FTN SSB 16-QAM Signal Transmission and Direct Detection using a THP-MIMO-FFE

Shaohua An, Jingchi Li, Hongxin Pang, Xingfeng Li, and Yikai Su*
State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering
Shanghai Jiao Tong University, 800 Dongchuan Rd, Shanghai, 200240, China
yikaisu@sjtu.edu.cn

Abstract: A joint equalization scheme consisting of Tomlinson-Harashima precoding and MIMO-FFE is proposed to effectively mitigate the ISI induced by FTN signaling. We experimentally demonstrate a 28-GBaud 16-QAM signal transmission with a record 16.67% FTN ratio. © 2020 The Author(s)

1. Introduction

Direct detection (DD) systems beyond 100 Gb/s are attractive for data center interconnects and metro applications. With the same spectral efficiency of a single-polarization coherent transceiver, a single-sideband (SSB) self-coherent detection (SCD) system offers a reduced number of opto-electronic components to minimize the power consumption and lower the cost. To further increase the spectral efficiency of a DD system, faster-than-Nyquist (FTN) signaling is an effective approach. The strong filtering in the FTN technique introduces frequency nulls and non-casual inter-symbol interference (ISI), which are destructive for the high-order quadrature amplitude modulation (QAM) format. A decision feedback equalizer (DFE) can alleviate the FTN-related ISI [1], but it suffers error propagation (EP) effect. To solve this problem, Tomlinson-Harashima precoding (THP) places the feedback circuit at the transmitter [2,3], and thus enables a reliable FTN transmission. Previous experiments have shown FTN pulse amplitude modulation (PAM) signal transmissions based on the THP in intensity modulation-direct detection (IM-DD) systems [4,5]. Nonetheless, the THP scheme faces challenges in coherent and SCD systems with high spectral efficiencies, due to the fact that the practical in-phase and quadrature (IQ) imbalance and delay prevent the accurate estimation of the feedback coefficients and thus degrade the FTN performance.

In this paper, we propose a THP - multiple input multiple output (MIMO) - feedforward equalizer (FFE) scheme to achieve an FTN 16-QAM signal transmission. In our scheme, two real-valued THP operations are applied at the transmitter, and a 2-by-2 MIMO linear equalizer is used at the receiver. To obtain the THP coefficients, a MIMO-FFE-DFE is designed and implemented, in which the feedforward and feedback coefficients are extracted simultaneously in the EP-free mode. Since the MIMO scheme is tolerant to the IQ imbalance and delay, the DFE coefficients can be estimated accurately and then back-propagated as the THP coefficients. By this means, the THP circuits can effectively suppress the ISI incurred by the FTN filtering, and the influence of the IQ crosstalk is minimized by the MIMO-FFE at the receiver. By using the proposed THP-MIMO-FFE, a 112-Gb/s FTN SSB 16-QAM signal is transmitted over an 80-km single mode fiber (SMF) in an SSB SCD system with a 4.13-b/s/Hz spectral efficiency. A 24-GHz narrow-band digital filter performs the FTN signaling with a record FTN ratio of 16.67% (28 GBaud / 24 GHz – 1) for the 16-QAM format. To the best of our knowledge, this is the first experimental demonstration of the THP-based FTN QAM format in optical communication systems.

2. Operation principle

The schematic diagram of the proposed THP-MIMO-FFE is depicted in Fig. 1(a). At the transmitter, two independent real-valued feedback filters are applied to the IQ parts of a 28-GBaud 16-QAM signal, respectively. By feeding the weighted sum of the previous symbols back to the current symbol, the post-cursor ISI caused by the FTN filtering can be mitigated. Two 2M modulo operations constrain the output amplitudes to (–M, M] for the two quadrature components, which are combined and then filtered by a 24-GHz real-valued FTN digital filter H(z). The value of M is 4 for the 16-QAM signal. After passing through a channel with a z-transform of C[z] and an electrical signal-to-noise ratio (ESNR) of 22 dB, the FTN 16-QAM signal shows a spectrum in Fig. 1(c). Here, C(z) is assumed to be 1. At the receiver, a 2-by-2 MIMO linear equalizer alleviates the residual ISI and recovers the signal constellation. Due to the 2M modulo functions in the THP, the amplitude of each quadrature component is increased to 10 levels, leading to a 100-QAM-like constellation diagram in Fig. 1(d). From the distribution histogram in Fig. 1(e), it can be observed that the occurrence probabilities of the inner symbols are higher compared to the outer symbols. After two 2M modulo devices, the extended constellation is converted back to a conventional 16-QAM constellation as plotted in Fig. 1(f). In addition, the filter coefficients used in the THP are obtained based on a

