240GBd-16QAM Single-Carrier Coherent Transmission over 120km SSMF for a Bandwidth Limited System with 1sps Speed and Simple DSP

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Abstract: The transmission over 120km SSMF of 240GBd-16QAM coherent system with optical bandwidth of 148GHz was experimentally demonstrated. The novel transceiver DSP was simply implemented at 1sample/symbol speed for low power consumption with high transmitter output. © 2024 The Author(s)

1. Introduction

Due to the incessant growth in capacity demand, the improvement of optical transceiver capacity is an endless challenge. To enlarge the capacity toward 1.6T with coherent system, the development of large bandwidth system was the main trend which can realize the high baud rate Nyquist signals with single carrier [1, 2]. On the other hand, the faster-than-Nyquist (FTN) technology could also realize the high baud rate signal even with a bandwidth limited system [3-5]. Along with development of higher capacity, the optical transceivers are required to be smaller formfactor and lower power consumption.

In this paper, Tomlinson-Harashima pre-coding (THP) [5, 6] was employed for the high baud rate system with low power consumption DSP. The whole transceiver DSP could be implemented at 1sample/symbol (sps) speed. The transmitter DSP could be extremely simple under this 1sps processing mode, and the optical power at the transmitter output could also be improved. In our work, the net rate of 831.1Gb/s and 779.2Gb/s for the back-to-back and 120km transmission were achieved by 256GBd and 240GBd-16QAM signals for the system with the optical bandwidth of 148GHz. The recent works for beyond 200GBd coherent experiments was shown in Fig. 1 when the DAC speed are lower than 264GSa/s, The Nyquist system and the FTN system are distinguished by circle and triangle marks. To the best of our knowledge, this work achieved the highest net data rate at the back-to-back condition and the longest distance for SSMF transmission among the reports of high baud rate coherent experiments.

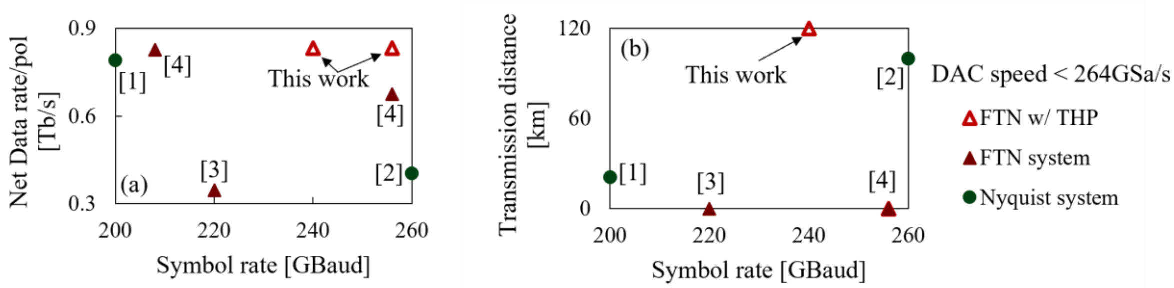

Fig. 1 Recent works for beyond 200GBd coherent experiments with faster-than-Nyquist and Nyquist systems. (a) Net data rate of single polarization with back-to-back condition. (b) Transmission distance as a function of symbol rate.

2. Experimental demonstration

The experimental setup is shown in Fig. 2. The Keysight arbitrary waveform generator (AWG) 8199B with two channels was used to drive the 35GHz LN modulator directly with the peak-to-peak voltage of Vpp = 1.9V. The electrical-electrical (EE) response includes the AWG and cables connected to the LN modulator is shown as green line in Fig. 2(c) when the sampling rate of AWG was set to be 256GSa/s. The EE response starts to drop rapidly from 74GHz where the transmittance was 5dB down. The programable optical filter was used between the transmitter and the SSMF fiber to enhance the optical bandwidth until 148GHz at 3dB down point which just corresponds to the EE response with 5dB down transmittance. The EDFAs were used before and after the programable optical filter to compensate the filtering loss and enhance the fiber input power to up to 7dBm for an optimal condition of nonlinear tolerance. The bandwidth of the photodiode in the coherent receiver was 90GHz. The channel bandwidth was limited by the transmitter side.

