# Demonstration of Beyond 100G Three-Dimensional Flexible Coherent PON in Downstream with Time, Frequency and Power Resource Allocation Capability

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**Abstract:** We propose and demonstrate a novel three-dimensional flexible coherent PON with the resource-allocation capability in time, frequency and power domain. High flexibility is demonstrated with >100G over 20-km fiber for coherent PON in downstream. © 2023 The Author(s)

## 1. Introduction

The emergence of multiple new mission-critical applications in the sixth generation (6G) such as mobile X-haul, 8K/16K streaming, and upcoming 3D holographic transmission are driving the next-generation optical access network toward a more flexible and higher data rate communication system [1,2]. Now with the IEEE's 25/50G NG-EPON and the ITU-T 50G PON standard (G.9804) has become a reality [3], 100G, 200G and beyond PON is the next pursuit for optical access network. To support the increasing demand for the bandwidth, coherent PON (CPON) based on local oscillator (LO) power-aided and powerful digital signal processing (DSP) is the most potential candidate [4], which can provide the system with beyond 200G data rate, higher sensitivity and extended power budget [5]. Also, thanks to the multi-dimensional modulation formats, it can help achieve beyond 100G access with more flexible and adaptive access rates [6].

Two types of coherent PON have been reported, comprising coherent time-division-multiplexing (TDM)-PON with low complexity and high delay and coherent wavelength-division-multiplexing (WDM)-PON with low latency and high cost. Recently, time and frequency division multiplexing (TFDM) CPON attracts many researchers' attention [7]. Compared with TDM-PON and WDM-PON, TFDM CPON can provide more flexible bandwidth allocation, taking the advantages of both TDM-PON and WDM-PON [8]. Also, Flexible PON (FLCS-PON) is an interesting research topic in these years, as it can extend the deployment scenarios to support more users with different channel conditions [9]. Based on the multi-dimensional modulation in both time and frequency dimensions, TFDM-PON has shown its ability for flexible rate allocation. However, in TFDM-PON system, all users are still allocated the same transmission power, which means that there is power waste for users with better channel conditions. To further improve the flexibility of TFDM-PON, how to allocate resources more rationally for users with different channel conditions and service requirements becomes more and more interesting.

To further explore the advantage of flexibility in CPON, in this paper, we propose and demonstrate a novel three-dimensional flexible coherent PON (3D FLCS-CPON) with the resource-allocation capability in the time, frequency and power domain. Digital subcarriers with power allocations in both time and frequency-domain achieve more flexible and adaptive access rates beyond traditional TDM and FDM. As a proof-of-concept, a 3D FLCS-CPON with four subcarriers is demonstrated in the downstream, achieving a peak data rate of 250 Gb/s/λ over 20-km fiber.

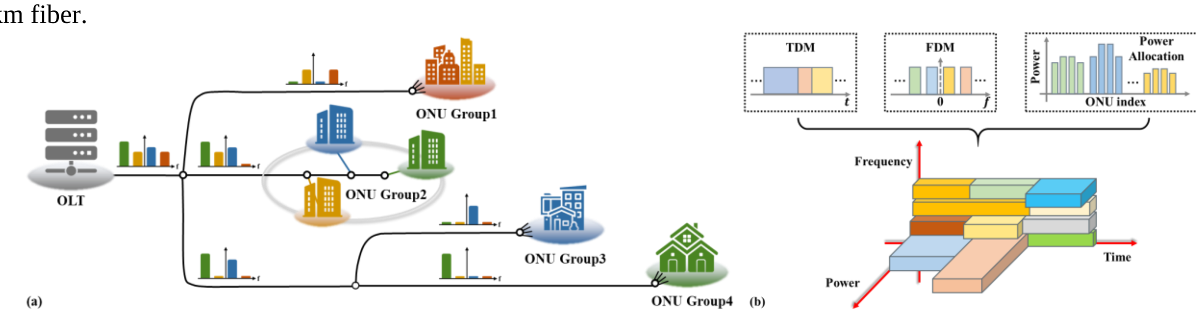


Fig. 1 (a) Architecture diagram of 3D FLCS-CPON. (b) Schematic diagram of 3D FLCS-CPON based on power allocation.

## 2. Principles and Experimental Setup

The architecture diagram of 3D FLCS-CPON shown in Fig. 1(a). To meet the changing needs of all ONUs, 3D FLCS-CPON needs to schedule resources in three dimensions: time, frequency and power. In the time dimension, each subcarrier can transmit QAM of different orders at different times, which means that the transmission rate of each subcarrier can change with time. In the frequency dimension, all subcarriers are in different frequency bands of the same wavelength, and each subcarrier can transmit QAM of different orders at the same time, which means that each subcarrier can be used to serve different ONUs at the same time. On this basis, combined with power allocation, it can ensure that each subcarrier reaches the BER threshold at any time. The situation of each subcarrier in three dimensions is shown in Fig. 1(b).

