Pilot-Aided Continuous Digital Signal Processing for Multi-format Flexible Coherent TDM-PON in Downstream

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Abstract: To avoid burst-signal processing in downstream transmission during modulation-format switching, we propose and experimentally demonstrate a pilot-aided DSP scheme with continuous SOP tracking, carrier-phase recovery, and channel estimation in 300G flexible CPON based on 4/16/64-QAMs. © 2023 The Author(s)

1. Introduction

Driven by the bandwidth-hungry emerging services, such as 5G/6G networks, 8K/16K video streaming, and mobile X-haul, the optical access network industry is embracing a new wave of bandwidth acceleration [1]. Coherent passive optical network (CPON) is a promising solution for the next-generation high-speed PONs due to its advantages including superior receiver sensitivity and the extended power budget [2]. In addition, the flexibility of PONs is another interesting feature for next-generation optical access networks [3]. Flexible PON optimizes the system throughput by adaptive baud rates, adaptive modulations, and multidimensional modulations. Recently, a probability shaping QAM-based flexible upstream coherent-PON with a 300G peak rate has been demonstrated [4], which heralds the rising interest for rate-adaptive PON.

In flexible PON, an important problem is the fast tracking of the channel status, such as the clock, state of polarization (SOP), and carrier phase. For upstream burst-mode coherent detection, efficient preambles are designed for fast frame synchronization, SOP estimation and frequency-offset estimation [5]. A pilot-aided burst DSP design for high-order QAM signals is proposed, which features modulation format independent and fast-convergence [6]. In [7], the pre-calculated finite impulse response (FIR) filter coefficients are used to shorten the preamble length. However, it is still a challenge to realize fast convergence in flexible downstream transmission due to the traditional DSP, such as blind and adaptive algorithms (CMA/CMMA), in which FIR coefficients need to be re-trained during modulation-format switching.

In this paper, we propose and experimentally demonstrate a pilot-aided DSP scheme for multi-format flexible coherent TDM-PON in downstream, avoiding the burst-signal processing during modulation-format switching. Inserted pilots realize fast SOP, carrier phase tracking, and channel estimation. The SOP information and pre-stored FIR coefficients reduce the convergence time for CMA/CMMA process. With the proposed DSP scheme, we realize continuous signal processing in the downstream coherent signal detection of 25-GBaud PDM 4/16/64-QAM, achieving 38, 30, and 20-dB power budgets after 20-km fiber transmission, respectively.

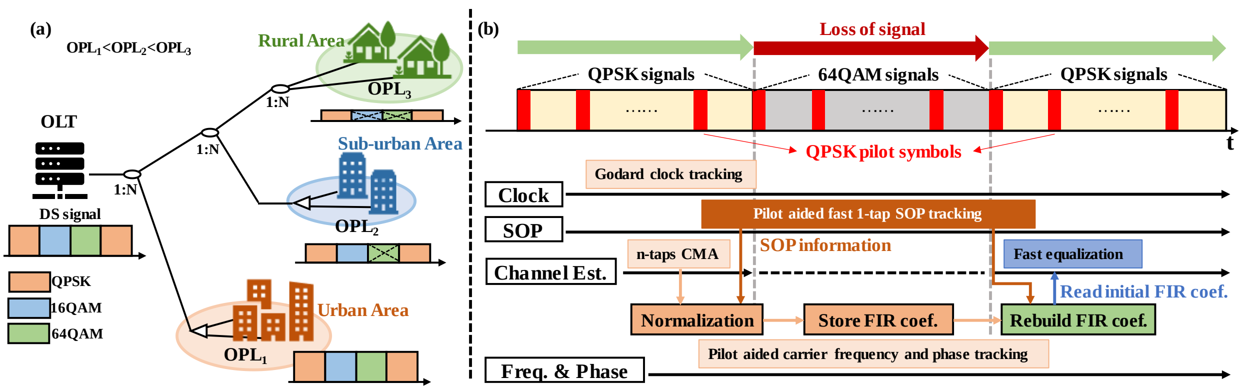

Fig. 1 (a) An example of future downstream TDM-PON system with continuous signals of different modulation formats; (b) the proposed downstream digital signal processing scheme.

2. Principles

Fig. 1(a) shows an example of future downstream TDM-PON where the ONUs are divided in several areas. They have different optical path losses (OPLs) due to the different distances from the OLT. There exists power margin for ONUs in urban and sub-urban areas to support higher order modulation formats than QPSK. If the continuous downstream signal is composed of different fomats in different time slots, such as QPSK, 16QAM and 64QAM, the ONUs in different areas can realize variable transmission rates based on the different signal-to-noise ratio (SNR). However, it's a challenge for this kind of burst-like signal to realize continuously channel state tracking, including the clock, SOP, carrier frequency and phase. For example, due to the limitation of SNR, the ONUs in rural area can't recover 64QAM signal, as shown in fig. 1(b). In the time slot the 64QAM signal comes, the performance of SOP tracking by the conventional CMA process degrades. When the QPSK signal in the next time slot comes, the CMA process needs to be re-trained, which results in more convergence time. Moreover, the decreased SNR degrades the performance of carrier phase estimation which is based on the original 64QAM signal.

