Hybrid, Multi-Format, Flexible-Rate Coherent PON Supporting Ultimate-Simplified Coherent and Full-coherent Receivers with Compatible OLT in Downstream

An Yan[1], Guoqiang Li[1], Sizhe Xing[1], Yongzhu Hu[1], Wangwei Shen[1], Junhao Zhao[1], Ziwei Li[1], Chao Shen[1], Jianyang Shi[1], Nan Chi[1] and Junwen Zhang[1 *]

[1]Key Laboratory of EMW Information (MoE), Fudan University, Shanghai 200433, China
*Corresponding Author: *junwenzhang@fudan.edu.cn*

Abstract: We propose and demonstrate a hybrid, multi-format and flexible-rate coherent PON system supporting ultimate-simplified coherent and full-coherent receivers based on the compatible OLT setup, achieving 50 to 300 Gbps access in FLCS-CPON based on 4/16/64-QAMs.

1. Introduction

Driven by the development of fifth and sixth generation (5G/6G) networks and multimedia services such as high-definition 8K/16K video stream, three-dimensional display and AR/VR applications, larger bandwidths are required in optical access networks [1-2]. For the future generation of PON to support the continuously growing bandwidth demand, it is envisioned that 100 Gb/s line-rate or beyond will be required [3]. Compared with intensity modulation and direct detection (IM/DD) system, coherent PON (CPON) is a promising solution for next generation 100G and beyond high-speed PON thanks to its high receiver sensitivity and larger power budget [4]. Besides, flexible PON (FLCS-PON) is another pivotal direction in the development of next-generation optical access networks [5].

Conventional full-coherent receivers, based on dual-polarization intradyne detection, deliver superior sensitivity and high-speed data rates for coherent access. Nevertheless, their cost is too high for optical access networks. Many simplified coherent receivers have been proposed for coherent optical access networks, however, most of them require specific transmitter settings, which undoubtedly limits the evolution capabilities of the access network [6]. Alternatively, simplified coherent receiver design based on single-polarization heterodyne detection and Alamouti coding has recently emerged as a cost-effective transitional solution, which use the same transmitter setup as the full-coherent optics [7]. This simplified receiver only requires a 3-dB coupler and a balanced photodiode (BPD). Moreover, replacing the BPD with a single-ended photodiode (SPD) can further simplify the coherent receiver [8]. However, the signal-signal beat interference (SSBI) caused by square-law detection will deteriorate the system performance, especially when the received optical power (ROP) is relatively high. In addition, the compatibility of this ultimate-simplified coherent receiver with a full-coherent receiver has not been fully verified.

Therefore, in this paper, we introduce and demonstrate a hybrid, multi-format, and flexible-rate coherent PON system that supports both ultimate-simplified coherent (USC) and full-coherent (FC) receivers, all of which are compatible with the OLT transmitter setup in the downstream. To mitigate the SSBI from a single-end PD, we apply the Kramers-Kronig (KK) receiving algorithm to the ultimate-simplified coherent receiver. This extends the dynamic range from 26/8 dB to 28/10 dB for 25-GBaud Alamouti-coded 16/64QAM signals, respectively. In the proposed coexistent hybrid coherent access architecture, we realize the downstream coherent detection of 25-GBaud 4/16/64-QAM after 20-km fiber transmission, with 39/31/21-dB power budget for the ultimate-simplified coherent KK receiver and 45/38/28-dB power budget for the conventional full-coherent receiver, respectively. Overall, a hybrid, multi-format and FLCS coherent PON is demonstrated with flexible access rate ranging from 50 to 300Gbps.

