The outlook for 100G and beyond passive optical network: from flexible rate to coherent architecture

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***Abstract*—ITU-T 50G passive optical network (PON) standard has been finalized. In this paper, we review 50G-PON and discuss the outlook for 100G and beyond PON from the perspective of flexible rate to coherent architecture.**

***Index Terms*—50G-PON, digital signal processing, flexible-rate PON, coherent PON, time-and-frequency division multiple access.**

I. Introduction

To satisfy the continuous growth of traffics demands, the ITU Telecommunication Standardization Sector (ITU-T) finalized the standard of 50G passive optical network (PON) in 2021 [1]. 50G-PON is the first PON using digital signal processing (DSP) to compensate for limited bandwidth, chromatic dispersion-caused distortions, and so on [2]. The penalty of the 50G-PON downstream transmission under 85-ps/nm dispersion has been reported to be reduced to below 1dB by receiver-side DSP [3]. 50G-PON based on the mature 25G components has been experimentally demonstrated, which utilized DSP to compensate for various distortions [4]. This shows that DSP is one of the most significant technologies to solve the challenges of 50G-PON.

It is a preferred choice that leverages mature and cost-effective 10G components using DSP for the 50G-PON. In our previous work [5], a DSP-enabled 50G on–off-keying (OOK)-PON using cost-effective O-band 10G components has been also experimentally demonstrated with a power budget beyond 29 dB. A 50-Gb/s multi-tone (DMT)-PON was experimentally demonstrated with a clipping-noise-cancellation (CNC) algorithm to improve the receiver sensitivity by about 2.5 dB [6], [7]. Three specific DSP algorithms have been proposed to deal with the main distortions of OOK, 4-ary pulse amplitude modulation (PAM4), and DMT signals for 50G-PON [8].

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As 50G PON has been approaching, it can be expected that 100G and beyond PON will be required. So far, all standardized PONs are based on intensity-modulation and direct-detection (IM/DD) systems with a fixed rate. The flexible rate might be an important feature for future PON and coherent optics are considered a more promising solution, especially for the beyond 100G PON. In this paper, we review the recent progress and discuss the outlook for 100G and beyond PON from the perspective of flexible rate to coherent architecture.

II. Flexible-rate PON

In this section, we discuss the flexible-rate technologies for the next-generation PON. The current PON delivers a downstream signal with the same data rate to all the optical network units (ONUs). However, the peak data rate is limited by the ONU with the worst-case optical budget. Flexible-rate PON is a concept that can adjust the parameters of the downstream signal on a time slot, which allows for throughput maximization by fully exploiting the available channel conditions of each ONU. The flexible-rate PON is based on four fundamental enabling techniques as shown in Fig. 1: (a) ONU grouping, (b) flexible forward error correction (FEC), (c-d) different modulation formats, and probabilistic constellation shaping (PCS).

A. ONU grouping & flexible forward error correction

The downstream transmission is organized by the data frame, which is subdivided into time slots. A group of ONUs with similar channel conditions and data rate requirements can be assigned the associated modulation and coding parameters at the allocated time slots as shown in Fig. 1(a). For example, ONUs with optical path loss (OPL) less than OPL_i (i = 1,2,3,..) are assigned the same parameters. The data rate should be adapted and controlled to make the optical power budget satisfy the OPL. The first 100 Gb/s flexible-rate PON was implemented by employing OOK and PAM4 with a subfamily of flexible rate codes [9].

