Up to 115GBaud Faster Than Nyquist PDM-64QAM Based on Tomlinson-Harashima Precoding with Single DAC

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Abstract *We experimentally demonstrated faster than Nyquist PDM-64QAM based on Tomlinson-Harashima precoding with single DAC. The -30dB bandwidth of the transmitter is lower than 57GHz. The signal speed was improved to 115GBaud by the precoding with an error free operation of more than 1.1 Tb/s throughput.*

Introduction

Along with the development of network services such as high-quality broadcasting, cloud computing, and internet of things (IoTs), the communication traffic keeps its exponential growth [1]. The cost-efficient way to support such traffic in optical networks is to enhance the spectral efficiency by maximizing the symbol rate and the order of modulation format. The analog bandwidth of the transmitter is necessary for the realization of the high speed. Among them, DAC is a key device. Until now, 1.52 Tb/s net rate is the record capacity with Silicon-Germanium (Si-Ge) DAC [2]. The complementary metal oxide semiconductor (CMOS) based DAC are common for the practical use due to its cost efficiency and low power consumption. However, CMOS DAC facing the bandwidth limit. In [3], 1.1 Tb/s net rate was achieved with CMOS DACs.

The faster-than-Nyquist technology has been widely investigated to realize the further enhancement of signal speed. The basic idea is to employ pre-coding in transmitter DSP to narrow the spectrum of the signal, then the symbol rate could extend the Nyquist limit. In paper [5], we have evaluated the faster-than-Nyquist system with Tomlinson-Harashima precoding (THP) by simulation. The simulation results have confirmed that high order modulation format such as 64QAM could give better improvement than the lower order.

In this paper, we experimentally demonstrated the polarization division multiplexed (PDM)-64QAM singal with THP. The faster than Nyquist rate has been evaluated for the system with -30dB bandwidth that lower than 57GHz. Error free operation was achieved with code rate of 5/6 of Low Density Parity Check-Forward Error Correction (LDPC FEC) for 115Gbaud PDM-64QAM. The capacity of throughput was higher than 1.1Tb/s.

THP feedback equalization in optical coherent system

The principle of THP feedback equalization (FBE) is shown in Fig. 1(a). The FBE to the original data of a_k is followed by a modulo processing. The precoding of changing the original data a_k to c_k was realized by the modulo operation. The equivalent FBE is shown in Fig. 1(b). At the output of THP-FBE, b_k is the result of FBE to c_k. The merit of THP FBE is that the absolute value of the peak amplitude of the output b_k can keep in a limited interval [-M, M]. So that the peak to average ratio (PAPR) of b_k can retain constant and the SNR degradation under the condition of a fixed ENOBs of the DAC can be prevented.

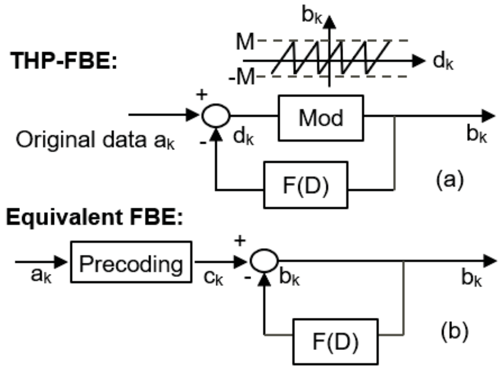

Fig. 1: Principle of THP feedback equalization

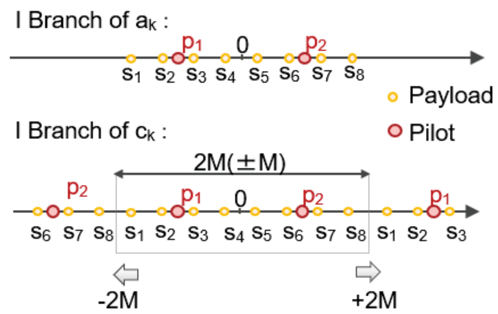

Fig. 2: I branch of 64QAM with and without THP

For polarization multiplexed coherent transceiver systems, pilot data as a low modulation format was normally employed for polarization de-multiplexing and phase noise mitigation. In our experiment, we use QPSK pilot for THP PDM-64QAM. The I branch of PDM-64QAM with and without THP is shown in Fig. 2. According to the

