Long-haul WDM transmission with over-1-Tb/s channels using electrically synthesized high-symbol-rate signals

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Abstract: Recent technical progress in 1-Tb/s/λ-class transmission systems based on high-speed electronics are reviewed, and key technologies and issues for beyond-1-Tb/s/λ WDM transmission systems with an over-100-Gbaud symbol rate for achieving long-haul transport are discussed.

1. Introduction

Cost-effective and high-capacity WDM transmission systems have grown significantly more important with the tremendous growth in traffic demand. In particular, transmission systems using high-speed channels with a capacity of 1 Tb/s and beyond have attracted much attention as has high-speed Ethernet standardization due to high demand from the data center community. Advances in digital-coherent technologies have led to drastic increases in the channel rate per wavelength and the total capacity of transmission systems. The results of recent WDM transmission experiments that used an optical bandwidth of over 3.5 THz are plotted in Fig. 1. The color gradations represent spectral efficiency. So far, the highest transmission capacity (150.3 Tb/s) was achieved by using 128-QAM WDM signals over three optical bands (the S-, C- and L-bands) [1]. Transoceanic transmissions with over-200-Gb/s channels and several-tens-Tb/s capacity have been reported [2-8]. Their key enablers were high-speed transceivers providing digital linear/nonlinear compensation and advanced multi-level modulation formats combined with strong forward error correction codes.

According to the Shannon theorem, there is an exponential trade-off between the achievable information rate and the required SNR, and the net rate of a signal is the product of the information rate and the symbol rate. In present transmission systems, Nyquist-pulse-shaped signals are densely multiplexed over the optical amplification band. Thus, a signal's information rate (or spectral efficiency) and fiber nonlinearities determine the total system capacity and reachable transmission distance for a certain SNR. So far, with the use of C-band and probabilistically-shaped (PS-) signals, 1-Tb/s/λ WDM transmission with 35-Tb/s capacity over 800-km fiber [9], over-1.25-Tb/s/λ WDM transmission with 50.8-Tb/s capacity over 93-km field-deployed fiber [10], and 1-Tb/s/ λ 100-km WDM transmission with 41-Tb/s capacity [11] have been demonstrated. However, as shown by the color gradation plot in Fig. 1, the transmission distances achieved in the over-1-Tb/s/λ experiments were much shorter than those achieved in the ≤ 400 Gb/s/λ experiments even though the spectral efficiencies were the same. In terrestrial optical transport networks, it is important to maintain backward compatibility for both a transmission distance of ~ 1000 km and an optical-repeater spacing of ~80 km.

In this paper, we review recent technical progress in WDM transmission systems with 1-Tb/s/λ-class channels. Additionally, the key technologies and issues for long-haul WDM transport with 1-Tb/s channels and beyond for terrestrial links are discussed. We also present the results of our recent long-haul 35-Tb/s WDM transmission experiment with 1-Tb/s channels over 800-km fiber.

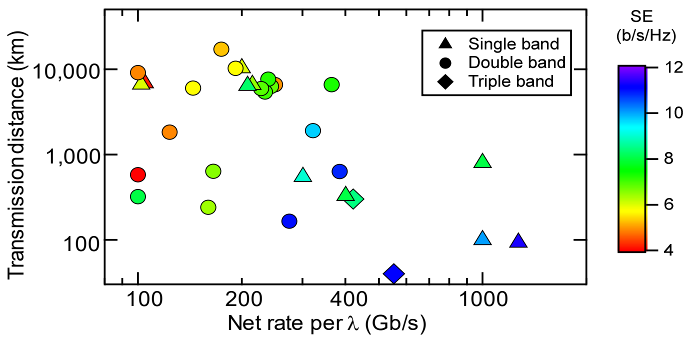


Fig. 1 Recent digital-coherent WDM transmission experiments using optical bandwidth >3.5 THz.