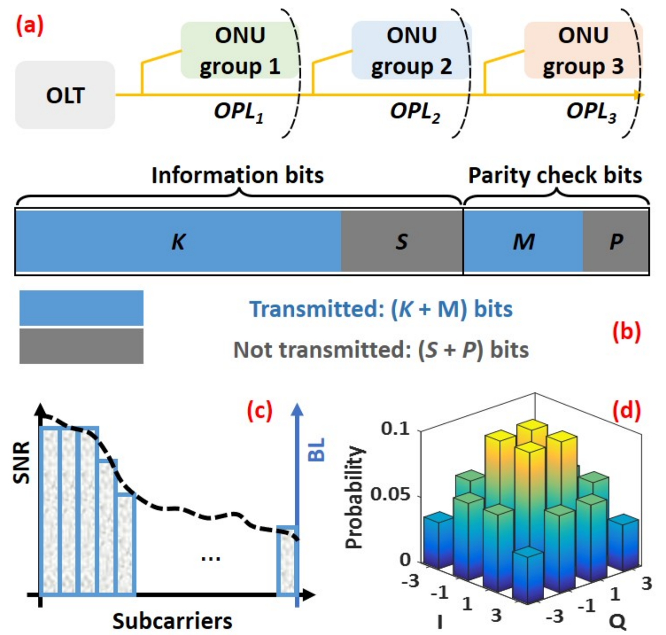

Fig. 1. Fundamental enabling techniques for flexible-rate PON: (a) ONU grouping, (b) flexible FEC, (c) different modulation formats, and (d) PCS.

The flexible FEC code family of the flexible-rate PON is based on the low-density parity check (LDPC) (17664,14592) mother code, which is defined in the IEEE 802.3ca [10]. By shortening S bits and puncturing P bits, the length of codewords is fixed at 11520 (i.e., $M+K$) bits as shown in Fig. 1(b). The code rates vary between 0.733 to 0.889, which can be calculated by $K/(K+M)$. It allows for net rate adaptation. However, the flexible FEC with fixed code length achieved by punching and shortening is at the expense of coding gain. The wider the rate adjustment range, the greater the total number of bits shortened and punched, which will also lead to the reduction of coding gain.

B. Different modulation formats

The single-carrier (SC) modulation can adopt PAM4, PCS-PAM4, and OOK to adjust the data rate. Although the gap of sensitivities between the OOK and PAM4 can be reduced by employing PCS for the 100 Gb/s flexible-rate PON [11], the data rate can not achieve the linear and continuous adjustment. As shown in Fig. 1(c), compared to SC modulation, multi-carrier (MC) modulation is more attractive for the flexible rate adjustment, which is able to continuously adjust the data rate by using bit loading (BL) according to the channel quality and optical power budget [12]. However, the high peak-to-average power ratio (PAPR) limits the performance of MC modulation in PON. A new 100 Gb/s fine-granularity flexible-rate PON based on DMT with PAPR optimization was demonstrated, which integrates the DMT subframe with time-division multiple access (TDMA) to achieve higher overall throughput [13]. The joint clipping operation and CNC algorithm were used to mitigate the high PAPR for the MC-BL DMT signal, which achieved a wide-range data-rate adjustment from 25 to 100 Gb/s with the 50-Mb/s granularity under the optical power budget from 36 to 26 dB.

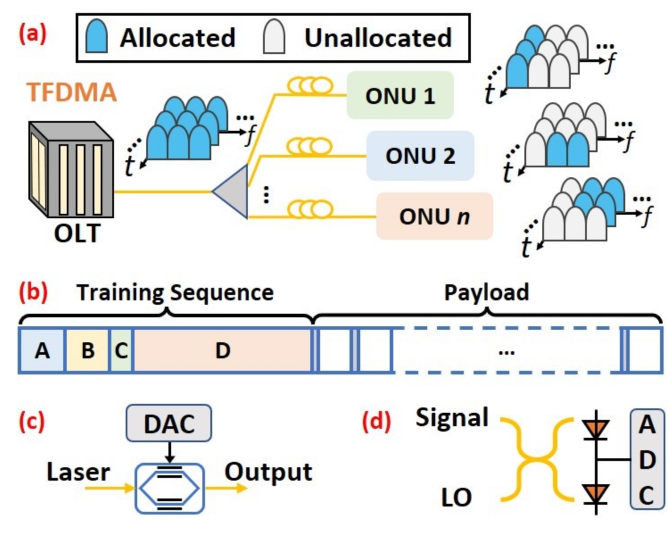

Fig. 2. (a) TFDMA-coherent PON architecture; (b) Data frame structure for fast-convergence DSP; (c-d) Ultra-simple ONU transmitter and receiver [16].