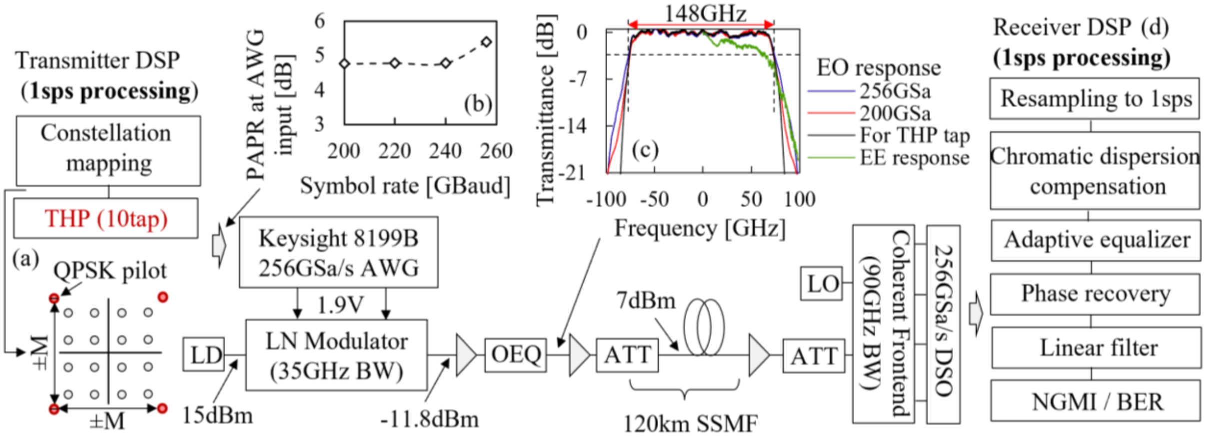

Fig. 2. Experimental setup and transceiver DSP. (a) Transmitter DSP and constellation after symbol mapping. (b) PAPR at AWG input. (c) EE/EO response and typical transmittance for the THP tap. (d) Receiver DSP

The transceiver DSP in our proposal is quite simple which could be observed in Fig. 2(a) and (d). The processing speed was 1sps for the whole DSP system. In the transmitter DSP, TH pre-coding was implemented only with 10taps to the symbols after the constellation mapping. The QPSK pilot was periodically inserted to the payload signal at an interval of 64symbols. The TH pre-coding is the feedback equalization with a modulo processing inside. The amplitude of the modulo process was defined to be 2M to pre-code the payload symbols by the $\pm$2M operation, where M should be larger than the maximum amplitude of the payload symbols. The constellation points of the payload will be increased by the pre-coding. However, by setting the amplitude of the QPSK pilot to be $\pm$M, the absolute amplitude of the QPSK pilots can remain unchanged when they satisfy the condition of $\pm$M = $\pm$M$\pm$2M. The constellation design of the QPSKs pilot is shown in in the lower side of Fig. 2(a). The AWG is to convert the DSP output into analog waveform with various sampling rates between 200 and 256GSa/s to match the symbol rates of the TH pre-coded signals. The transmittance of the transmitter was changed for different sampling rates which could be observed by the comparison of the EO responses with the sampling rate of 256GSa and 200GSa drawn by the red and blue lines in Fig. 2(c). There is a merit of our proposal that the implementation of flexible rates function for an optical transceiver could be easily realized by varying the symbol rate with the corresponding THP taps. The THP tap could be simply updated for different symbol rates with one typical channel transmittance. For our experiment, the THP tap was derived with the MMSE method [7] from a typical transmittance of the transmitter which is shown in Fig. 2(c) by the black line. Another merit is the absence of resampling processing after THP which can enhance the optical power at the transmitter output due to the low PAPR realized by the modulo processing of THP. The PAPR of different symbol rates at the AWG input could be observed in Fig. 2(b). We can find that the PAPR was almost constant as 4.7dB until 240GBd and changed a bit for the 256GBd symbol rate. The low PAPR indicates the advantage of back-to-back OSNR including transmitter amplification relative to the Nyquist signals especially when the digital pre-emphasis is used to compensate the bandwidth limitation. In our experiment, the laser power at the LN modulator input was set to be 15dBm. The optical power at the transmitter output was measured to be -11.8dBm for a back-to-back OSNR at the first EDFA output of 40dB.

In the receiver DSP, the received samples were firstly resampled to match the different symbol rates since that the sampling rate of the digital storage oscilloscope (DSO) was non-adjustable of 256GSa/s. For the transmission of 120km standard single mode fiber (SSMF), the chromatic dispersion of 1.98×10^3ps/nm was compensated at the frequency domain after the 1sps resampling. The least mean square (LMS) based decision directed equalizer with 35tap was employed to act as the adaptive equalizer (AEQ). The Viterbi-Viterbi algorithm for the carrier phase recovery (CPR) was followed. The QPSK pilots were extracted to converge the AEQ tap and estimate the phase noise. The SNR of the QPSK pilots is 12dB higher than the payload signals, which guarantees that the AEQ and CPR blocks could work simply and sufficiently accurate for the payload symbols. The linear filter after CPR was to compensate the transmitter imperfections and the residual filtering noise. At last, the normalized generalized mutual information (NGMI) and bit error ratio (BER) were calculated basing on the log-likelihood ratio (LLR) of the recovered data.

