Entropy and Symbol-rate Optimized 120 GBaud PS-36QAM Signal Transmission over 2400 km at Net-rate of 800 Gbps/λ

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Abstract: We apply symbol-rate and entropy optimization to over-100-GBaud PS-36QAM signal generation. It enables 800-Gbps/λ signal transmission over 2400 km in 125GHz-spaced WDM system by maximization of SNR margin from the required SNR at FEC limit. © 2020 The Author(s)

1. Introduction

With the rapid growth in communication traffic, large capacity optical transport network is required. Dual carrier 400-Gbps system is practical early solution to accommodate next generation 800-Gbps Ethernet [1]. However, single wavelength 800 Gbps transceivers based on high-speed/wide-band electronics are promising for cost-effective system by reducing the number of optical devices. Therefore, high symbol-rate signal with high order modulation formats based on integrated high-speed digital-to-analog converters (DACs) [2] or electrical bandwidth extender [3-5] has attracted research interests to increase net date rate per wavelength as shown in Fig. 1. [6-9]

According to the Shannon theorem, increasing symbol rate can reduce required signal to noise ratio (SNR) at same capacity. In practical modulation format, a probabilistic shaping (PS) scheme [10] can approach the Shannon limit by arbitrarily changing entropy of transmit symbols. However, considering the transceiver's implementation with analog devices operating at severe conditions against the required specification, their bandwidth limitations degrade the quality of high symbol rate signal . In addition, the requirements to the devices are varied by modulation format. For example, the peak-to-average-power ratio (PAPR) of the signal is changed by shaping factor of PS. Therefore, a design of both symbol rate and entropy is required to generate high symbol-rate signal with a sufficient signal quality for long-haul application.

In this paper, we apply entropy and symbol-rate optimization scheme to 800-Gbps/λ long-haul WDM transmission with a high symbol rate of over 100 Gbaud. This scheme maximizes SNR margin from the required SNR at forward error correction (FEC) limit for PS-36QAM signal generated by an electrical spectrum synthesis technique [5]. Based on the scheme, we demonstrate 800 Gbps/λ 2400-km transmission at the optimized symbol rate of 120 Gbaud in full C-band 125-GHz-grid WDM configuration.

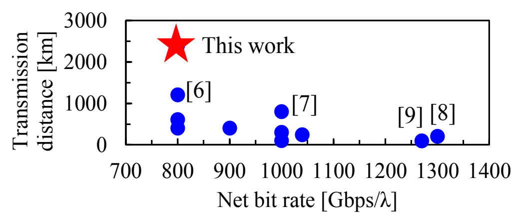

Fig. 1: Transmission distance versus net data rate

2. Entropy and symbol rate optimization for probabilistically shaped signal

A probabilistic shaping technique can set various information rate by changing the probability distribution of the constellation points [10]. A net data rate per wavelength C at a polarization multiplexed signal is obtained from following equation.

$$\mathrm{C} = 2 \cdot [\mathrm{H} - (1 - \mathrm{R}_c) \cdot m] \cdot B \cdot \frac{1}{1+P_{OH}/100} \tag{1}$$

,where H means entropy of constellation pre QAM symbol, $\mathrm{R_c}$ is FEC code rate, m is bit number of base constellation, B means symbols rate, and $\mathrm{P_{OH}}$ means pilot overhead. When we fixed base constellation, code rate, and pilot overhead, entropy H and symbol rate B are in a trade-off relationship. In the case of an ideal transceiver with enough analog bandwidth, increasing the symbol rate B (or decreasing the entropy H) reduces the required SNR at the same net data rate C. However, considering the implementation of analog devices, the signal quality degrades in severe band limitations when the symbol rate B is increased. Therefore, there is an optimal symbol rate and entropy for transmission at the same data rate using the probabilistically shaped signal in the case of a practical system.

For 800-Gbps signal generation with symbol rate over 100 GBaud, we use the following parameter: 64QAM as a base constellation (m=6), the FEC code rate of 0.826 (NGMI threshold of 0.857) [7], and 1.7 % pilot overhead. We also apply truncated PS-QAM [11] scheme to reduce PAPR; only 36QAM points are used in original 64QAM constellation points. The PS-36QAM signal in accordance with a discrete Maxwell Boltzmann distribution was generated by the probabilistic amplitude shaping scheme with constant composition distribution matcher [10]. The required symbol rate for 800 Gbps/λ and required SNR of PS-36QAM signal at the FEC limit as a function of the entropy are shown in Fig. 2 (a). The required SNR of PS-36QAM signal at the FEC limit (NGMI threshold of 0.857) [7] was derived by Monte Carlo simulation in additive white Gaussian noise (AWGN) condition. The required SNR reduced as entropy H decreases. This means that the probability of symbols near the center of the constellation increases when entropy is decreasing, then the average signal power decreases and the Euclidean distance between symbols increases. As a result, the required SNR at the FEC limit in ideal AWNG condition is reduced by increasing the symbol rate (or decreasing the entropy) as shown in Fig. 2 (b).