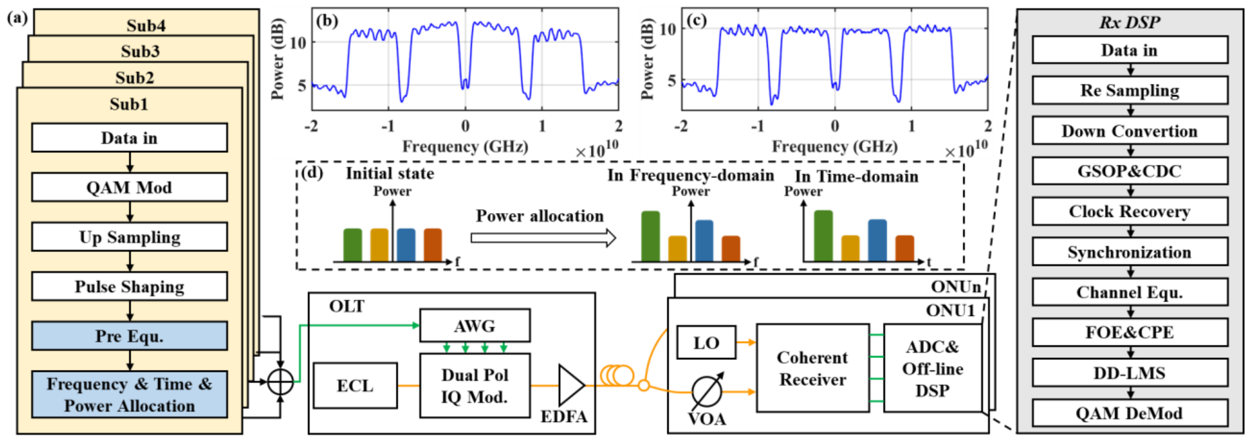


Fig. 2 (a) Schematic of the experimental setup. (b) The spectrum of the received signal without power pre-equalization. (c) The spectrum of the received signal with power pre-equalization. (d) Schematic diagram of power allocation in time domain and frequency domain (different colors represent different QAMs)

Fig. 2(a) shows the experimental setup for a 3D FLCS-CPON downstream based on a four-subcarriers multiplexing scheme. Four subcarriers, Ch1, Ch2, Ch3 and Ch4, each carrying 6.25-GBaud MQAM (in this experiment, M can be selected from 4, 8, 16, and 32), are generated by 100GSa/s arbitrary waveform generators (AWGs) and then modulated by a dual polarization (DP) I/Q modulator on single wavelength in the OLT-side. An ECL is used as the laser source with a wavelength at 1553.6 nm and <100 kHz linewidth. Signals are launched into fiber after a boost EDFA, with a launch power of 6 dBm. After 20 km fiber transmission, a variable optical attenuator (VOA) is used for power control in the BER performance test. The optical signals are detected by an integrated coherent receiver (ICR). Another ECL is used as LO at the wavelength of 1553.6 nm and less than 100 kHz linewidth. The detected signals are captured by an 80GSa/s digital storage oscilloscope (DSO) for offline DSP. The DSP of subcarriers generation on the Tx side and demodulation on the Rx side are also shown in Fig. 2(a). For signal generation, the data is first mapped and modulated on each subcarrier. After upsampling by a factor of 16, the signal on each subcarrier is Nyquist pulse-shaped with a roll-off of 0.1. To better perform power allocation, power pre-equalization is applied first to make the power of the four subcarriers of the signal flat in the frequency domain. Fig. 2(b) shows the received signal without power pre-equalization, and Fig. 2(c) shows the received signal with power pre-equalization. According to the need of each subcarrier, its power can be adjusted to achieve power allocation. After pre-equalization, the four 6.25-GBaud subcarriers are up-converted to four inter-frequencies: -12 GHz, -4 GHz, 4 GHz and 12 GHz. For the receiver-side DSP, the inverse processing flow is performed. Subcarriers are first filtered out, separated and then down-converted to the baseband. They are processed independently with several key signal recovery functions [7].

## 3. Results

To verify that the 3D FLCS-CPON can flexibly allocate resources in the face of any distribution and demand of ONU, we designed experiments in three cases. In the first case, the downstream signal transmitted from the OLT reaches each ONU with similar optical path loss (OPL). We verified that four subcarriers transmit QAMs of the same or different order and the results are shown in Fig. 3(a). When we consider the most extreme case, that is, four subcarriers transmit 8QAM, 32QAM, 16QAM and QPSK, the result is shown in (iii) of Fig. 3(b). Under a BER threshold of $1\times10^{-2}$, a total power budget of 36.2 dB and total data rate of 175 Gb/s/λ are achieved. Other more general situations are shown in (i), (ii) and (iv) of Fig. 3(b). When a higher rate is required, each subcarrier can transmit 32QAM, up to 250 Gb/s/λ, and the power budget is 29.3dB through power allocation.