MIMO-FFE-DFE, which is implemented after the same FTN channel. In Fig. 1 (b), we optimize the coefficients of the feedforward and feedback filters simultaneously, thus minimizing the influence of IQ crosstalk to the estimation of the DFE coefficients. The EP-free mode is achieved by replacing the decision values by the original symbols. Therefore, the two independent real-valued THP processes in the proposed scheme are sufficient to suppress the FTN-induced ISI, and eliminate the need for a butterfly THP structure [6].

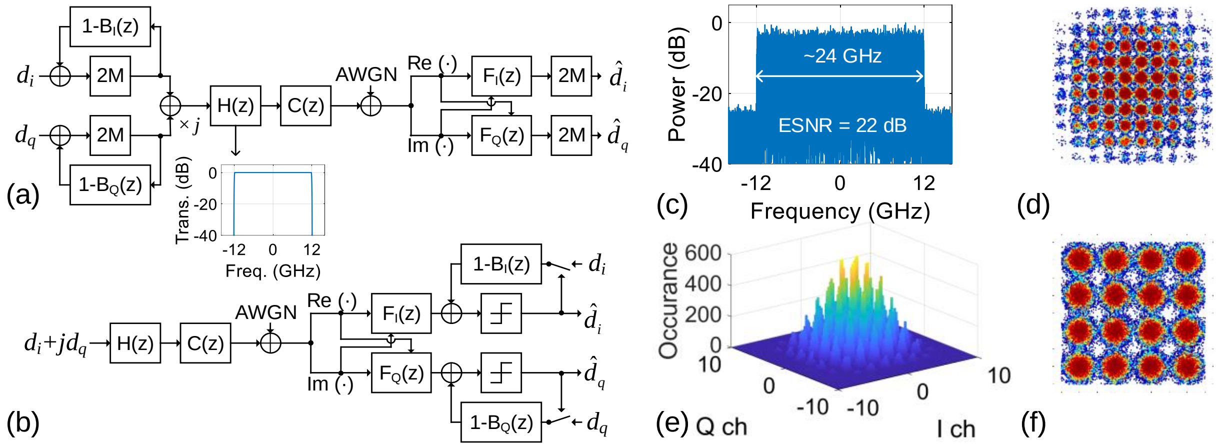

Fig. 1. (a-b) Schematic diagrams of the proposed THP-MIMO-FFE and MIMO-FFE-DFE, respectively. (c) Spectrum of a 28-GBaud THP 16-QAM signal after the FTN channel. (d-e) Constellation diagram and amplitude distribution of the complex signal recovered by the MIMO-FFE. (f) Constellation diagram of the 16-QAM signal after the 2M modulo operations. Inset: transfer function of the 24-GHz FTN filter.

