1.024-Tbit/s CDM-SDM Coherent PON over 10-km Weakly-Coupled MCF

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Abstract: 1.024-Tbit/s CDM-SDM coherent PON is experimentally demonstrated based on weakly-coupled MCFs and Walsh code assignment. Space-time coding is utilized for balancing the inconsistency of the reception performances of CDM-assigned ONUs.

1. Introduction

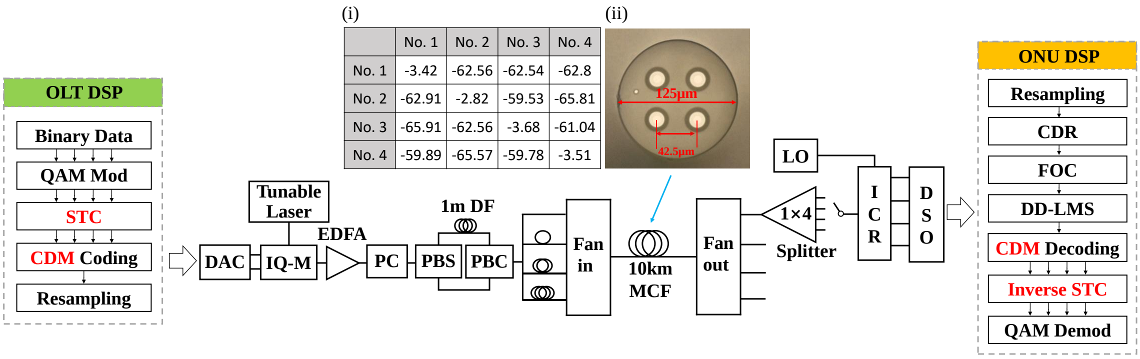
Passive optical network (PON) based on intensity modulation and direct detection (IM/DD) scheme has been developed tens of years, but exhibits the limitations of constraint channel bandwidth, low receiving sensitivity and severe transmission impairments raised by fiber dispersion along with the ever-increasing transmission capacity [1]. As the comparison, coherent PON (CPON) has the benefits of longer transmission distance, higher access speed and receiver sensitivity [2], which is a promising solution for the future PON application. As for the multiplexing schemes in CPON system, the time division multiplexing (TDM) and wavelength division multiplexing (WDM) technologies have been already investigated [3,4]. WDM CPON possesses advantages of large capacity and scalability by the means of multiplexing on optical wavelength domain [2]. With the assistance of coherent detection, TDM CPON assigning time slots for different optical network units (ONUs) can offer the adaptive capacity to meet the end-user requirements. However, the resulted burst mode of time slots places the heavy burden on the receiving digital signal processing (DSP) [5]. Moreover, the guard time between time slots also reduces the efficient capacity of TDM CPON. On the other hand, the code division multiplexing (CDM) technology has advantages over TDM solution in CPON systems, providing the larger spectral efficiency, higher power budget and better information security due to the unique code words for ONUs [6,7]. Moreover, CDM is compatible to the WDM CPON framework, which enlarges the capacity and expands the connectivity with more accessed ONUs. Recently, space division multiplexing (SDM) PON is proposed to further improve the capacity of PON [8,9]. Moreover, the large scale of SDM can also increase the number of ONUs in PON. Thus, the combination of CDM and SDM technologies is expected to realize the advanced PON with large throughput capacity and massive connection.

In this work, we realize a 1.024-Tbit/s CDM-SDM CPON using Walsh codewords and 4-core weakly-coupled multicore fibers (WC-MCFs) with standard cladding diameter. We investigate the inconsistent reception performances of CDM-assigned ONUs in the downstream signaling. With the increasing baud rate, the inconsistency of reception performances among CDM tributaries becomes more obvious. To deal with this issue, we innovatively utilize the space-time coding (STC) technique which is normally applied to mitigate the mode dependent loss in SDM links. With the assistance of STC, we successfully realize the 16×64-bit/s (1.024-Tbit/s) CDM-SDM CPON using dual polarization 16-quadrature amplitude modulation (16-QAM) formats over 10-km 4-core WC-MCF.

2. Experimental Setup

Experimental setup of the downstream signaling in CDM-SDM CPON and the corresponding DSP flowcharts are depicted in Fig. 1. At the optical line terminal (OLT) side, four paralleling tributaries modulated into 16-QAM format are pre-coded by STC using Hadamard transform before CDM coding to balance the reception performances of CDM-assigned ONUs. If the original sequence vector is presented as $\boldsymbol{x}(t) = [x_1(t), x_2(t), \ldots, x_N(t)]^T$, the space-time coded symbol sequence $\boldsymbol{y}(t)$ is obtained by:

$$\boldsymbol{y}(t) = \frac{1}{\sqrt{N}} H_N \boldsymbol{x}(t), \tag{1}$$



	No. 1	No. 2	No. 3	No. 4
No. 1	-3.42	-62.56	-62.54	-62.8
No. 2	-62.91	-2.82	-59.53	-65.81
No. 3	-65.91	-62.56	-3.68	-61.04
No. 4	-59.89	-65.57	-59.78	-3.51

