High Symbol-Rate Signal Optimization for Long-Haul Transmission Systems over 1-Tbps/λ Net-Data Rate

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Abstract *We discuss the theoretical and practical aspects of high symbol-rate signal optimization techniques for realizing a >1-Tbps/λ long-haul transmission system. We also review the key technologies for transmitting the high symbol-rate signal such as modulation format design, bandwidth extension techniques, and equalization schemes.*

Introduction

Large-capacity, cost-effective optical transport networks with digital coherent transceivers are increasingly essential for the rapid growth in communication traffic. Transmission capacity per wavelength (capacity/λ) must be increased to accommodate high-capacity client signals such as next-generation Ethernet[1] without increasing the number of transceivers.

To further improve the capacity/λ, the symbol-rate and modulation order must be increased. A high order quadrature amplitude modulation (QAM) with high spectral efficiency is achieved by exponentially increasing the signal-to-noise ratio (SNR). Significant SNR improvement is difficult due to the limitations of fibre nonlinearity[5] although there have been many studies on improving the SNR of the optical transmission line (e.g., low loss and low nonlinearity fibre with low noise optical amplification scheme[2], optical phase conjugation[3], and digital backpropagation[4]). In contrast, based on the Shannon theorem, high symbol-rate signalling ideally does not change the required SNR. Therefore, high symbol-rate signalling is a promising way to increase the capacity/λ for long-haul transmissions.

Figure 1 shows transmission experiments with high symbol-rate signals. The colour scale reflects the symbol-rates. A 120-GBaud 1-Tbps/λ wavelength-division multiplexing (-WDM) signal transmitted over 800 km[6] and a 168 GBaud 1.3-Tbps/λ signal transmitted over 200 km[7] using an electrical bandwidth extension scheme[8, 9]. The highest net-data rate (1.61 Tbps/λ) transmitted over 80 km[10] using a 128-GBaud signal was generated with a high-speed silicon-germanium (SiGe) integrated digital-to-analogue converter (DAC)[11]. As Fig. 1 shows, both capacity/λ and transmission distance are improved by high symbol-rate signals over 100 GBaud.

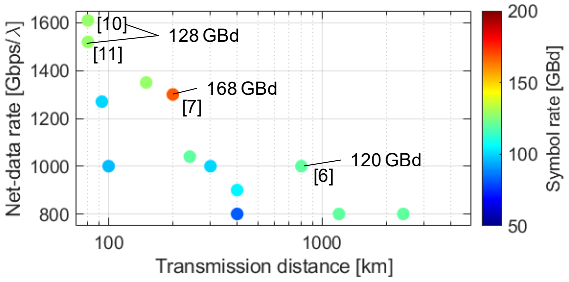

Fig. 1: Net-data rate per wavelength as a function of transmission distance

In this paper, we discuss the theoretical and practical aspects of transmitting high symbol-rate signals beyond 1 Tbps/λ for long-haul application. We also review key technologies for high symbol-rate signal transmission such as modulation format design, bandwidth extension techniques and equalization schemes. We introduce our work on 1.3-Tbps/λ transmissions over 200 km[7] with probabilistic constellation shaping (PCS), an integrated optical module, and an optical equalization (OEQ)-aided digital pre-equalization technique.

Theoretical and practical aspects of high symbol-rate signals

Per the Shannon theorem, the upper bound of capacity/λ of the polarization multiplexed signal in an additive white Gaussian noise (AWGN) channel is calculated by the SNR and signal bandwidth of the system as

$$C = 2B\log_2\left(1 + \mathrm{SNR}_{\mathrm{system}}\right), \qquad (1)$$

where C is the capacity, B is the signal bandwidth, and $\mathrm{SNR}_{\mathrm{system}}$ is the total SNR of the optical transmission system. In a Nyquist-shaped signal with a small roll-off factor <0.01, the signal bandwidth is approximately equal to the symbol rate. Figure 2(a) shows the capacity as a function of the SNR in each symbol rate. Under an ideal condition, the SNR required to achieve 1 Tbps can be reduced by ~16 dB by increasing the symbol rate from 64 GBd to 192 GBd. A high symbol-rate signal is suitable for long-haul transmission while a high symbol-rate signal