3. Experimental setup and results

Figure 2(a) illustrates the experimental setup of an SSB SCD transmission system. A 64-GSa/s arbitrary waveform generator (AWG) (Keysight M8195A) outputs a 28-GBaud FTN 16-QAM signal. After amplified by two electrical amplifiers (EAs), the 16-QAM signal drives a 22-GHz IQ modulator (IQM) biased at the transmission null. A continuous wave (CW) light from a 15-KHz external cavity laser (ECL) at 1550.38 nm is fed into the IQM. To generate an optical SSB signal, a CW tone from another ECL is added to the edge of the QAM signal spectrum. Then, the optical signal is boosted by an erbium-doped fiber amplifier (EDFA) before launched into an 80-km SMF. At the receiver, another EDFA is used to compensate for the transmission loss, and an optical bandpass filter (OBPF) (EXFO XTM-50) is employed to remove the out-of-band amplified spontaneous emission noise. After a 50-GHz photo detector (PD), the electrical signal is sampled by an 80-GSa/s digital storage oscilloscope (DSO) (LeCroy 36Zi-A). The insets (i) and (ii) show the optical and electrical spectra at the transmitter and the receiver, respectively. The digital signal processing (DSP) flow charts are provided in Fig. 2(b). At the transmitter, 204800 16-QAM symbols are generated, followed by the synchronization and training symbols adding. The signal frame is then processed by the THP circuits given in Fig. 1(a). After up-sampled by 2 times, a 24-GHz raised cosine filter (RCF) with a roll-off factor of 0.01 is used to realize FTN signaling. The chromatic dispersion (CD) is pre-compensated digitally before the resampling and clipping modules. Considering the frame redundancy and the 7% hard decision forward error correction (HD-FEC) overhead, we achieved a data rate of 101.6 Gb/s with a record FTN ratio of 16.67%, to the best of our knowledge. The spectral efficiency is 4.13 b/s/Hz (101.6 Gb/s / 24.6 GHz), which could

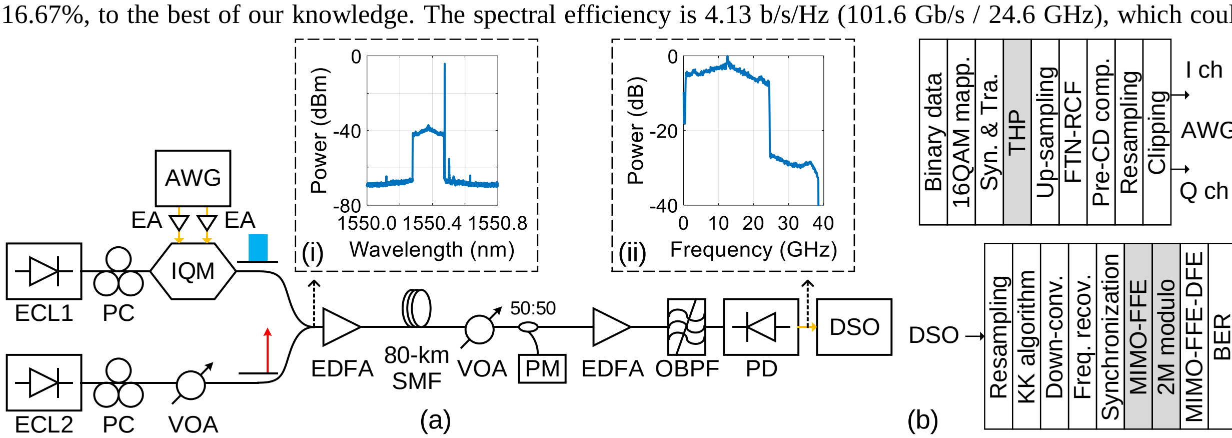

Fig. 2 (a) Experimental setup of the SSB SCD system. PM: power meter. (b) Transceiver DSP flow charts. The operations in the grey blocks are performed only if the THP is applied. Inset (i) Optical spectrum with a 1.12-pm resolution at the transmitter. (ii) Received electrical spectrum.

be slightly reduced in a wavelength-division-multiplexed transmission system. In the receiver DSP, the signal is first resampled to 4 symbols per symbol (SPS), and the Kramers-Kronig (KK) algorithm is used to reconstruct the optical field. After the frequency offset compensation and synchronization, the MIMO-FFE and the modulo operations are performed to recover the 16-QAM symbols. When estimating the THP coefficients, the MIMO-FFE-DFE is applied, which is bypassed in the THP FTN transmission.