2. Signal design for long-haul WDM transmission with over-1-Tb/s/λ signals

In this section, we describe the signal design of 1 Tb/s and beyond for long-haul transmission. Fig. 2(a) shows the relative required SNR and required symbol rate as a function of the information rate per polarization component. The relative required SNR is defined as the required SNR difference between the ideal capacity and the information rate of a 16QAM signal assuming FEC redundancy of 20%. For 5-b/symbol information (e.g., a 1-Tb/s signal with a 100-Gbaud symbol rate), at least a 6-dB higher SNR is required compared with the 16QAM signal in order to maintain backward compatibility of the transmission distance. The way to achieve a higher SNR is to reduce electrical noise and interference in the transceiver and optical ASE and fiber nonlinearities in the optical link. However, advanced DSP technologies such as high-coding-gain FEC, probabilistic constellation shaping, and precise equalization as well as low-noise optical links consisting of low-loss and low-nonlinearity fiber with distributed Raman amplifiers are already being used. Thus, a promising approach for long-haul transmission with a channel rate of 1 Tb/s and beyond is to increase the symbol rate while reducing the information rate. The information rate can be finely tuned to a desired value by using a constellation-shaping technique based on 64-ary modulation or more without changing FEC redundancy [12]. In high-symbol-rate signal generation, minimizing bandwidth narrowing by the devices in the transmitter is a key to achieving the ideal capacity at a given SNR. Wide-bandwidth devices have been intensively studied, including a 67-GHz InP-based IQ-modulator sub-assembled with a driver IC [13], a 100-GHz thin-film $LiNbO_3$ modulator [14], and a 241-GHz electrical amplifier [15] as well as an integrated transmitter with a 100-GHz bandwidth [16]. The main obstacle to increasing the baud rate is the electrical bandwidth of the digital-to-analog converters (DACs) integrated with a DSP based on CMOS technology. The expected bandwidth of a CMOS DAC is ~50 GHz [17], which is insufficient to generate an over-1-Tb/s signal with a symbol rate beyond 100 Gbaud. Bandwidth extenders of several types (e.g., TDM switch [18] and DSP-assisted multiplexers [19, 20]), which can double or triple the bandwidth of DACs, were recently developed and demonstrated. The plots in Fig. 2 (b) show the results of recent transmission experiments using electrically synthesized high-speed signals (≥800 Gb/s) [9–11, 21–28]. The triangles represent signal generation using a single DAC, and the circles represent signal generation using bandwidth extenders. As shown by the color gradation, the higher-symbol-rate signals generated using bandwidth extenders achieved longer transmission distances. Bandwidth extenders can increase the symbol rate and simplify the transmitter optics so that cost-effective transmission using signal multiplexing in the electrical domain can continue to be achieved. A dual-carrier logical channel combined with two optical transceivers (e.g., 500 Gb/s × 2 λ) is often used as an initial way to meet the high demand for high-speed channel transmission pending the emergence of transceivers with higher capability (e.g., 1 Tb/s/λ) [29]. However, creating a high-speed channel by simply increasing the symbol rate sacrifices spectral efficiency. Using a parallel transmission technology such as amplification-bandwidth extension [1] or spatial division multiplexing [30] is thus a better way to achieve higher transmission capacity.

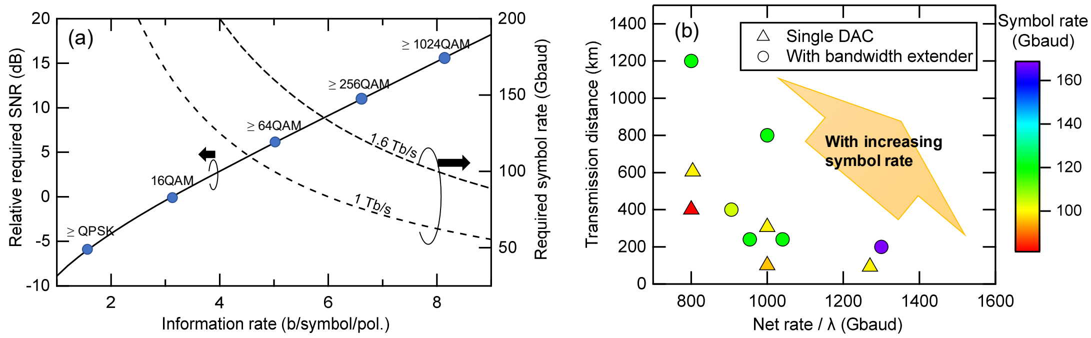
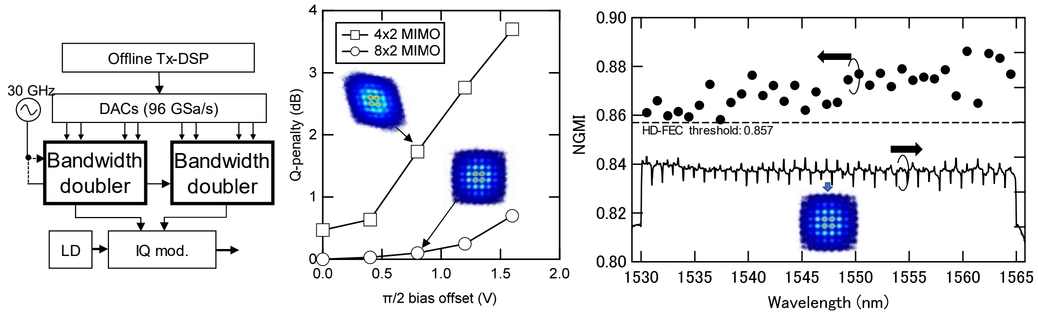