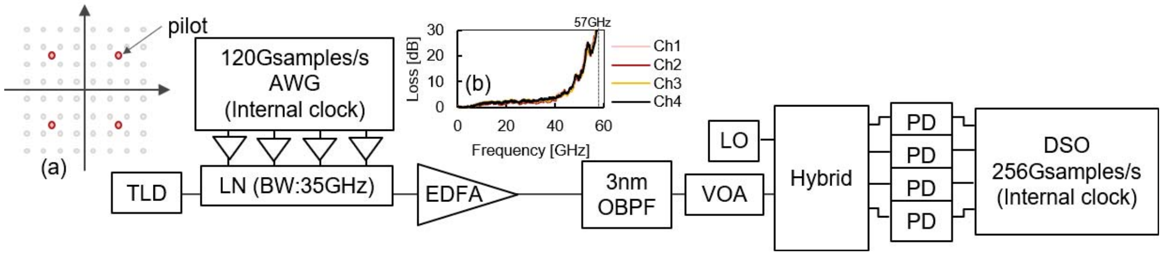

Fig. 4: Experimental setup. (a) Constellation before precoding. (b) Transmittance of AWG

modulo processing, the data levels of c_k is ±2M shifted of a_k. Under this processing, the data number of levels of the QSPK pilot may increase from 2 to 4 or even higher. If we choose the amplitude of the QPSK pilot to be at the centre of the payload, the increased level of the precoded pilot can keep evenly distributed. In this case, the algorithms of adaptive equalizer (AEQ) and carrier phase recovery (CPR) blocks for 16QAM or even higher order modulation formats can deal with the polarization demultiplexing and phase noise mitigation to the precoded signal.

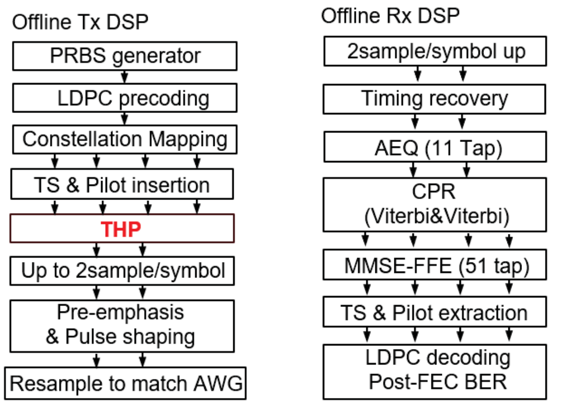

Fig. 3: Offline DSP

The block diagram of the offline DSPs for the transmitter and receiver are shown in Fig. 3. We use LDPC-FEC coding to a binary sequence. Constellation mapping was done to the binary sequence after FEC coding. The LDPC code defined as digital video broad cast satellite generation 2 (DVB-S2) was applied. The code rate was 5/6 (64800, 54000). THP was implymented symbol by symbol to 4 CHs of PDM-64QAM with pilot and training sequence (TS) inserted. After THP, we implimented pre-emphasis as feed forward equalization (FFE). The inter symbol interference (ISI) induced by the bandwidth limitaton was mostly compensated in the transmitter DSP. At last, data resampling was done to match the sampling rate of abitary wave generator (AWG). In the receiver DSP, timing recovery proposed in [6] was employed to synchronize the sampling phase between the transmitter and receiver. The algorithms of CMA [7] and Viterbi&Viterbi [8] for 16QAM signal were chosen for the AEQ and CPR. The tap length of CMA was set to 11. Minimum mean square error (MMSE)-FFE was used after CPR to compensate the residual deteriorations such as transmitter skew [9] and ISI. The tap length of MMSE is 51. At last, the recovered constellation was processed by soft decision decoding of LDPC. The log-likelihood ratio (LLR) was calculated for NGMI and post-FEC bit error ratio (BER).

Experimental demonstration

The experimental setup is shown in Fig. 4. The constellation of the 64QAM before precoding is shown in Fig. 4 (a). The red circles are pilots with the amplitude at the centre of 64QAM. We insert 1 pilot for every 31 payload symbols for AEQ and CPR. The TS were also employed for data synchronization and rough frequency offset estimation. The amplitude of the TS is same as the pilot data. Due to the AWG specification of the requirement of sampling length, the frame length was set to 512×symbol rate (GBaud). The TS of 256 symbols was placed at the head of each frame. The symbol rate of the precoded signal was swept from 110GBaud to 120GBaud.

For the experimental setup, we use AWG to act as DAC with -3dB bandwidth of 45GHz at the speed of 120Gsamples/s and LN modulator with -3dB bandwidth of 35GHz. The transmittance of the transmitter is shown in Fig. 4(b). The -30dB bandwidth could be observed as lower than 57GHz. A 3nm OBPF was used at the input of the front end of optical coherent receiver. The photodiode (PD) and digital storage oscilloscope (DSO) with wider bandwidths were used in the receiver side. The sampling rate of DSO is 256Gsamples/s. The AWG and DSO were operated asynchronously. The digital timing recovery proposed in [6] was employed with the forms of $P(t+T/2)P(t)$. Where P represents the