C. Probabilistic shaping-based entropy loading

PCS adjusts the entropy by adjusting the probability of the symbols in the constellation as shown in Fig. 1(d). The entropy loading (EL) using PCS provides a way of approaching the Shannon limit and fine-granularity rate adaptation. The world's first real-time prototype of a flexible-rate PON with MC-EL transceivers was presented in 2022. The prototype supports symmetric transmission of 12.5-Gb/s to 63-Gb/s signals using low-cost 10G-class optics over 20 km fiber transmission [14]. A flexible-rate PON based on entropy-loaded clipping DMT for increasing the capacity has been experimentally demonstrated [15]. The clipping operation and simplified LDPC-assisted CNC algorithm have been proposed to improve the performance of DMT, which used a segment LDPC decoder to reduce the computational complexity of the CNC algorithm.

III. Beyond 100G coherent PON

Up to now, the deployed PONs were based on the IM/DD systems [17]. It is acknowledged that the optical power budget and data rate of IM/DD systems, and O-band wavelength resources are not enough for the beyond 100G PON. In this section, we discuss the recent progress and outlook for the future beyond 100G PON based on the coherent PON, including the new time-and-frequency division multiple access (TFDMA)-architecture, fast-convergence DSP, and the ultra-simple transceiver for coherent PON as shown in Fig. 2.

A. TFDMA-coherent PON architecture

Recently, digital subcarrier multiplexing (DSCM) has attracted much attention for flexible bandwidth allocation [18]–[20]. Coherent PON using DSCM can provide frequency-division multiple access (FDMA) by the wavelength tuning

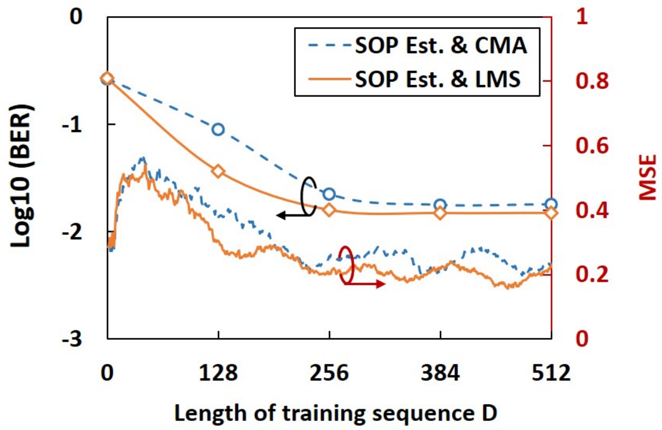

Fig. 3. MSE using the SOP estimation and LMS algorithm or CMA and BER using CMA and radius-directed equalization or LMS and DD-LMS versus the length of training sequence D [25].

of the local oscillator (LO) and coherent detection [21]–[23]. It has the advantages of low latency and flexible bandwidth allocation [24]. It also allows the low-bandwidth receiver at ONU. To combine the advantages of FDMA-PON with the statistical multiplexing capability of TDMA-PON, TFDMA-coherent PON architecture has been proposed as shown in Fig. 2(a). In the TFDMA-PON, the subcarriers of the DSCM signal can be divided into time slots to provide a larger number of users with low latency and flexible bandwidth resources. Therefore, the TFDMA-coherent PON shows great potential for the future beyond 100G PON. However, the coherent PON faces some challenges.

B. Fast-convergence DSP for coherent PON

The slow convergence of DSP is one of the main obstacles limiting the application of coherent optical communication systems in PON. The traditional DSP using blind and complex algorithms for coherent optical communication is difficult to achieve fast convergence. There are many contributions to the fast-convergence DSP of coherent TDMA-PON. A DSP and an 816-ns training sequence (TS) were proposed for the burst-mode detection of 100-Gb/s coherent PON [26]. A 100-Gb/s real-time burst-mode coherent receiver realized 120-ns convergence using the data-aided algorithms [27]. A 71.68-ns TS and DSP were proposed for the burst-mode detection of coherent TDMA-PON [28].