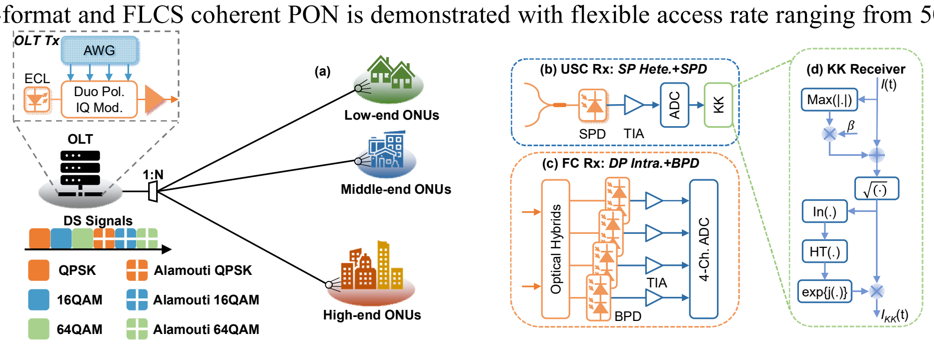

Fig. 1 (a) An example of future downstream TDM-PON system with different types of coherent receivers. (b) and (c) are the ultimate-simplified coherent receiver and full coherent receiver. (d) Diagram of KK receiver.

2. Principles

Fig. 1 (a) show an example of future downstream TDM-PON where the ONUs are categorized into different tiers. Diverse types of ONUs employ the coherent receivers with different complexity and cost. For the high-end ONUs with higher bandwidth demands and greater cost tolerance, the conventional full coherent receiver is selected to meet their requirements. As for the cost-sensitive middle- and low-end ONUs with relatively lower demands for data rate, the ultimate-simplified coherent receiver is sufficient to meet power budget and data-rate requirements simultaneously. As shown in Fig. 1 (c), the ultimate-simplified coherent receiver consists of only a 3-dB coupler and a single-end PD, achieving a remarkable reduction in complexity and cost. However, the SSBI induced by the square-law detection of single-end PD will deteriorate the system performance and thereby reduce the dynamic range. For the simplified coherent receiver, the complex optical field envelope of the signal before impinging upon the single-end PD can be expressed as $E(t) = E_{LO} + s(t)e^{j\pi f_{IF} t}$, where E_{LO} is the amplitude of the local oscillator (LO), $s(t)$ is the baseband QAM signal and f_{IF} is the intermediate frequency. The generated electrical signal after the square-law detection is shown as the following formula:

$$I(t) = \left|E_{LO}\right|^2 + 2Re\left[s(t)e^{j\pi f_{IF} t} \cdot E_{LO}^*\right] + \left|s(t)\right|^2 \tag{1}$$

where the second term is the desired useful signal, and the last term is the SSBI component whose magnitude is directly influenced by the ROP of the received signals. When the ROP is small, the SSBI remains negligible, with minimal impact on the system performance. In contrast, the influence of SSBI becomes notably more pronounced, leading to performance penalty and a reduction in the dynamic range.

To extend the dynamic range of the ultimate-simplified coherent receiver, we propose to adopt the KK relation [9] to mitigate the SSBI and reconstruct complex optical field, as shown in Fig. 1 (d). Furthermore, we implement the FLCS-CPON in the proposed hybrid coherent PON system. Within the hybrid FLCS-CPON framework, ONUs have different tiers but also different optical path losses (OPLs) due to the different distances from the OLT. ONUs with lower OPLs benefit from extra power margin, enabling to employ higher-order modulation formats beyond QPSK. The downstream signal, consisting of diverse formats such as QPSK, 16QAM, and 64QAM in separate time slots, permits ONUs in different regions to adapt their transmission rates based on varying signal-to-noise ratios.

