# Hybrid TFDM Coherent PON Featuring Adaptable Capacity and Out-of-band Communication Channels

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**Abstract:** We present a novel TFDM coherent PON architecture supporting adaptable modulation across subcarriers. Experimental validation highlights its flexibility in various link distance/splitting configurations, featuring out-of-band communication subcarriers. Downstream broadcasting and upstream burst transmission were demonstrated. ©2024 The Author(s)

## 1. Introduction

In response to the ever-increasing demands for enhanced bandwidth, today's optical access networks are evolving rapidly to develop new technologies, aiming for greater capacity, extended coverage, and longer reach. Among various access technologies, passive optical network (PON) stands out due to its efficient point-to-multipoint architecture and efficient utilization of deployed fibers. PON technology has seen widespread global deployment in the past two decades [1]. However, existing PON solutions primarily rely on intensity-modulation direct-detection (IM-DD) technology, facing challenges for the emerging 100G PON implementations due to link budget limitations and transmission impairments. Coherent PON technology offers a forward-looking solution with heightened sensitivity, advanced modulation, and robust digital signal processing (DSP). Various coherent PON technologies have been developed over time, including time-division-multiplexing (TDM) PON [2], wavelength-division-multiplexing (WDM) PON [3], and time-and-frequency-division multiplexing (TFDM) PON [4, 5]. TFDM coherent PON, leveraging digital subcarrier multiplexing, enables versatile bandwidth sharing across time and frequency domains over a single wavelength, making it a promising candidate for future access networks [4, 5].

TFDM technology enables multiple optical signals to share the same fiber link by allocating distinct digital subcarriers to each signal. Within these subcarriers, time slots facilitate data transmission from various users or services. As illustrated in Figure 1(a), the optical line terminal (OLT) manages digital subcarriers' transmission and reception, while individual optical network units (ONUs) can modulate and demodulate specific subcarriers, each with varying capacity. A hybrid TFDM coherent PON presents a notable degree of versatility by capitalizing on bandwidth sharing in both the time and frequency domains without the need for colored optics. Distinct frequency bands can be designated for network services or groups of ONUs with unique latency or capacity requirements, as depicted in Figure 2(b). This approach also supports both point-to-multipoint (P2MP) and point-to-point (P2P) services.

In this study, we present an innovative hybrid TFDM coherent PON architecture with an aggregated capacity of 150 Gb/s. It offers notable flexibility by allowing adaptable modulation formats across subcarriers, allowing data rates of 25 Gb/s or 50 Gb/s per subcarrier, and upstream burst transmission. Additionally, it incorporates supplementary communication channels for management and monitoring in various application scenarios, making it versatile for optical access requirements. Through experimental validation, we evaluate the technical feasibility of the TFDM coherent PON, emphasizing its capability to effectively accommodate distributed configurations across varying distances and split ratios, ranging from 25 km with 128 splits to 80 km with 32 splits, as well as a 50 km P2P link.

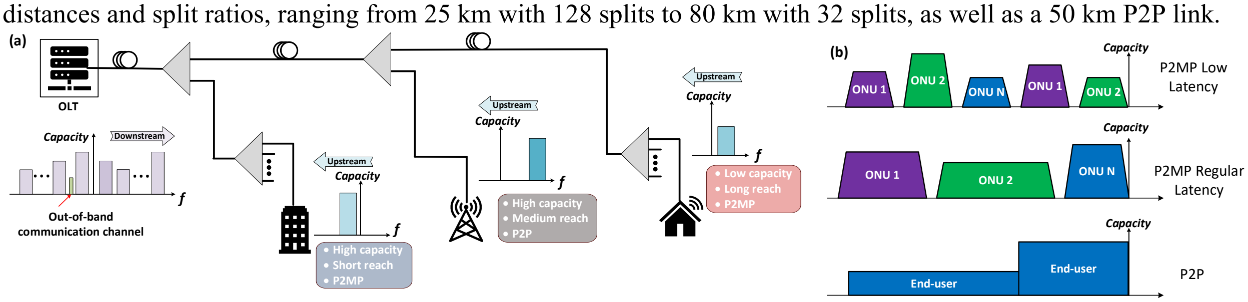


Fig. 1. (a) Coherent TFDM PON featuring adaptive capacity and distributed splitting; (b) TFDM subcarriers support various services with different capacity and latency requirements.

## 2. Operating Principles

Figure 2(a) shows the proposed coherent TFDM PON transmitter DSP, which supports different modulation formats and digital subcarrier capacities. It also incorporates out-of-band (OTB) communication subcarriers for media access control (MAC) layer control signals and operations, administration, and management (OAM) data. Data from MAC layer is first divided into communication subcarriers (low speed) and data subcarriers (high speed), each individually encoded and assigned to specific frequency bands. For ONU burst transmitters, data subcarriers involve generating burst frames with guard bands, receiver settling patterns, synchronization patterns, and payload data. The OLT transmitter, for broadcasting signals, follows a similar process without the burst frame generation. In this demonstration, the four data subcarriers are each assigned a distinct modulation format. Specifically, CH1 and CH3 use DP-QPSK signals at 6.25 GBd, while CH2 and CH4 employ DP-16QAM signals at the same 6.25 GBd rate. The two communication subcarriers run at 312.5 MBd using the DP-QPSK modulation format, they can also employ alternative modulation formats like unipolar/bipolar NRZ or BPSK since only small bandwidth is required. After applying Nyquist pulse shaping and digital up-conversion to specific inter-frequencies, the data frames from the data subcarriers and communication subcarriers are multiplexed before driving the modulator. Furthermore, leveraging the time-domain flexible rate and modulation format identification method outlined in [6], variable modulation formats can be allocated to different time frames within each subcarrier for adaptable capacity sharing in the time-domain.