Fig. 2 (a) Relative required SNR as a function of information rate; (b) technical trend in high-speed channel transmission with electrically synthesized high-speed signals over 800 Gb/s.

3. Issues and key technologies for long-haul 1-Tb/s/λ WDM transmission

Several fundamental issues have been studied for long-haul transport using over-1-Tb/s signals with a high symbol rate and high-order modulation. They include DSP complexity and signal equalization. Increasing the symbol rate makes the signals more sensitive to time-dispersive impairments. An adaptive equalizer, which tracks and compensates for the polarization effect, needs additional taps, the number of which is proportional to the symbol rate increment, to cover the same time window. The complexity of a fixed equalizer, corresponding to the number of FFT points for a frequency domain equalizer, for chromatic dispersion compensation is proportional to the symbol rate squared. The development of computationally efficient algorithms is important as well as improvement of DSP integration density by advancing Si-CMOS technologies. Three types of equalizers (a fractional-sampled equalizer [31], a symbol-spaced equalizer [32], and a sub-band equalizer [33]) have been reported for reducing computational complexity by reducing the required number of taps compared to that for a half-symbol-spaced equalizer. Moreover, high-order modulation formats with multiplicity 64 and beyond are highly sensitive to transceiver imperfections such as IQ imbalance, lane-to-lane skew, and different frequency response. Precise digital calibration techniques have been studied for preventing static impairments [34–35]. Additionally, MIMO processing with a higher dimension [9, 36] than that of conventional complex 2×2 MIMO has been proposed for time-varying impairments mixed with lane-to-lane skew and IQ imbalance.

We recently demonstrated 35-Tb/s 800-km WDM transmission with 1-Tb/s channels [9]. The transmitter structure for a polarization tributary is shown in Fig. 3(a). 120-Gbaud PS-64QAM signals were successfully generated using digital-preprocessed analog multiplexers, which can expand the bandwidth of DACs from 32 to 64 GHz. Furthermore, we introduced complex 8×2 MIMO processing into the receiver-side DSP that simultaneously compensates for transmitter and receiver imperfections. As shown in Fig. 3(b), this MIMO equalizer improved the quadrature bias error tolerance and the signal quality at both incorrect and optimal bias points while compensating for residual and time-varying impairments after 480-km transmission. The performance of 35-Tb/s C-band WDM signals at a transmission distance of 800 km is shown in Fig. 3(c). The signals were PDM PS-64QAM signals transmitted at 1.002-Tb/s/λ over 35 channels with 125-GHz spacing. The transmission link (G.654.E fiber) was a 160-km recirculating loop with optical-repeater spacing of 80 km and all-Raman amplification. The normalized generalized mutual information (NGMI) of all channels was better than the HD-FEC threshold of 0.857.



(a) (b) (c)

Fig. 3 Full C-band 35-Tb/s WDM transmission over 800 km G.654.E fiber with 1-Tb/s/λ PS-QAM signals:
(a) 1-Tb/s transmitter with bandwidth doublers (one pol.), (b) Tx bias offset compensation with complex 8×2 MIMO processing, (c) 35-Tb/s 800-km WDM transmission results.

4. Conclusion

Recent technical progress in 1-Tb/s/λ-class transmission systems based on high-speed electronics was reviewed. To achieve 1-Tb/s/λ long-haul transmission (>1,000 km), it is important to increase the signal symbol rate to >100 Gbaud. Electrical bandwidth extenders in particular are a key to overcoming the bandwidth limitation of CMOS DACs as well as to simplifying transceiver optics. Advanced DSPs are indispensable for improving the quality of high-symbol-rate signals for long-haul transmission.

4. References

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