1.96Tbps and 256-Gbaud Dual-carrier Faster than Nyquist Signal Transmission Using Two Narrow-bandwidth Modulators and Single Coherent Receiver

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Abstract: A large capacity system basing on Faster-than-Nyquist technologies using narrow-bandwidth components was experimentally demonstrated with a hybrid of simple transmitter DSP and optical-equalization for an efficient spectrum-shaping to achieve 1.96Tbps net rate over 120km transmission.

1. Introduction

The demand of improving the capacity of optical transport is being fueled by the development of 5G (and beyond in future 6G) mobile communication system and new services such as high-quality broadcasting, cloud and metaverse [1]. The fundamental requirement for the development of high-capacity optical transport is the reduction of cost and power consumption per bit/s that has been achieved by upgrading the transceiver capacity. The capacity of the transceiver is limited by the analog bandwidths of the system components. The faster-than-Nyquist (FTN) is the DSP technology that can enhance the signal speed to beyond the analog limitation of the system. The basic idea of FTN is to pre-code the bit stream so that the system is more tolerant to the analog bandwidth limitation of the system. In [2], the benefit of FTN was confirmed by theory with a comparison to the Nyquist shaped signal. In [3], we showed an evident improvement of the achievable capacity of Tomlinson-Harashima (TH) pre-coded PDM-16QAM with the symbol rate higher than the Nyquist frequency of the system in comparison to the conventional Nyquist shaped signal.

In this paper, we experimentally demonstrate the large capacity transmission with 256Gbaud dual-carrier 16QAM signal based on FTN with two narrow bandwidth LN modulators and single coherent receiver. The 3 dB E/O response of each of the two-modulation front-end including the characteristic of the modulator, drivers and arbitrary waveform generation (AWG) was 22 GHz that considerably lower than the symbol rate. The hybrid of optical equalization (oEQL) to enhance the optical bandwidth and quite simple transmitter DSP for an efficient spectrum shaping at the output of the transmitter was proposed. The transmitter DSP in our system was entirely designed at the speed of 1sample/symbol that should lead to reduced power consumption. These benefits are brought by the pre-equalization and pre-coding functions of TH pre-coding [4]. The oEQL was emulated by a programable optical filter with WaveShaper^{TM}. The Q factor after 120km SSMF transmission was about 8.9dB when the bandwidth of the coherent receiver to detect the dual-carrier was 90GHz. The net rate of 1.96Tbps was achieved.

2. Experimental verification and discussions

In our experiment, the data was modulated into 2 carriers in the transmitter side and detected by a single coherent receiver. The experimental setup is shown in Fig.1. The signals in the transmitter side were divided into Data#1 and Data#2 which were modulated by two LN modulators with the bandwidth of 35GHz. The AWGs with the speed of 128GSa/s were employed to drive these LN modulators for the generation of 128GBaud 16QAM optical signal to each carrier. The frequency spacing of the dual-carrier was tuned by the frequency setting of each laser diodes. The E/O responses of each transmitter is shown in Fig.1 (iii). We can confirm that the 3dB down bandwidth of the E/O response was only 22GHz. The programable optical filter was employed to multiplex the dual-carriers for the transmission and to enhance the band width of the total transmitter transmittance for an efficient spectrum shaping at the output of the transmitter. The latter was realized by oEQL function of the programable optical filter to suppressing the transmittance of the central frequency. The transmittance of the programable optical filter for dual-carrier multiplex can be confirmed in Fig.1 (iv). The central frequency suppression for the transmitter of Data#1 is a bit deeper than the Data#2 due to its narrower E/O response. Two EDFAs were employed for each carrier before the programable optical filter because of the large insertion loss of WaveShaper^{TM} that used in our experiment. By this configuration, the optical bandwidth for the 3dB down transmittance of each transmitter could be enhanced to be 80GHz. The optical spectrum at the output of the transmitter is shown in Fig.1 (v) by black lines. The optical bandwidth improvement could be confirmed by the comparison of the solid and dashed line which represents the optical spectrum with and without oEQL.