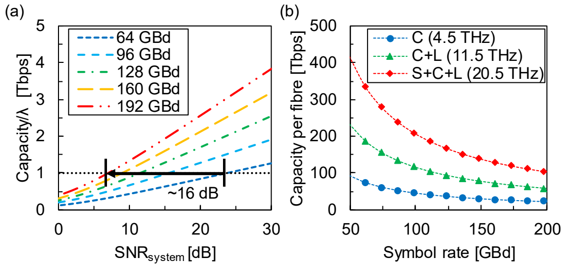

Fig. 2: Achievable capacity: (a) capacity per wavelength versus SNR in each symbol rate and (b) capacity per fibre versus symbol rate in 1-Tbps/λ WDM system.

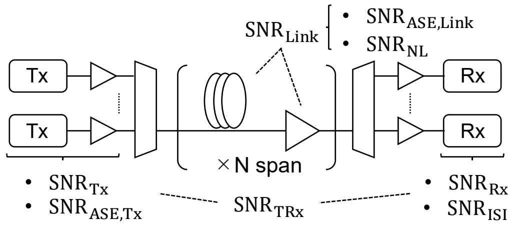

Fig. 3: System model of optical transmission.

decreases the capacity per fibre in a WDM system at the same capacity/λ as shown in Fig. 2(b). In addition, ultra-wideband transmission[12] such as S-, C-, and L-band WDM is effective to improve the capacity per fibre even for high symbol-rate signal.

The system SNR for the optical transmission as shown in Fig. 3 can be expressed as,

$$\frac{1}{\mathrm{SNR}_{\mathrm{system}}} = \frac{1}{\mathrm{SNR}_{\mathrm{TRx}}} + \frac{1}{\mathrm{SNR}_{\mathrm{Link}}}, \quad (2)$$

where $\mathrm{SNR}_{\mathrm{TRx}}$ is the SNR of the transceiver, and $\mathrm{SNR}_{\mathrm{Link}}$ is the SNR of the transmission link. In the following, the symbol-rate dependences of the $\mathrm{SNR}_{\mathrm{TRx}}$ and the $\mathrm{SNR}_{\mathrm{Link}}$ are described in a practical optical transmission system. $\mathrm{SNR}_{\mathrm{Link}}$ depends on amplified spontaneous emission (ASE) noise from the optical amplifiers and fibre nonlinearities in the optical line as shown in the following equation:

$$\frac{1}{\mathrm{SNR}_{\mathrm{Link}}} = \frac{1}{\mathrm{SNR}_{\mathrm{ASE,link}}} + \frac{1}{\mathrm{SNR}_{\mathrm{NL}}}, \quad (3)$$

where $\mathrm{SNR}_{\mathrm{ASE,link}}$ is the SNR per unit frequency of the optical signal and the ASE noise in the transmission link, and $\mathrm{SNR}_{\mathrm{NL}}$ is the nonlinear interference that is not compensated. The optical ASE noise is generally measured by an optical spectrum analyser as the optical signal-to-noise ratio (OSNR). The relationship between the $\mathrm{SNR}_{\mathrm{ASE}}$ and the OSNR for the polarization multiplexed signal is as follows[13]:

$$\mathrm{SNR}_{\mathrm{ASE}} = \frac{B_{ref}}{R_s}\mathrm{OSNR}, \quad (4)$$

where B_{ref} is the reference noise bandwidth and R_s is the symbol rate of the signal. Note that the bandwidth B_{ref} with 0.1 nm is commonly used in optical transmission[13]. In a WDM transmission scenario, $\mathrm{SNR}_{\mathrm{ASE,link}}$ is independent of the symbol rate of the signal when the optical amplification bandwidth of the WDM signal does not change such as a full C band configuration. This is because the OSNR improves by increasing the symbol rate of the signal at the condition of the same amount of ASE noise in the amplification bandwidth while not increasing the $\mathrm{SNR}_{\mathrm{ASE,link}}$ (see Eq. 4). Therefore, the required SNR can be effectively improved by increasing the symbol rate (shown in Fig. 2) under the presence of ASE noise in the transmission link.