In the second case, if the OPL of the ONU is different, then it is necessary to give higher power to the ONU with the larger OPL, and vice versa. Therefore, we tested the BER of the four subcarriers with the same order but different OPL, the spectrum with and without power allocation is shown in (I) and (II) of Fig. 3(c). At the same time, the corresponding BER curve is shown in Fig. 3(d). When power allocation is not used, the system power is in the state shown by the average power in the schematic diagram of case 2. At this time, only ONU4 and ONU3 with smaller OPL can receive signals normally. After using power allocation, the surplus power of ONU4 and ONU3 is redistributed to ONU2 and ONU1 to support more ONUs to meet the BER threshold. After using power allocation, the sensitivities of the four ONUs are -32.1dBm, -35.9dBm, -38.4dBm, -39.7dBm based on measurement of total power.

The third case verifies that when the same subcarrier transmits QAMs with different modulation orders at different timeslots, it is also possible to make each subcarrier meet the BER threshold through power allocation. The result is shown in Fig. 3(c). At timeslot 1, the four subcarriers transmit 8QAM. At timeslot 2, subcarriers 1 and 4 are converted to transmit 16QAM. The power of the subcarriers at different times is adjusted by power allocation to make them all meet the error code threshold $1\times10^{-2}$. The combination of these three situations and mutual assistance can prove that the allocation of time, frequency and power allows the entire network to accommodate more complex states and more ONUs, achieving greater flexibility.

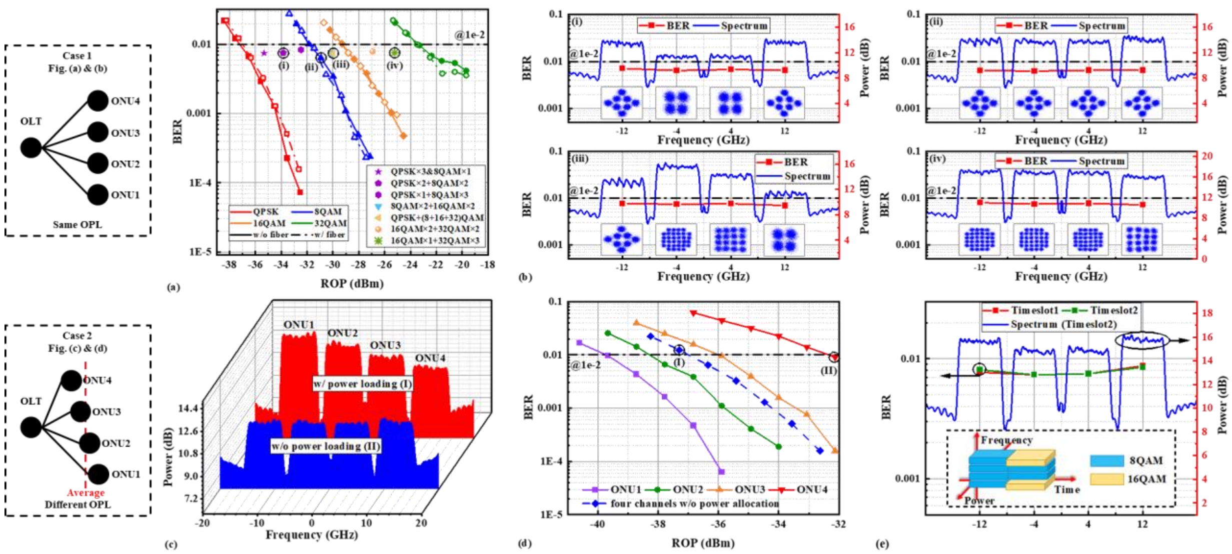


Fig. 3 (a) Sensitivity test of 3D FLCS-CPON under different transmission schemes. (b) Constellation and frequency spectrum of four transmission schemes. (c) The frequency spectrum with and without power allocation. (d) BER of 3D FLCS-CPON under different OPLs when four subcarriers with different powers transmit the same QAM. (e) Schematic diagram, spectrum diagram and BER curve corresponding to the case3.

## 4. Conclusions

A novel 3D FLCS-CPON is experimentally demonstrated with the resource-allocation capability in the time, frequency and power domain. As a proof-of-concept, a 3D FLCS-CPON is demonstrated in downstream based on four digital subcarriers with power allocations in both time and frequency-domain, achieving a peak data rate of 250 Gb/s/λ over 20-km fiber for different use scenarios.

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## References

[1] C. Ranaweera, et al., J. Opt. Comm. Netw., 14.2, A143-A153(2022).
[2] Van Veen D, et al., J. Opt. Comm. Netw., 12.1, A95-A103(2020).
[3] E. Harstead, et al., J. Light Technol, 37.2, 657-664(2019).
[4] J. Zhang, et al., IEEE Network., 36.2, 116-123(2022).
[5] G. Li, et al., in OFC 2022, paper Th3E.3.
[6] S. Xing, et al., in OFC 2022, paper 1-3.
[7] J. Zhang, et al., in OFC 2020, paper W1E.5.
[8] M. Xu, et al., in OFC 2022, paper Th3E.2.
[9] Borkowski R, et al., J. Light Technol, 39.16 5314-5324(2021).