Since the convergence time is equal to the baud dividing the length of the training sequence, it is a great challenge for the coherent TFDMA-PON with low baud-rate subcarriers to converge within the same period. In our previous work [25], we have designed a specific training sequence structure and proposed data-aided DSP for coherent PON. The structure of the data frame is shown in Fig. 2(b), which contains four TSs for the data-aided DSP. TS-A is used for frame detection, coarse frequency offset estimation (FOE), and initial sampling phase estimation. TS-B is designed for frame synchronization and fine FOE, while TS-C is for the state of polarization estimation (SOP Est.). TS-D is used for equalizer training. Moreover, pilot symbols can be periodically inserted into the payload for fast carrier phase recovery.

The mean-square error (MSE) and bit-error ratio (BER) versus the length of training sequence D are shown in Fig. 3. Compared to the blind constant modulus algorithm (CMA), the training-based least-mean square (LMS) algorithm makes the MSE drop more rapidly and converge. After the compensation for FOE, timing recovery, SOP estimation using the TSs-A, B, and C, BER using LMS and decision-directed LMS algorithms with carrier phase recovery can converge using the TS-D with 256 training symbols. Fast convergence of a 400Gb/s-net-rate TFDMA-coherent PON was achieved by using a 416-symbol training sequence with a 52-ns duration. It is worth mentioning that hardware-efficient and fast-convergence DSP for coherent PON needs to be further investigated.

C. Ultra-simple transceiver for coherent PON

Except for the slow convergence of DSP, the high cost is another problem. The full coherent transceiver for ONU is still unaffordable. To reduce the cost for ONU, the simplified coherent optical systems using the single-polarization heterodyne receiver can be the valid solution [29], [30]. The first real-time TFDMA-coherent PON system using ultra-simple ONUs was demonstrated in 2023 [16]. An Alamouti coding-based single-polarization heterodyne receiver instead of a full coherent receiver was used in downstream transmission. In the upstream transmission, a single Mach-Zehnder modulator (MZM) rather than a dual-polarization IQ modulator was employed. This ultra-simple ONU contains only one digital-to-analog converter (DAC) and one MZM at the transmitter, one balanced photo-detector, and one analog-to-digital converter (ADC) at the receiver as shown in Figs. 2 (c-d). Such first real-time TFDMA-coherent PON with single-DAC and single-ADC ONUs can support up to 256 users with peak line rates of 100/200 Gb/s in the upstream/downstream, respectively.

IV. Conclusion

In this paper, we review the 50G-PON and discuss the recent progress and outlook for 100G and beyond PON from the perspective of flexible rate to coherent architecture. Flexible-rate PON can maximize the throughput by four enabling techniques, including ONU grouping, flexible FEC, different modulation formats, and PCS. For the future beyond 100G PON, TFDMA-coherent PON architecture is a promising solution. Fast-convergence DSP and ultra-simple transceivers will facilitate the application of coherent PON. Moreover, the flexible-rate coherent PON is also worthy of study.

References

[1] "50-Gigabit-capable passive optical networks (50G-PON): Physical media dependent (PMD) layer specification," ITU-T G.9804.3, 2021.

[2] R. Bonk, D. Geng, D. Khotimsky, D. Liu, X. Liu, Y. Luo, D. Nesset, V. Oksman, R. Strobel, W. Van Hoof *et al.*, "50G-PON: The first ITU-T higher-speed PON system," *IEEE communications magazine*, vol. 60, no. 3, pp. 48–54, 2022.

[3] M. Tao, J. Zheng, X. Dong, L. Zhou, H. Zeng, Y. Luo, S. Li, X. Liu *et al.*, "Improved dispersion tolerance for 50G-PON downstream transmission via receiver-side equalization," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2019, pp. M2B–3.

[4] B. Li, K. Zhang, D. Zhang, J. He, X. Dong, Q. Liu, and S. Li, "DSP enabled next generation 50G TDM-PON," *Journal of Optical Communications and Networking*, vol. 12, no. 9, pp. D1–D8, 2020.

[5] W. Liang, H. Wang, J. Wei, J. Zhou, D. Guo, and W. Liu, "DSP-enabled 50G OOK-PON with beyond 29 dB power budget using O-band 10G DML and 10G APD," *Optics Communications*, vol. 504, p. 127486, 2022.