The transmitter DSP for each carrier which is shown in Fig.1 (i) is quite simple and entirely processed at the speed of 1sample/symbol. Firstly, the binary data of PRBS17 was mapped to 16QAM modulation format basing on gray code. Then, TH pre-coding was processed to generate the FTN signal to break the analog bandwidth limitation by the functions of both feedback equalization and pre-coding. The pre-coding was realized by a modulo processing inside the feedback equalization which can keep the amplitude of the output sequence from TH pre-coding among a fixed range of [-M, M] in order to suppress the effect of PAPR degradation induced by conventional pre-equalization. The spectrum at the output of TH pre-coding is whitened by the random sequence during a fixed interval which is also different with the conventional pre-equalization. This is because of the that the pre-coding process result in a spectrum shaping, and the spectrum of the pre-coded data will be same with the system transmittance which was used for the calculation of the tap coefficient of the feedback equalization. In our experiment, the transmitter transmittance was used for the tap calculation and the spectrum of the pre-coded signal of Data#1, #2 are shown in Fig.1 (v) by yellow and green lines, respectively. They match well with the optical spectrum at the output of the transmitter which means an efficient utilization of the transmitter transmittance. The constellation of the pre-coded signal which will be recovered in the receiver DSP is shown in Fig.1 (ii). The constellations of the original 16QAM signal are within the green area in the figure. The level of the modulation format was increased by the pre-coding, however, the information bit retained to be 8 bits/symbol at dual polarization. The red points in the constellations represents the QPSK pilots to assistant the receiver DSP to recover the pre-coded constellation. The amplitude of the QPSK pilots was set to be M that same as the amplitude of the modulo processing of TH pre-coding. By this setting, the QPSK pilots are immune to the constellation expansion of the pre-coding process. Meanwhile, the SNR of QPSK pilots is 12dB higher than the pre-coded payload signal.

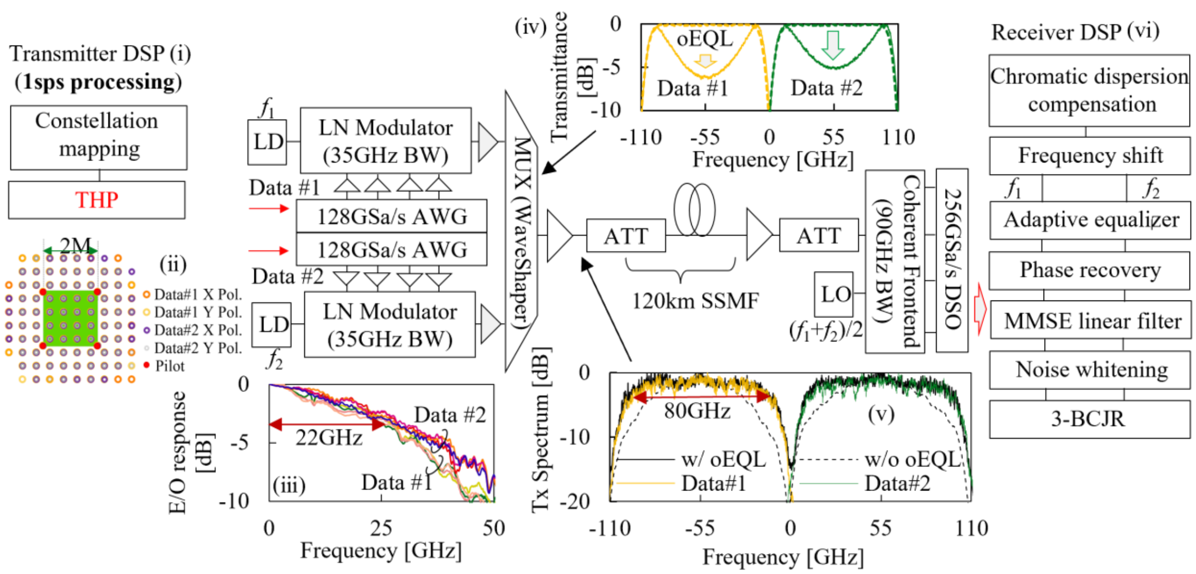

Fig. 1 Experimental setup. (i) Transmiter DSP. (ii) Constellations after TH pre-coding as Data#1, #2. (iii) EO response. (iv) Transmittance of the programable optical filter for dual-carrier multiplex. (v) Tx spectrum of the optical output and the power spectrum density of pre-coded Data#1, Data#2. (vi) Receiver DSP.