Fig. 1. Experimental setup of the downstream CDM-SDM CPON supporting 16×64-Gbit/s ONUs and DSP flowcharts. Insets: (i) crosstalk matrix of the 4-core WC-MCF, (ii) cross-section micrograph of the 4-core WC-MCF.

where H_N is the Hadamard matrix with the order of N [10]. In our work, N is set at 4. For the CDM coding, signals are coded by four corresponding orthogonal Walsh codewords before combining together. Afterwards, resampling is necessary to match the 96-GSa/s sampling rate of the digital-to-analog converter (DAC) with the 25-GHz analog bandwidth. The wavelength of the light emitted from the tunable laser is 1550 nm. The generated signals are modulated onto the optical carrier through the IQ-modulator (IQ-M). After the erbium-doped fiber amplifier (EDFA), the dual polarization signal is emulated through the polarization beam splitter (PBS) and the polarization beam combiner (PBC). The polarization controller (PC) is used to control the polarization and the delay fiber (DF) is used for decorrelation of the two polarization signals before combining together.

At the optical distribution network (ODN), the 4-core WC-MCF with the standard cladding diameter of 125 μm and the core pitch of 42.5 μm is used. The corresponding crosstalk matrix is shown in the inset (i), indicating that the inter-core crosstalk of the SDM link is below -55 dB. Then, the optical signal is detected by the integrated coherent receiver (ICR) and the electrical waveforms are digitized in the 256-GSa/s digital storage oscilloscope (DSO). The offline DSP of ONUs includes resampling, clock and data recovery (CDR), frequency offset compensation (FOC), decision-directed least mean square (DD-LMS) algorithm, CDM decoding, inverse STC and QAM demodulation.

3. Results and Discussions

In the CDM-SDM CPON system, every core of the MCF contains the signal coded by four different orthogonal CDM codewords. As a result, every ONU corresponds to one of the decoded signals. As shown in Fig. 2(a), for the single polarization signals of 16×32 Gbit/s at -15-dBm received optical power (ROP), different cores have the similar circumstance of Q factors while different CDM-assigned ONUs have the different reception performances within the same core. ONU1 coded by $[1,1,1,1]$ has the best performance and ONU2 coded by $[1,-1,1,-1]$ has the worst performance. To address the inconsistency of the reception performances, we employ the STC technique to the OLT DSP. As shown in Fig. 2(b), the CDM-assigned ONUs show the consistent Q factors with the assistance of STC, which indicates that the WC-MCF is applicable for the SDM PON to enlarge the capacity and expand the connection. It is evident that the employment of the STC brings an overall signaling quality improvement with the

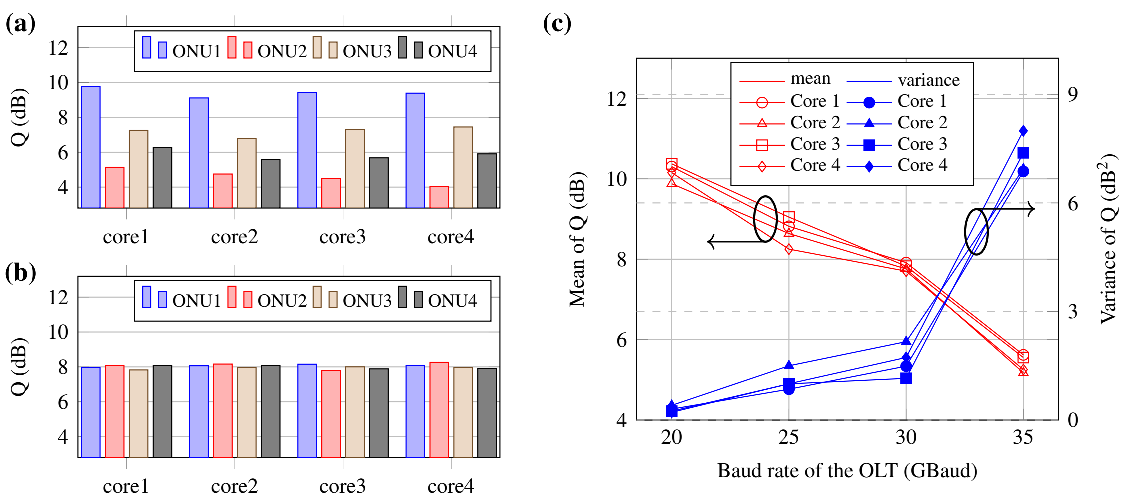


Fig. 2. Q factors of 16×32-Gbit/s CDM-assigned ONUs: (a) without STC, (b) with STC. (c) Mean values and variances of Q factors for the decoded signals in different cores at different band rates.

acceptable deterioration of ONU1 reception performances.

With the increasing OLT baud rate, we observe that the reception performances of the CDM-assigned tributaries appear more inconsistent, as shown in Fig. 2(c). At the baud rate of 20 GBaud, the signaling performances of four CDM-assigned ONUs in the same core are similar to each other. However, at the baud rate of 35 GBaud, the variances of Q factors increase more rapidly than before due to the spectrum narrowing from the limited device bandwidth at the transceiver. The mean values of Q factors decrease and the variances of Q factors increase with the rise of the baud rate, indicating the worse reception performance and the worse consistency of the CDM-assigned ONUs due to the higher capacity.