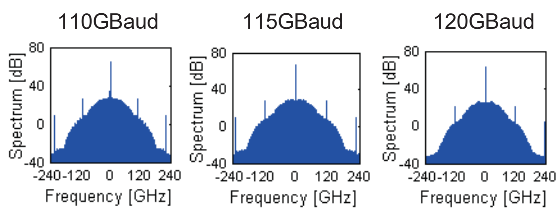

Fig. 5: Spectrum of $P(t+T/2)P(t)$ for clock recovery

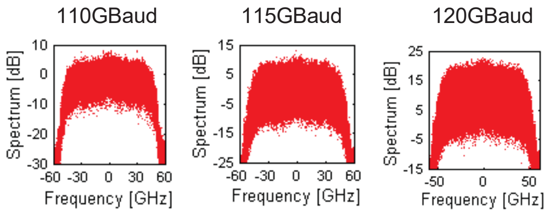

Fig. 6: Spectrum of the received signal

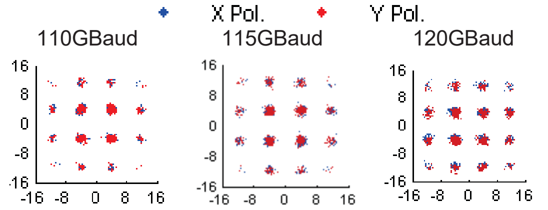

Fig. 7: Constellation of Pilots

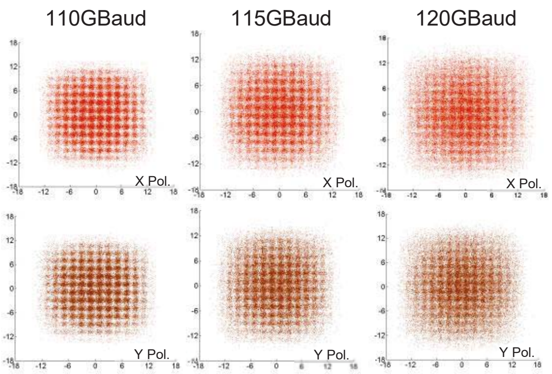

Fig. 8: Constellation of THP DP-64QAM

power of the received signal. This digital clock recovery method is highly tolerated to bandwidth limitation. The spectrum of $P(t+T/2)P(t)$ is shown in Fig. 5. The peaks of the spectrum at the corresponding frequency of 1/T are shown clearly, so the timing error detector is expected to be effective for the precoded signal.

The received signal spectrum with different baud rates are shown in Fig. 6. The signal spectrum was reshaped with precoding tap, so they are almost the same for different baud rates. The precoding tap weight were derived from the frequency response of the transmitter. The constellations of the pilot and the payload after MMSE-FFE are shown in Figs. 7 and 8. The precoded pilot were well recovered to 16QAM by the AEQ and CPR processing. The signal level of the precoded PDM-64QAM was increased as shown in Fig. 8. The scale of data level corresponds to the relativeness between data speed and bandwidth limitation.

The simulation results of NGMI versus bit error rate (BER) is shown in Fig. 9. NGMI 0.88 was used to be a reference for 5/6 code rate LDPC-FEC to achieve the error free performance. The experimental results of NGMI versus different baud rates are shown in Fig. 10. As a comparison, the PDM-64QAM signal without THP was evaluated as red symbols shown in Fig. 10. The blue symbols are the results for precoded data. The NGMI of the un-precoded signal drops suddenly when the baud rate increased to 110GBaud. It implies that the pre-emphasis reached the limit to compensate the ISI of such high-speed signal. For the same equipment specification, the precoding improved the data speed up to 115GBaud. After FEC decoding, the error free operation was confirmed, and several margins were observed for transmission. The relative throughput is shown in the lower horizontal axis of Fig. 10. Thanks to THP, high capacity with the throughput of more than 1.1Tb/s was achieved.

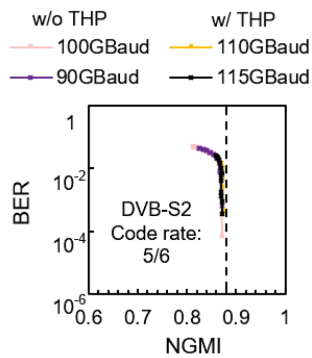

Fig. 9: Required NGMI

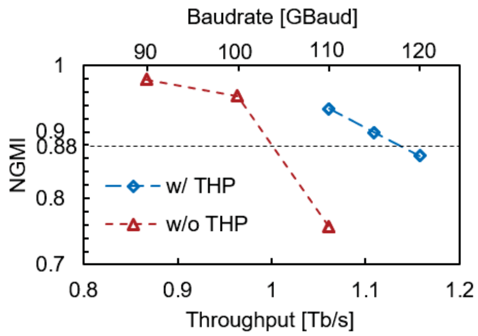

Fig. 10: Experimental results of NGMI

Conclusion

In this paper, we experimentally demonstrated the PDM-64QAM singal with THP. The faster than Nyquist rate has been evaluated with the bandwidth limitated system. The bandwidth limitation was from the transmitter with -30dB bandwidth of lower than 57GHz. After FEC decoding, error free operation was achieved with code rate of 5/6 of LDPC-FEC for 115Gbaud THP PDM-64QAM. The capacity was improved to be more than 1.1Tb/s throughput basing on the precoding technology.

Acknowledgements

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