To confirm the performance of the forward error correction (FEC) with low density party check (LDPC) to the THP signal, we test 6×10^7 symbols for the code rate of 5/6 and 8/9. There was no LDPC floor observed with the samples under test, which are shown in Fig. 3(a). The NGMI for the post FEC BER to be lower than 10^{-5} were 0.88 and 0.93, respectively, for the test code rates. We assume a concatenation with an outer Bose-Chaudhuri-Hocquenghem (BCH) code rate of 0.9922, which will bring the post-FEC BER down to 10^{-15} [8]. The frame length of the measured signal was 92160 including 256 head symbols as training sequence (TS) to synchronize the frame at the receiver DSP. By subtracting the TS and pilot symbols, the NGMI and the corresponding achievable information rates (IR) for the optical back-to-back and 120km SSMF transmission are shown in Fig. 3(b). At the back-to-back condition, the NGMIs of the 240GBd and 256GBd-16QAM signal as 0.947 and 0.913 were higher than the LDPC threshold of 5/6 and 8/9 code rates, respectively. The net bit rate could be calculated as $(240\times 8/9 \text{ or } 256\times 5/6)\times 4 \times 63/64 \times (92160-256)/92160 \times 0.9922=$ 831.1Gb/s. The achievable information rates were 892.1Gb/s and 916.6Gb/s, respectively. For the 120km transmission, the NGMI of 240GBd-16QAM was 0.9158. The achievable information rate and net bit rate were 862.5Gb/s and 779.2Gb/s, respectively, for LDPC FEC with the code rate of 5/6. The capacity could be doubled for the polarization multiplexed system if four channels AWG was available.

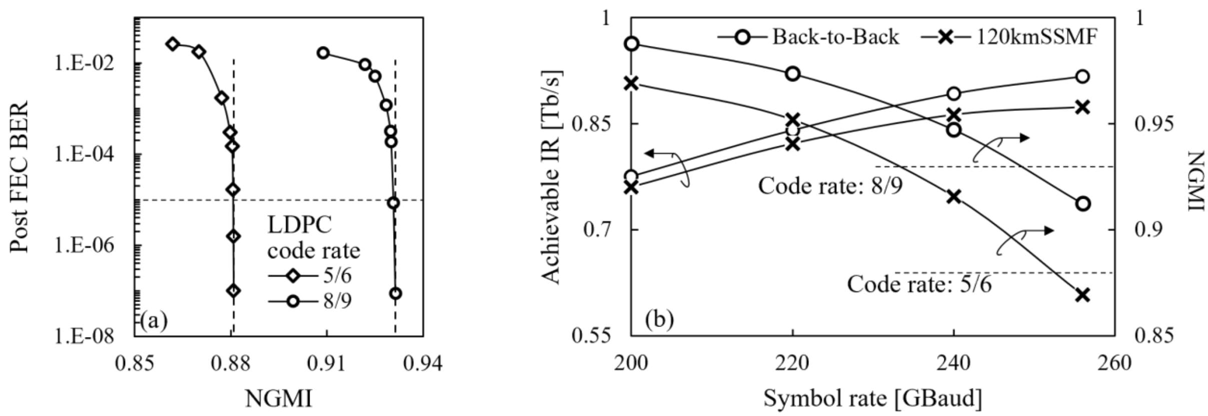

Fig. 3. Experimental results. (a) LDPC performance for the THP signal. (b) Achievable information rate and NGMI of the THP signal for back-to-back and 120km SSMF transmission

3. Conclusion

In this paper, the novel and simple transceiver DSP with TH pre-coding was proposed and implemented at 1sample/symbol speed for the low power consumption with high transmitter output optical power. The performance of beyond 200GBd-16QAM signals were evaluated for a system with optical 3dB down bandwidth of 148GHz. The net rate of 831.1Gb/s and 779.2Gb/s for the back-to-back and 120km transmission were achieved for 256GBd and 240GBd-16QAM signals for LDPC code rates of 8/9 and 5/6 with an outer BCH code rate of 0.9922.

4. Acknowledgment

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