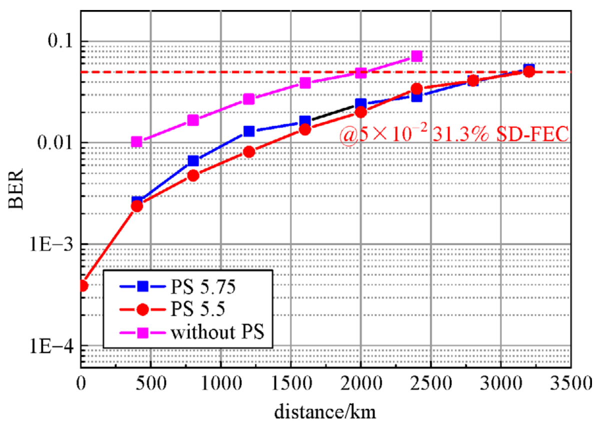


Fig. 7 Relationship between BER and transmission distance when the channel spacing is 50 GHz. Insert: constellation with PS-5.5 and back-to-back

7 Conclusions

The progress of SC 400G coherent detection based on DSP is moving very fast. We have adopted these advanced technologies to achieve transmission records of 10000 km of 400G SC PM-QPSK signals, 6000 km of SC PM-16QAM signals, and 3000 km of SC PM-64QAM signal transmissions. In these transmission systems, we use the baud rate of the signal up to 128.8 Gbaud and the high-order QAM up to PM-256QAM. We use low-loss large-area fibers, Raman amplification and several advanced digital signal processing technologies for coherent detection including PS to extend the transmission distance effectively.

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