At last, we measure the Q factor versus received optical power (ROP) of different ONUs within the same core. As shown in Fig. 3(a), Q factors of all ONUs decrease with ROP declining due to the deterioration of the optical signal-to-noise ratio. With the employment of STC, the reception performances of CDM-assigned ONUs have an overall improvement. At the hard-decision forward error correction (HD-FEC) threshold of 8.5281 dB [11], the sensitivity of the signals with STC has a maximum increment of about 4 dB compared with the signals without STC. Considering 10-dBm launch power, the power budget of 24 dB are achieved at the soft-decision FEC (SD-FEC). Fig. 3(b) shows the reception performances of 1.024-Tbit/s dual polarization 16-QAM signals using STC in CDM-SDM CPON. Based on the above results, the proposed structure of CPON has advantages of large connection numbers and capacity.

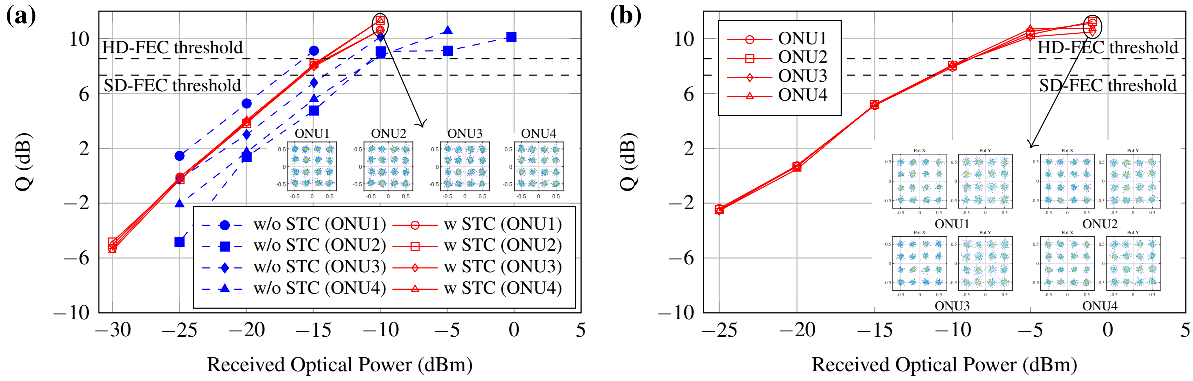


Fig. 3. Q factors at different ROP: (a) 16×32-Gbit/s CDM-assigned ONUs. (b) 16×64-Gbit/s CDM-assigned ONUs with STC.

4. Conclusion

We experimentally investigate the inconsistency of reception performances of CDM-assigned ONUs. Through innovatively utilizing STC technique in the CDM-SDM CPON, the reception performances of ONUs become consistent and get an overall improvement of Q factor. With using the proposed CPON scheme and the corresponding DSP technologies, a 1.024-Tbit/s CDM-SDM CPON based on 10-km 4-core WC-MCF and Walsh code assignment has been experimentally demonstrated, which is a promising candidate for the future advanced PON system with large capacity and massive connections.

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References

1. H. Zhang *et al.*, "Rate-Flexible Coherent PON Up To 300 Gb/s Demonstrations with Low ...," in *OFC 2023,* p. W1I.2.
2. J. Zhang *et al.*, "Flexible and adaptive coherent PON for next-generation ...," Opt. Fiber Technol. **75**, 103190 (2023).
3. G. Li *et al.*, "Local Oscillator Power Adjustment-Based Adaptive ...," J. Light. Technol. **41**, 1240–1249 (2023).
4. J. Li *et al.*, "Demonstration of 128×100-Gb/s Real-Time Coherent UDWDM-PON with ...," in *OFC 2022,* pp. 1–3.
5. H. Wang *et al.*, "Fast-Convergence Digital Signal Processing for ...," J. Light. Technol. **41**, 4635–4643 (2023).
6. T. Kodama *et al.*, "Mode and Code Division Multiplexing System for ...," in *Advanced Photonics 2017,* p. PW3D.1.
7. D. Schaber *et al.*, "PON Downstream Scheme Supporting ...," IEEE Photonics Technol. Lett. **35**, 1171–1174 (2023).
8. F. Bao *et al.*, "300 Gb/s IM/DD based SDM-WDM-PON with laserless ONUs," Opt. Express **26**, 7949–7954 (2018).
9. F. Bao *et al.*, "DSP-free single-wavelength 100 Gbps SDM-PON with ...," Opt. Express **27**, 33915–33924 (2019).
10. K. Shibahara *et al.*, "Space-Time Coding-Assisted Transmission for Mitigation of MDL ...," in *OFC 2016,* p. Th4C.4.
11. J. Zhang *et al.*, "SOA Pre-Amplified 100 Gb/s/λ PAM-4 TDM-PON ...," J. Light. Technol. **38**, 185–193 (2020).