To address these problems, we propose a pilot-aided downstream DSP scheme that realizes fast SOP tracking, CMA/CMMA process convergence, and carrier frequency and phase tracking. As shown in fig. 1(b), spaced QPSK pilot symbols are inserted in the continuous downstream signal to aid the optimal convergence of CMA/CMMA and fine carrier phase estimation. During the signal transmission, clock tracking is realized by Godard algorithm after chromatic dispersion compensation (CDC) [8]. The SOP is tracked by 1-tap CMA process among the whole time and the coefficients are updated by every QPSK pilot symbol. Channel equalization is realized by another n-taps CMA/CMMA process. To reduce the convergence time of the CMA/CMMA process for the signal with the same modulation format in the subsequent time slot, the FIR coefficients in the current time slot will be normalized and stored based on the current 1-tap SOP coefficient. When the new signal comes, the pre-stored FIR coefficients are read and rebuilt based on the updated 1-tap SOP coefficient. Then fast channel equalization is realized. The carrier frequency and phase are continuously tracked and recovered by the inserted QPSK pilot. To mitigate the impact of phase noise, the estimated phase can be averaged by several adjacent pilot symbols.

3. Experiment and Discussions

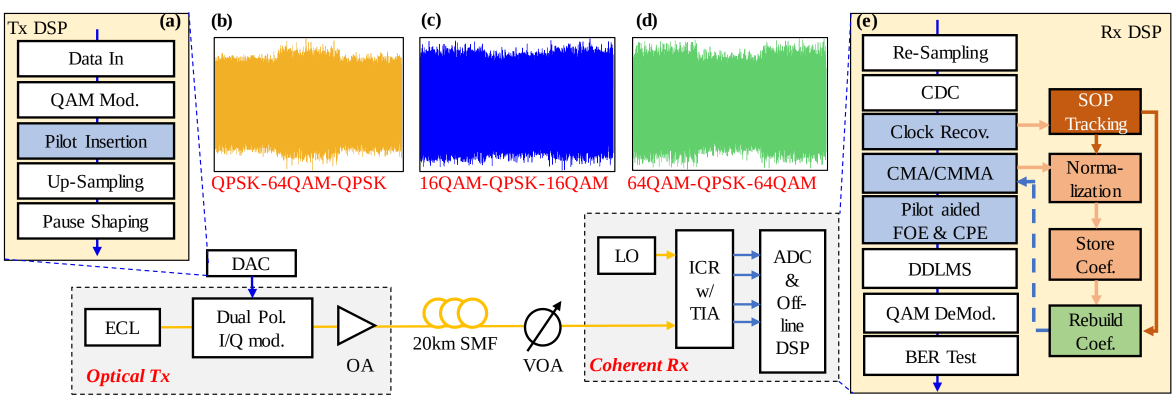

Fig. 2 Experimental setup of the flexible downstream coherent TDM-PON system, (a) and (e) are the Tx and Rx DSP, (b)-(d) are the traced combined-signals with different modulation formats.

Fig. 2 shows the experimental setup of the downstream coherent TDM-PON system. At the transmitter side, the bits are first mapped into QAM symbols and the distributed QPSK pilot symbols are inserted. Adjacent pilot symbols are separated by 47 data symbols. After 4 times up-sampling and pause shaping, the transmitted signal is generated and sent to a 120 GSa/s digital-to-analog converter (DAC). The baud rate of the signal is set at 25 GBaud. Three kinds of combined signals are used to evaluate the performance of the proposed downstream DSP scheme (continuous signals of three time slots with different modulation formats: QPSK-64QAM-QPSK, 16QAM-QPSK-16QAM and 64QAM-QPSK-64QAM). The signal is then modulated by a dual polarization I/Q modulator with an external cavity laser (ECL) operating at 1551.9 nm. Finally, the signal is launched into a 20-km single mode fiber (SMF). At the receiver side, the optical signal is detected by an integrated coherent receiver (ICR). The local oscillator (LO) operates at the same wavelength of the ECL for homodyne detection. Here a variable optical attenuator (VOA) is used for received optical power (ROP) adjustment. The receiver-side DSP is as discussed in principles. Fig (b)-(d) show the traced combined-signals with different modulation formats.