We experimentally evaluated symbol rate dependence of measured SNR in a single-channel back-to-back configuration. For generation a high-speed signal over 100 GBaud, we used an electrical spectrum synthesis technique with a bandwidth doubler [5, 7]. The experimental set up is the same as [7] except for the bandwidth of optical equalization (OEQ). In order to measure a high symbol rate over 120 GBaud, we extended the bandwidth of the OEQ up to 150 GHz. Figure 2 (b) shows the measured SNR of PS-36QAM at 800-Gbps net rate in each symbol rate. Note that we did not use additional amplified spontaneous emission (ASE) noise loading in this measurement. The measured SNR decreases as the symbol rate increases due to the bandwidth limitations. The SNR tolerance in each symbol rate corresponds to the difference between the measured SNR and the required SNR at the FEC limit shown in Fig. 2 (b). Therefore, we define the difference as a SNR margin. Figure 2 (c) indicates the SNR margin as a function of the symbol rate. The optimal symbol rate at the peak of the SNR margin is 120 GBaud. The NGMI dependence of symbol rate is also plotted in Fig. 2 (c). Similarly, the NGMI is maximized at 120 GBaud. Therefore, we choose the symbol rate of 120 GBaud and accordingly the PS-36QAM entropy of 4.435 bit, considering flexible-grid WDM spacing of 125 GHz for both high spectrum efficiency and high SNR margin. Figure 2 (d)-(f) indicate the constellation diagram of PS-36QAM in each symbol rate. The 104 GBaud PS-36QAM signal with high entropy is unclear compared of the 120 GBaud signal. On the other hand, the 140 GBaud signal is degraded by bandwidth limitation.

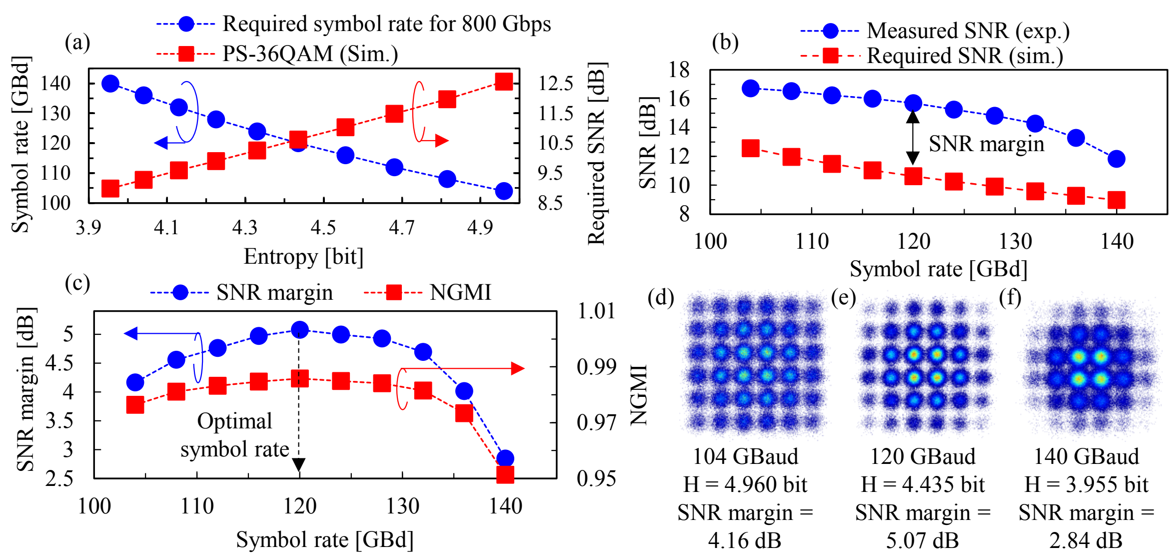

Fig. 2: Simulation and experimental results: (a) required symbol rate for 800 Gbps signal and required SNR of PS-36QAM as a function of entropy, (b) symbol rate dependence of measured SNR and required SNR dependence, (c) SNR margin and NGMI characteristics as a function of symbol rate, (d-e) constellation diagram of each symbol rate and entropy.