[6] J. Zhou, L. Li, J. He, X. Lu, Y. Bo, G. Wang, Y. Huang, G. Liu, Y. Lu, S. Gao, Y. Feng, S. Zhao, W. Liu, C. Yu, and Z. Li, "Clipping discrete multi-tone for peak-power-constraint IM/DD optical systems," *SCIENCE CHINA Information Sciences*, 2022.

[7] J. Zhou, Q. Sui, and Z. Li, "Non-Orthogonal Discrete Multi-Tone: Toward Higher Spectral Efficiency for Optical Networks," *IEEE Communications Magazine*, vol. 59, no. 10, pp. 70–75, 2021.

[8] H. Wang, W. Mo, G. Liu, W. Liu, D. Guo, C. Yu, and J. Zhou, "Performance Comparison of OOK, PAM4 and DMT for 50Gb/s Passive Optical Networks," in *2022 IEEE/CIC International Conference on Communications in China (ICCC)*. IEEE, 2022, pp. 821–825.

[9] R. Borkowski, M. Straub, Y. Ou, Y. Lefevre, Ž. L. Jelić, W. Lanneer, N. Kaneda, A. Mahadevan, V. Hückstädt, D. van Veen *et al.*, "FLCS-PON–a 100 Gbit/s flexible passive optical network: concepts and field trial," *Journal of Lightwave Technology*, vol. 39, no. 16, pp. 5314–5324, 2021.

[10] "IEEE Standard for Ethernet Amendment 9: Physical Layer Specifications and Management Parameters for 25 Gb/s and 50 Gb/s Passive Optical Networks," IEEE 802.3ca, 2020.

[11] R. Borkowski, Y. Lefevre, A. Mahadevan, D. Van Veen, M. Straub, R. Kaptur, B. Czerwinski, B. Cornaglia, V. Houtsma, W. Coomans *et al.*, "FLCS-PON—an opportunistic 100 Gbit/s flexible PON prototype with probabilistic shaping and soft-input FEC: operator trial and ODN case studies," *Journal of Optical Communications and Networking*, vol. 14, no. 6, pp. C82–C91, 2022.

[12] J. Zhou, J. He, X. Lu, G. Wang, Y. Bo, G. Liu, Y. Huang, L. Li, H. Wang, W. Mo *et al.*, "First 100Gb/s Fine-Granularity Flexible-Rate PON Based on Discrete Multi-Tone and PAPR Optimization," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2022, pp. Th2A–23.

[13] J. Zhou, J. He, X. Lu, G. Wang, Y. Bo, G. Liu, Y. Huang, L. Li, C. Yang, H. Wang *et al.*, "100G fine-granularity flexible-rate passive optical networks based on discrete multi-tone with PAPR optimization," *Journal of Optical Communications and Networking*, vol. 14, no. 11, pp. 944–950, 2022.

[14] G. Liu, G. Wang, Y. Huang, J. He, Y. Bo, K. Zheng, M. Li, Y. Wu, Y. Lu, Z. Ye *et al.*, "World's First Demonstration of Real-time Symmetric Flexible Rate PON with Entropy-Loading and 10G-class Optics," in *European Conference and Exhibition on Optical Communication*. Optica Publishing Group, 2022, pp. Th3A–3.

[15] W. Mo, J. Zhou, G. Liu, Y. Huang, L. Li, H. Cui, H. Wang, Q. Lu, W. Liu, and C. Yu, "Simplified LDPC-assisted CNC algorithm for entropy-loaded discrete multi-tone in a 100G flexible-rate PON," *Optics Express*, vol. 31, no. 4, pp. 6956–6964, 2023.

[16] Z. Xing, K. Zhang, X. Chen, F. Qiguang, K. Zheng, Y. Zhao, Z. Dong, J. Zhou, T. Gui, Z. Ye, and L. Li, "First Real-time Demonstration of 200G TFDMA Coherent PON using Ultra-simple ONUs," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2023, pp. Th4C–4.

[17] M. S. Faruk, X. Li, D. Nesset, I. N. Cano, A. Rafel, and S. J. Savory, "Coherent passive optical networks: why, when, and how," *IEEE Communications Magazine*, vol. 59, no. 12, pp. 112–117, 2021.