The $\mathrm{SNR}_{\mathrm{TRx}}$ in Eq. (2) depends on electrical noise such as that from a DAC, an analogue-to-digital converter (ADC), a driver amplifier (DRV), a trans-impedance amplifier, residual inter-symbol interference (ISI), and optical ASE noise from optical amplifier. This dependency can be described as

$$\frac{1}{\mathrm{SNR}_{\mathrm{TRx}}} = \frac{1}{\mathrm{SNR}_{\mathrm{Tx}}} + \frac{1}{\mathrm{SNR}_{\mathrm{Rx}}} + \frac{1}{\mathrm{SNR}_{\mathrm{ISI}}} + \frac{1}{\mathrm{SNR}_{\mathrm{ASE,Tx}}}, \quad (5)$$

where $\mathrm{SNR}_{\mathrm{Tx}}$ and $\mathrm{SNR}_{\mathrm{Rx}}$ are electrical noise in transmitter and receiver sides, respectively, and $\mathrm{SNR}_{\mathrm{ISI}}$ is the SNR degradation caused by residual ISI at the condition of minimum mean-squared error (MMSE) equalization[14]. The amount of the optical ASE noise in the transmitter depends on the output power from the optical modulator. $\mathrm{SNR}_{\mathrm{ASE}}$ decreases based on how the symbol rate increases unless the input power for the modulator, DAC-output power and/or DRV gain does not improve. Moreover, the DAC-output power and the DRV gain generally decrease in the high-frequency region. Bandwidth limitations of the electrical and optical device also cause severe residual ISI at the receiver based on MMSE equalization. A Digital pre-equalization scheme[15] can mitigate the residual ISI, but it degrades $\mathrm{SNR}_{\mathrm{Tx}}$ because the peak-to-average power ratio increases the DAC input signal. Thus, the modulation format, high-speed signal generation, and the equalization scheme should be optimized for high-capacity and long-haul transmissions because increasing the symbol rate while maintaining the $\mathrm{SNR}_{\mathrm{TRx}}$ is challenging with only digital signal processing techniques.

Key technologies for high symbol-rate signal transmission

The system SNR must be maximized to improve the transmission capacity and distance by optimizing the parameters in a practical optical transmission system. Key technologies for high symbol-rate signal transmission are described in this section, such as modulation format design using PCS, high-speed signal generation methods with an electrical bandwidth extender, and equalization techniques.

The capacity derived from Eq. 1 is an upper bound of mutual information in the AWGN channel with a Gaussian constellation configuration. PCS with a probabilistic amplitude shaping (PAS) scheme[16] can approach near the theoretical limits with a practical soft-decision forward error correction code. The PAS scheme can set various information rates by changing the probability distribution of the constellation points. A net-data rate per wavelength at a polarization multiplexed signal is obtained as

$$C_{pcs} = 2[H - m(1 - R_c)]\frac{R_s}{1 + P_{OH}/100}, \qquad (6)$$

where H is the entropy of constellation per QAM symbol, R_c is the FEC code rate, m is the bit number of the base constellation, R_s is the symbol rate, and P_{OH} is the pilot overhead. To achieve a target net-data rate for an ideal transceiver with enough analogue bandwidth and optical power, increasing the symbol rate (or decreasing the entropy) reduces the required SNR at the same net-data rate (see Fig. 2). However, the system SNR in the practical transceiver decreases as the symbol rate increases, as explained in the previous section. Therefore, the entropy and the symbol rate must be optimized with the PCS scheme to improve the transmission capacity and distance.