In the optical back-to-back (OBTB) case, we first implement the MIMO-FFE-DFE under the EP-free condition. The DFE coefficients are extracted through the training-based least mean square (LMS) algorithm, and then used in the THP circuits. In the practical MIMO-FFE-DFE with EP, a high bit error ratio (BER) of 1.04×10^{-2} is measured, with the constellation diagram depicted in the inset (i) of Fig. 3. By using the proposed THP-MIMO-FFE scheme, the EP effect can be avoided, thus the BER is significantly reduced to 1.26×10^{-3}. The insets (ii) and (iii) present the constellation diagrams at a received optical power (ROP) of 0 dBm before and after the modulo functions, respectively. Besides, compared to the BER of 1.02×10^{-3} for the DFE case without EP, the slightly degraded BER performance of the THP scheme is due to the penalty of precoding. Then, the same THP coefficients are employed for the 80-km SMF transmission. In order to improve the transmission performance, we optimize the launch power at different carrier-to-signal power ratios (CSPRs). As indicated in Fig. 3(a), the BER achieves the minimum value with a 6-dBm launch power and a 13.5-dB CSPR, which are used in the following measurements. Figure 3(b) gives the BER versus ROP in the OBTB case and after the fiber transmission, respectively. In the experiment, the gain of the second EDFA in Fig. 2(a) is slightly saturated, thus we measure the ROP rather than the optical signal-to-noise ratio (OSNR). As observed from Fig. 3(b), the 28-GBaud FTN 16-QAM signal can reach the BER of 3.09×10^{-3} after the fiber transmission, achieving error-free operation with the 7% FEC. The constellation diagrams at the –10-dBm ROP after the MIMO-FFE and the modulo devices are shown in the insets (iv) and (v), respectively. The inset (vi) plots the corresponding distribution histogram of the constellation in the inset (iv). Compared to the OBTB case, the 3.1-dB transmission penalty is attributed to the increased quantization noise with the higher peak-to-average power ratio (PAPR) after the CD pre-compensation, and fiber nonlinear effects.

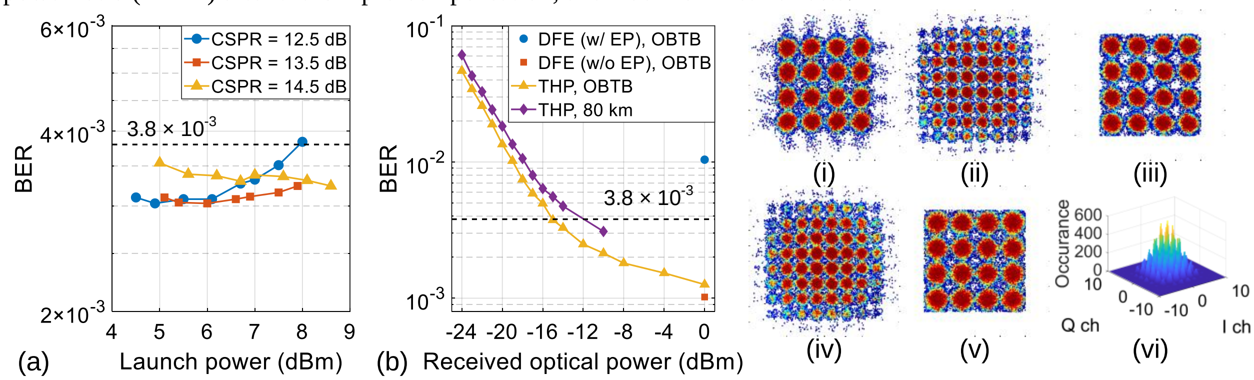

Fig. 3. (a) BER versus launch power at different CSPR values after the 80-km SMF transmission. (b) BER curves for different equalization schemes in the OBTB case and after the fiber transmission, respectively. Inset (i) Constellation diagram in the OBTB case for the DFE with EP. (ii-iii) Constellation diagrams in the OBTB case at the 0-dBm ROP for the THP scheme before and after the modulo operations, respectively. (iv-v) Same with (ii-iii), but after the 80-km transmission at the –10-dBm ROP. (vi) Amplitude distribution of the constellation in inset (iv).

4. Conclusion

We proposed and demonstrated a THP-MIMO-FFE scheme to realize an FTN 16-QAM signal transmission. By using two real-valued THP operations at the transmitter and a MIMO-FFE at the receiver, the detrimental influence of error propagation, IQ imbalance and delay can be avoided, thus effectively mitigating the ISI incurred by the FTN filtering. In an SSB SCD system, we successfully transmitted a 112-Gb/s 16-QAM signal over an 80-km SMF with a 4.13-b/s/Hz spectral efficiency. A record 16.67% FTN ratio was also achieved for the 16-QAM format.

5. References

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