3. Experimental Setup and Results

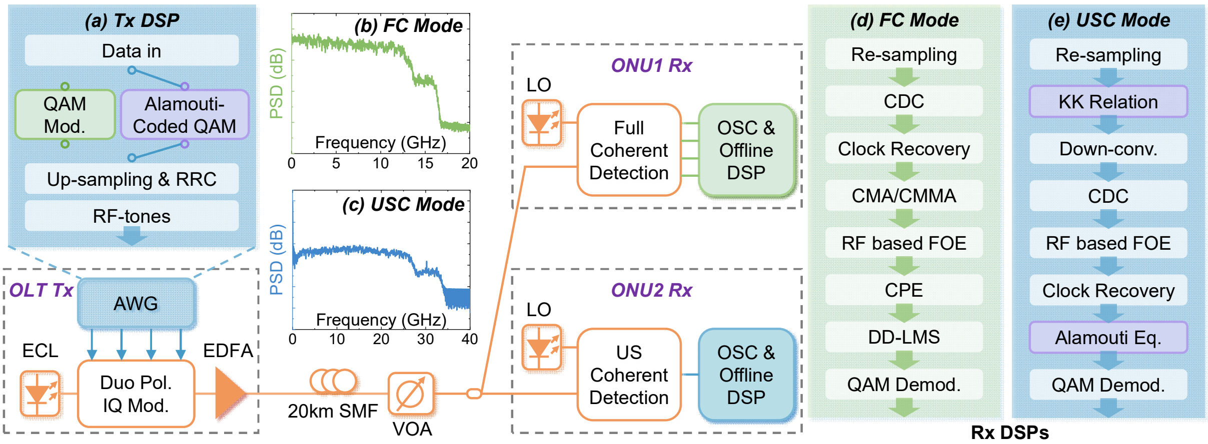

Fig. 2 Experimental setup of the downstream hybrid FLCS-CPON system. (a) the Tx DSP. (b) and (c) are the electrical spectrum after full coherent and ultimate-simplified coherent detection, respectively. (d) and (e) are the Rx DSP for these two types of coherent receivers.

Fig. 2 shows the experimental setup of the downstream hybrid FLCS-CPON system. At the transmitter side, we generate 25-GBaud dual-polarization QAM signals for high-end ONUs equipped with full coherent receivers, and 25-GBaud Alamouti-coded QAM signals for middle to low-end ONUs employing simplified coherent receivers. The signal is then modulated by a dual polarization I/Q modulator with an external cavity laser (ECL) operating at 1551.9 nm. After amplified by an Erbium-doped Fiber Amplifier (EDFA) to 7-dBm, the optical signal is launched into a 20-km single mode fiber (SMF). Here a variable optical attenuator (VOA) is used for ROP adjustment. At the receiver side, the downstream signal is divided and routed to individual ONU, each utilizing specific coherent receiver and digital signal processing (DSP) scheme for signal recovery. The receiver-side DSP is presented in Fig. 2 (d) and (e). For the ultimate-simplified coherent receiver based on Alamouti coding, KK relation is used for SSBI mitigation, and a specific Alamouti equalizer [10] is adopted to perform joint equalization and phase recovery.

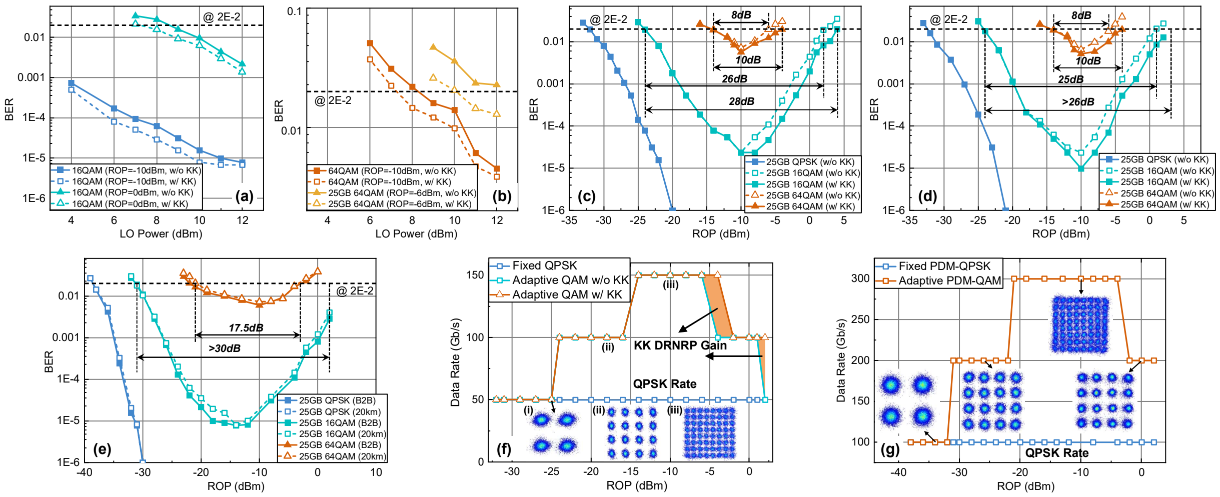

Fig. 3 (a) BER versus LO power for Alamouti-coded 16QAM. (b) BER versus LO power for Alamouti-coded 64QAM. (c) and (d) show BER versus ROP for ultimate-simplified coherent Rx in B2B and fiber transmission cases. (e) BER versus ROP for full coherent Rx. (f) and (g) illustrate the data rate under different schemes in the total dynamic range for simplified coherent Rx and full coherent Rx, respectively.