In the receiver side, a single coherent receiver with the bandwidth of 90GHz was used to detect the dual-carriers together. The frequency of the local oscillator (LO) was adjusted to be at the center of the dual-carriers. The sampling rate of the digital storage oscilloscopes (DSO) was 256GSa/s. In the transmission part, 120km SSMF was inserted. The receiver DSP is shown in Fig.1 (vi). Firstly, chromatic dispersion compensation (CDC) was done to compensate the transmission distortion for both carriers in a single block. After that, the frequency shift was done for each carrier to recover the base frequency, separately. A rectangular filter with the cutoff frequency of 66GHz was used to filter out the unexpected carrier for the calculation. Then, adaptive equalizer and phase recovery was implemented to recover the constellations of pre-coded signal as shown in Fig.1. (ii), with the assistance of high SNR QPSK pilots. The decision directed least mean squares (LMS) and 4^{th} power phase algorithms were used for the blind processing of adaptive equalizer and phase recovery. The MMSE linear filter with 1sample/symbol processing was done to compensate the transmitter imperfections. At last, 13 tap noise whitening and the 3-level Bahl, Cocke, Jelinek, Raviv (BCJR) algorithm was processed to compensate the receiver filtering effect [5].

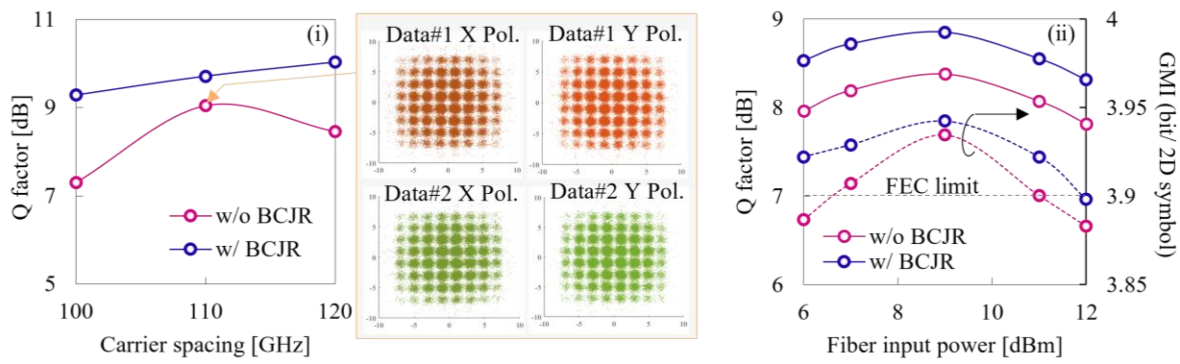

Fig. 2 Performance of (i) optical B2B and (ii) 120km SSMF transmission

The Q-factor of the B2B setup is shown in Fig.2 (i) when the received OSNR was about 42dB which was limited by the transmitter side EDFA. The carrier spacing was swept from 100GHz to 120GHz by 10GHz step to check the balance between the distortions from neighbor crosstalk and the filtering effect from the bandwidth limitation of the coherent receiver front-end. The best performance without 3-BCJR was achieved with 110GHz carrier spacing. For this channel spacing, the recovered constellations of pre-coded signal as shown in Fig.1. (ii) at the input of BCJR can be confirmed in Fig.2 (i). The improvements by BCJR for the carrier spacing of 100GHz and 120GHz are obviously larger which indicates that both the crosstalk and the bandwidth limitation effect were well compensated. The Q factor of 120km SSMF transmission with the carrier spacing of 110GHz is shown in Fig.2 (ii) which is much higher than the limit of the FEC with low power consumption in [6]. The best performance was achieved with the fiber input power of 9dBm for the trad-off between OSNR degradation and the fiber nonlinearity distortion. The OSNR after 120km SSMF transmission for 9dBm fiber input power was reduced to about 37.2dB. The degradation of the Q factor after 120km transmission was about 0.9dB. The improvement by 3-BCJR is about 0.5dB that is a bit lower than the B2B setup, this is because of that the 3-BCJR can make a better improvement when the receiver filtering noise or the neighbor crosstalk dominant the signal degradation. The generalized mutual information (GMI) after 120km transmission can be confirmed from the secondary coordinate axis in Fig. 2 (ii). The net data rate was achieved to be 1.96Tbps for the GMI of 3.94bit per 2D symbol by the optimal fiber input power.

3. Conclusion

In this paper, a high symbol-rate transmission at 256Gbaud dual-carrier 16QAM modulation format was demonstrated by employing two E/O front-end (each having 22 GHz analog bandwidth) and a single ICR (having 90GHz analog bandwidth) by employing Faster than Nyquist technology. The optical spectral shaping was employed to enhance the transmittance of the E/O front-end. The transmitter DSP in our system was quite simple and thoroughly designed at the speed of 1sample/symbol, which was enabled by the pre-equalization and spectrum shaping function of TH Pre-coding to generate the signal with an efficient spectrum. The net rate of 1.96Tbps was achieved after the transmission over 120km SSMF.

4. Acknowledgements

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5. References

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