Fig. 3(a) shows the normalized time error of clock tracking. With the increase of symbols, the error converges to a stable value, which means the clock is recovered. With inserted QPSK pilot symbols, carrier frequency and phase keep continuously tracking, as shown in fig. 3(b). Fig. 3(c) represents the process of pilot-aided 1-tap SOP tracking. From the initial value of [1, 0; 0, 1], 1-tap coefficients keep adjusting over time according to the change of SOP. Thanks to the QPSK pilot, the tracking is stable although the data symbols change suddenly from QPSK to 64QAM, when it's not able to recover 64-QAM signal due to the limitation of SNR. We also test the performance of conventional CMA process, which FIR coefficients are continuously tracked, as shown in fig. 3(d). The CMA estimated error increase rapidly when the signal switch from QPSK to 64QAM due to different moduli. Here the number of CMA FIR tap is fixed at 9. Fig. 3(e) gives the signal MSE versus the number of training symbol under different SOPs. It should be noted that the parameters of Jones matrix are calculated based on the experimental data. Without SOP tracking, the CMA process for channel equalization should be re-trained and needs a long convergence time due to the random SOP. The 1-tap SOP tracking and prestored FIR coefficients greatly reduces the channel estimation time. Fig. 3(f) shows the BER performance versus the ROP under different modulation formats. Under the BER threshold of 1×10^{-2}, the sensitivities of QPSK, 16QAM and 64QAM signals are -37, -29 and -19-dBm, respectively. Similar BER performance is obtained with 1-tap SOP tracking and pre-stored FIR coefficients compared with conventional CMA/CMMA process that needs a long convergence time. We also test the BER performance of 20-km fiber transmission. Acceptable penalty of less than 0.5-dB is induced. Considering 1-dBm launch power, total power budgets of 38, 30 and 20 dB are achieved for QPSK, 16QAM and 64QAM signals, respectively. Finally, we successfully realize 100-300 Gbps flexible downstream signal transmission. The insets show the corresponding constellations.

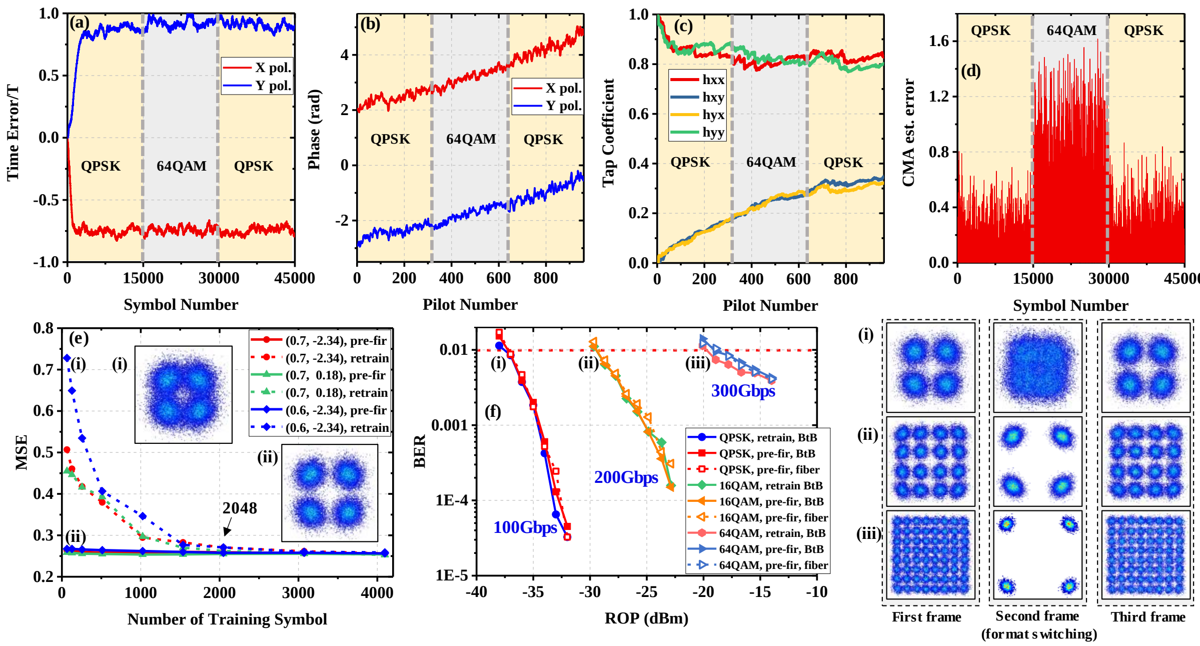

Fig. 3 (a) The time error of clock tracking; (b) the tap coefficients of 1-tap SOP tracking; (c) MSE versus the number of training symbol, the notation (A, B) means the calculated parameters of alpha (α) and delta (δ) of the Jones matrix; (d) CMA estimation error for conventional CMA process; (e) the estimated phase of pilot-aided carrier frequency and phase tracking; (f) BER versus ROP under different modulation formats.

4. Conclusion

We report pilot-aided DSP scheme for multi-format flexible coherent TDM-PON in downstream. The performance of the proposed scheme is verified by three kinds of continuous signal that combines different modulation formats. Inserted QPSK pilots are used for fast SOP tracking, carrier phase recovery, and channel estimation. To reduce the convergence time of the CMA/CMMA process, FIR coefficients for channel equalization are pre-stored and then rebuilt based on the tracked SOP information. Finally, we realize 300G flexible coherent PON of 25-GBaud PDM 4/16/64-QAM, achieving 38, 30, 20-dB power budgets after 20-km fiber transmission, respectively.

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