Bandwidth extension schemes that generate high symbol-rate signals from multiple low-speed signals without degrading the SNR have been proposed in the optical[17, 18] or electrical[8, 9, 19] domain to overcome the bandwidth limitations of a complementary metal oxide semiconductor (CMOS) DAC. The bandwidth extension scheme in an optical domain has more bandwidth scalability than that in an electrical domain because it uses multiple optical modulators. In contrast, an electrical domain bandwidth extension technique based on a high-speed device that uses a compound semiconductor such as indium phosphide (InP) is a promising scheme for a cost-effective transceiver because it makes possible to increase transmission capacity without increasing the number of optical devices.

In the electrical bandwidth extension scheme, the bandwidth limitations of the high-speed signal interconnection among the DACs, driver amplifiers, and an in-phase-and-quadrature modulator (IQM) through coaxial cables makes implementation challenging. Thus, an integrated ultra-broadband electro-optical frontend module has been developed with an analogue bandwidth multiplication function[20, 21]. The integrated module shown in Fig. 4 doubles the symbol rate without increasing the interconnection speed between each sub-DAC and the module because it consists of an analogue multiplexer with driver amplifiers (AMUX-DRVs) and an IQM based on InP technologies[21, 22]. The module has successfully generated and detected 192-GBaud quadrature phase-shift keying (QPSK) and 160-GBaud 8QAM signals[20].

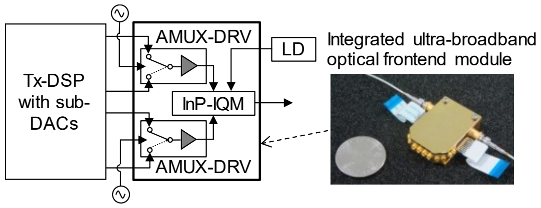

Fig. 4: High speed optical transmitter based on integrated ultra-broadband optical frontend module

An OEQ scheme combined with precise digital equalization[23] should be utilized to suppress noise enhancement and residual ISI. Figure 5(a) shows optical spectra with optimized digital pre-equalization for our OEQ-aided digital pre-equalization technique (blue dotted line) and the applied the OEQ-aided digital pre-equalization technique (red line). The net rate of a 1.3-Tbps/λ signal transmission with PCS-64QAM over 2×100-km pure-silica-core fibre under a full C-band (4.2-THz) WDM condition has successfully been demonstrated using the OEQ-aided digital pre-equalization technique with the integrated module[7] as shown in Fig. 5(b).

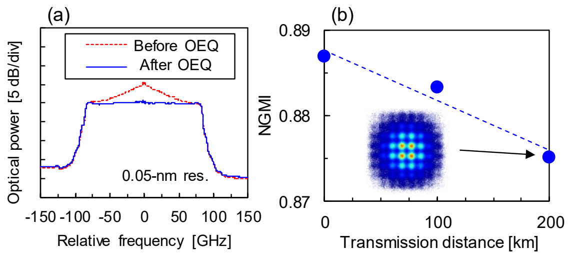

Fig. 5: Experimental results of 1.3-Tbps PCS-64QAM: (a) optical spectra before/after OEQ and (b) NGMI versus transmission distance (NGMI limit: 0.857)

Conclusions

We discussed the theoretical and practical aspects of transmitting high symbol-rate signals beyond 1-Tbps/λ for long-haul application. A high-symbol rate signal that theoretically has a high noise tolerance is indispensable for >1-Tbps/λ long-haul transmissions. To achieve practical optical transceivers with high symbol rates will require not only improvement of device technology but also establishment of sophisticated modulation format, a bandwidth extension scheme, and an OEQ-aided digital pre-equalization technique.

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