3. Transmission experiments

The experimental setup is shown in Fig. 3. The 120-GBuad PS-36QAM signals output from the bandwidth doublers were input to $LiNbO_3$ I/Q modulators (IQMs) with 3-dB bandwidth of 20-GHz via 60-GHz bandwidth linear driver amplifiers. A tunable external cavity laser (ECL) used for the signal under test and local oscillator had a linewidth of ~60 kHz. For interference channels, 36 distributed feedback (DFB) lasers with wavelength ranging from 1527.57 nm to 1564.47 nm with 125 GHz spacing were used. The polarization division multiplexed signals were generated by using polarization division multiplexing emulators (PDMEs) with delay lines of 185 ns. The interference channels were de-correlated through 20-km standard single mode fiber (SSMF). Then, the signal under test and the interference channels were multiplexed and performed OEQ by a flexible-grid wavelength selective switch (flex-WSS). The recirculating loop consisted of two 80-km spans of pure silica core fibre (PSCF: 0.17 dB/km, 20 ps/nm/km at 1550 nm and A_{eff} = 110 μm^2). Each span loss was compensated by backward-pumped distributed Raman amplifiers. At the end of the loop, a loop synchronous polarization controller (LSPS) was placed before an optical gain equalizer (GEQ). EDFAs were used for compensation of optical loss of the components such as GEQ and LSPS. The optical signals were detected by a polarization-diverse optical coherent receiver composed of an optical 90-degree hybrid and four balanced photo-diodes (BPDs) with a bandwidth of 70 GHz. Signals from the BPDs were digitized by a real-time oscilloscope with an analogue bandwidth of 70 GHz and a sampling rate of 200 GSa/s.

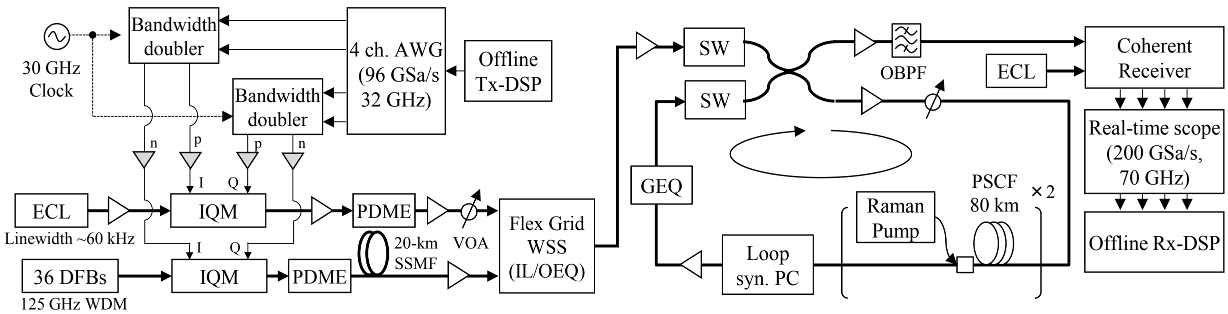

Fig. 3: Experimental setup

Figure 4 (a) shows the 125-GHz-grid full-C-band WDM (4.5-THz) optical spectra at back-to-back and after the 2400-km transmission. Figure 4 (b) shows the results for the WDM transmission configuration. The NGMI as a function of transmission distance at input power per channel of 1 dBm/channel are plotted for three WDM channels: channel 10 (1537.40nm), 18 (1545.32 nm) and 26 (1553.33 nm). The measured NGMIs after the 2400-km transmission were observed to be better than the NGMI threshold of 0.857 [7]. Therefore, we achieved 2400 km transmission at net rate of 800 Gbps/λ by using entropy- and symbol-rate-optimized 120-GBaud PS-36QAM signal. The potential spectrum efficiency of the signal in the 125-GHz-grid WDM configuration was 6.4 bps/Hz.

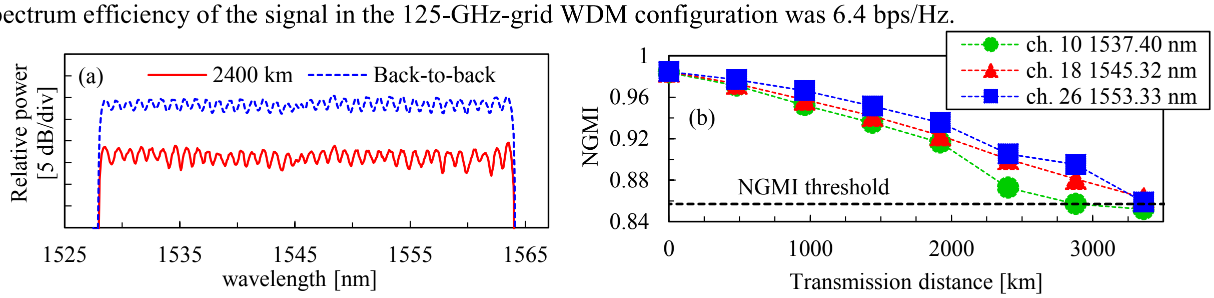

Fig. 4: Transmission results: (a) optical spectra of 125 GH-grid full C-band WDM at back-to-back and after 2400 km, (b) transmission distance dependence of NGMI.

4. Conclusion

We have generated high quality 800 Gbps/λ signal by optimization of entropy and symbol rate for up to 140 GBaud signal based on the electrical spectrum synthesis technique. By evaluating the SNR margin from the required SNR at the FEC limit, 120 GBaud PS-36QAM with the entropy of 4.435 bit was selected from 104- to 140-GBaud signal. The optimized signal at net-rate of 800 Gbps/λ have successfully transmitted over 2400 km at the three-channels (1537.40nm, 1545.32 nm and 1553.33 nm) of a 125-GHz-spaced 4.5-THz WDM configuration.

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