[18] H. Wang, J. Zhou, J. Wei, D. Guo, Y. Feng, W. Liu, C. Yu, D. Wang, and Z. Li, "Multi-rate Nyquist-SCM for C-band 100 Gbit/s signal over 50 km dispersion-uncompensated link," *Journal of Lightwave Technology*, vol. 40, no. 7, pp. 1930–1936, 2022.

[19] H. Wang, J. Zhou, J. Wei, W. Mo, Y. Feng, W. Liu, C. Yu, and Z. Li, "Record Capacity-Reach of C band IM/DD Optical Systems over Dispersion-Uncompensated Links," in *2022 Conference on Lasers and Electro-Optics (CLEO)*. IEEE, 2022, pp. SM2J–6.

[20] W. Mo, J. Zhou, H. Wang, W. Liu, D. Guo, and C. Yu, "Adaptive Frequency-Domain Power Optimization for NOMA-SCM Passive Optical Networks," in *TENCON 2022-2022 IEEE Region 10 Conference (TENCON)*. IEEE, 2022, p. 4551.

[21] J. Zhang and Z. Jia, "Coherent Passive Optical Networks for 100G/λ-and-Beyond Fiber Access: Recent Progress and Outlook," *IEEE Network*, vol. 36, no. 2, pp. 116–123, 2022.

[22] J. Zhang, Z. Jia, H. Zhang, M. Xu, J. Zhu, and L. A. Campos, "Rate-flexible single-wavelength TFDM 100G coherent PON based on digital subcarrier multiplexing technology," in *2020 Optical Fiber Communications Conference and Exhibition (OFC)*. IEEE, 2020, pp. W1E–5.

[23] M. Xu, Z. Jia, H. Zhang, L. A. Campos, and C. Knittle, "Intelligent Burst Receiving Control in 100G Coherent PON with 4$\times$ 25G TFDM Upstream Transmission," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2022, pp. Th3E–2.

[24] Y. Zhang, M. O'Sullivan, and R. Hui, "Digital subcarrier multiplexing for flexible spectral allocation in optical transport network," *Optics Express*, vol. 19, no. 22, pp. 21 880–21 889, 2011.

[25] H. Wang, J. Zhou, Z. Xing, Q. Feng, K. Zhang, K. Zheng, X. Chen, T. Gui, L. Li, J. Zeng *et al.*, "Fast-Convergence Digital Signal Processing for Coherent PON using Digital SCM," *Journal of Lightwave Technology*, 2023.

[26] R. Matsumoto, K. Matsuda, and N. Suzuki, "Burst-mode coherent detection using fast-fitting pilot sequence for 100-Gb/sM coherent TDM-PON system," in *2017 European Conference on Optical Communication (ECOC)*. IEEE, 2017, p. W.3.D.5.

[27] M. Li, N. Deng, Q. Xue, G. Gong, Z. Feng, and S. Cao, "A 100-Gb/s real-time burst-mode coherent PDM-DQPSK receiver," in *39th European Conference and Exhibition on Optical Communication (ECOC 2013)*. IET, 2013, pp. OTu1G–3.

[28] J. Zhang, Z. Jia, M. Xu, H. Zhang, and L. A. Campos, "Efficient preamble design and digital signal processing in upstream burst-mode detection of 100G TDM coherent-PON," *Journal of Optical Communications and Networking*, vol. 13, no. 2, pp. A135–A143, 2021.

[29] M. S. Faruk, X. Li, and S. J. Savory, "Experimental demonstration of 100/200-Gb/s/λ PON downstream transmission using simplified coherent receivers," in *Optical Fiber Communication Conference*. Optica Publishing Group, 2022, pp. Th3E–5.

[30] M. Erkılınç, D. Lavery, K. Shi, B. Thomsen, R. Killey, S. Savory, and P. Bayvel, "Bidirectional wavelength-division multiplexing transmission over installed fibre using a simplified optical coherent access transceiver," *Nature communications*, vol. 8, no. 1, p. 1043, 2017.