Fig. 3 shows the results for the hybrid FLCS-CPON in downstream. We consider a 15 % overhead soft decision FEC with a BER threshold of 2e-2 in this work. We vary the LO power and evaluate the BER performance for the ultimate-simplified coherent receiver, as shown in Fig. 3 (a) and (b). With the increase of LO power up to 12 dBm, the BER performance demonstrates consistent enhancement due to the improved SNR. Notably, the maximum LO power is restricted to 12 dB, given the maximum acceptable optical power of the PD. Therefore, the LO power is set to 12 dBm in the following discussions. The benefits from the employment of KK relation can be also illustrated in Fig. 3 (a) and (b), where the selected ROP is relatively high. Fig. 3 (c) and (d) show the calculated BER versus ROP in back-to-back (B2B) and 20-km SMF transmission cases. In B2B case, the dynamic range of the ultimate-simplified coherent receiver extends from 26/8 dB to 28/10 dB for 25-GBaud Alamouti-coded 16/64QAM signals, respectively, with the employment of KK relation. For the transmission over 20-km SMF, the KK receiver effectively extends the dynamic range by mitigating SSBI, resulting in nearly a 2-dB improvement. Fig. 3(f) illustrates the data-rate performance under different schemes in the total dynamic range for the ultimate-simplified coherent receiver in the hybrid multi-format FLCS-CPON. The blue line denotes the data-rate when only employing QPSK format. The green line shows the flexible data-rate when adopting adaptive QAM formats while the orange line shows the rates that we can achieve when using KK relation for SSBI removal. The orange area marks the gain of dynamic-range and net-rate product (DRNRP) by KK relation. For the full coherent receiver in the hybrid FLCS-CPON architecture, the LO power is set to fixed 12dBm for fair comparison. As shown in Fig. 3(e), the achieved dynamic ranges for 25-GBaud polarization-division-multiplexing (PDM) 16QAM and 64QAM are beyond 30 dB and 17.5 dB, respectively. Similarly, Fig. 3(f) illustrates the flexible data-rate in the total dynamic range for the full coherent receiver in the hybrid multi-format FLCS-CPON. Finally, we successfully realize 50-300 Gbps hybrid FLCS-CPON in downstream with different types of coherent receivers.

4. Conclusion

A novel hybrid, multi-format, and flexible-rate coherent PON system that supports both ultimate-simplified coherent and full-coherent receivers, is demonstrated with compatible OLT transmitter setup in the downstream. For the ultimate-simplified coherent receiver, the dynamic range is extended by nearly 2-dB for both Alamouti-coded 16QAM and 64QAM thanks to the KK receiving algorithm. Finally, in the proposed hybrid FLCS-CPON system, we achieve 39/31/21-dB power budget for the ultimate-simplified KK receiver with data-rates ranging from 50 to 150Gbps, while 45/38/28-dB power budget for the conventional full coherent receiver with data-rates ranging from 100 to 300Gbps, respectively.

Acknowledgment: This work is partially supported by National Natural Science Foundation of China (62171137, 61925104, 62031011), Natural Science Foundation of Shanghai (21ZR1408700).

References

[1] Z. Zhang, et al., IEEE Commun. Mag. 57.4, 144-150 (2019).
[2] Bonk, René, et al., IEEE Commun. Mag. 60.3, 48-54 (2022).
[3] J. Zhang, et al., J. Opt. Comm. Netw., 12.1, A1-A8(2020).
[4] S. Xing, et al., J. Light. Technol., 41.4, 1230-1239 (2022)
[5] G. Li, et al., in OFC 2023. paper W1I.3.
[6] M.S. Erkılınç, et al., J. Light. Technol. 36.16, 3453-3464 (2018)
[7] A. Hraghi, et al., Opt. Exp., 30.26, 46782-46797 (2022).
[8] M. S. Faruk, et al., in OFC 2022, paper Th3E.5.
[9] A. Mecozzi, et al., Optica, 3.11, 1220-1227 (2016).
[10] M. S. Faruk, et al., Opt. Exp., 24.11, 24083–24091 (2016).