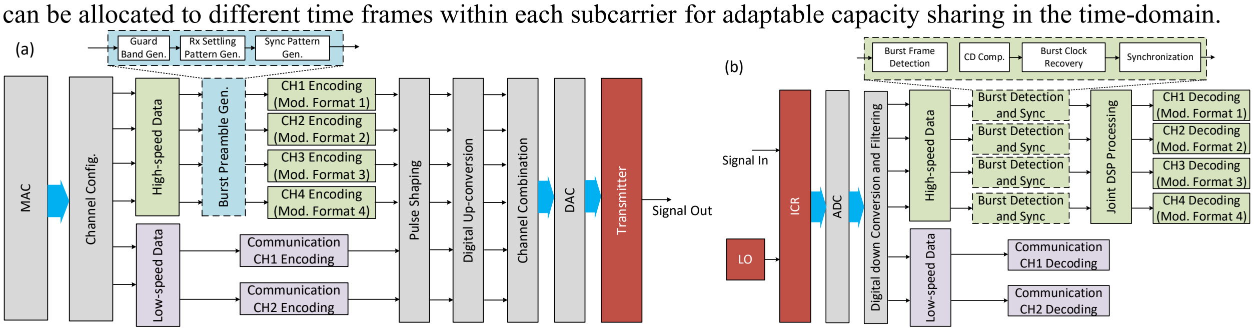


Fig. 2. (a) Proposed coherent TFDM PON transmitter DSP; (b) Proposed coherent TFDM PON receiver DSP.

Figure 2(b) shows the proposed DSP at the receiver side. It begins by sampling received analog signals into digital signals, followed by subcarrier extraction and separation, and then digital down-conversion to baseband. This process handles both high-speed data subcarriers and low-speed communication subcarriers independently. Note that this approach is not limited to the mentioned modulation formats; other signals like DP-8QAM, DP-32QAM, DP-64QAM, and probabilistic constellation shaping (PCS) can be used in the subcarriers following the same principles. For burst receivers in the OLT, the process includes burst signal detection, starting with power-based burst frame detection, followed by chromatic dispersion (CD) compensation and clock recovery, and ending with a double-correlation-based burst frame synchronization algorithm [7]. Once burst signals are received, payload signals undergo conventional first-stage coherent DSP processing with the use of demodulated information in the preamble. In ONU receivers, which only receive continuous mode signals, burst detection stages are unnecessary. In first-stage coherent DSP, signals using the two modulation formats can be processed through the same DSP procedures up to the constant modulus algorithm (CMA). Subsequently, DP-16QAM is processed using additional K-means and Gaussian mixture model algorithms to improve the performance of the multi-modulus algorithm and carrier phase estimation [8].

## 3. Experimental Setup and Results

Experimental validations were conducted to assess the performance of the proposed TFDM coherent PON architecture featuring adaptable data rates and link budgets, along with OTB communication subcarriers (Fig. 3(a)). At the OLT, four data subcarriers and two communication subcarriers were generated and propagated downstream. Within the data subcarriers, CH1 and CH3 used 6.25 GBd DP-QPSK modulation, while CH2 and CH4 used 6.25 GBd DP-16QAM modulation. The two communication subcarriers operated at 312.5 MBd each with DP-QPSK modulation, one for P2MP applications (MAC control signals and OAM information) and the other for P2P scenarios. The optical distribution network (ODN) featured distributed splitting to cater various connectivity requirements, thereby offering greater flexibility. Subcarriers modulated by QPSK support medium to long-reach services with large link budgets, while 16QAM subcarriers offer higher capacity over shorter to medium-range links. As an example, CH1 supported a 50 km reach with a 1x64 split, CH3 extended to 80 km with a 1x32 split for medium to long-range services. CH2 provided P2MP services over a 25 km link with a 1x128 split, and CH4 facilitated P2P services across a 50 km fiber link. In the upstream direction, CH1, CH2, and CH3 transmitted TFDM burst signals, while CH4 operated continuously alongside the communication subcarrier to support the P2P service.

Positioning the OTB communication subcarrier between TFDM data subcarriers requires assessing its impact on neighboring data subcarriers, as the communication subcarrier can affect power distribution and signal-to-noise ratio of data subcarriers. To prevent crosstalk, a guard band between the communication and data subcarriers is crucial. Optimizing power distribution, Fig. 3(b) shows the influence of the Pc/Pd power ratio (Pc: communication subcarrier power, Pd: data subcarrier power) on data subcarrier Bit Error Rate (BER) performance. When Pc/Pd stays below -8.5 dB, data subcarrier performance remains unaffected. Fig. 3(c) explores the impact of guard band size (keep Pc/Pd ratio at -10 dB), demonstrating that if it exceeds 0.5 GHz, there is no significant data subcarrier performance penalty. In our experiments, a guard band of 1.875 GHz was maintained for minimal data subcarrier impact.

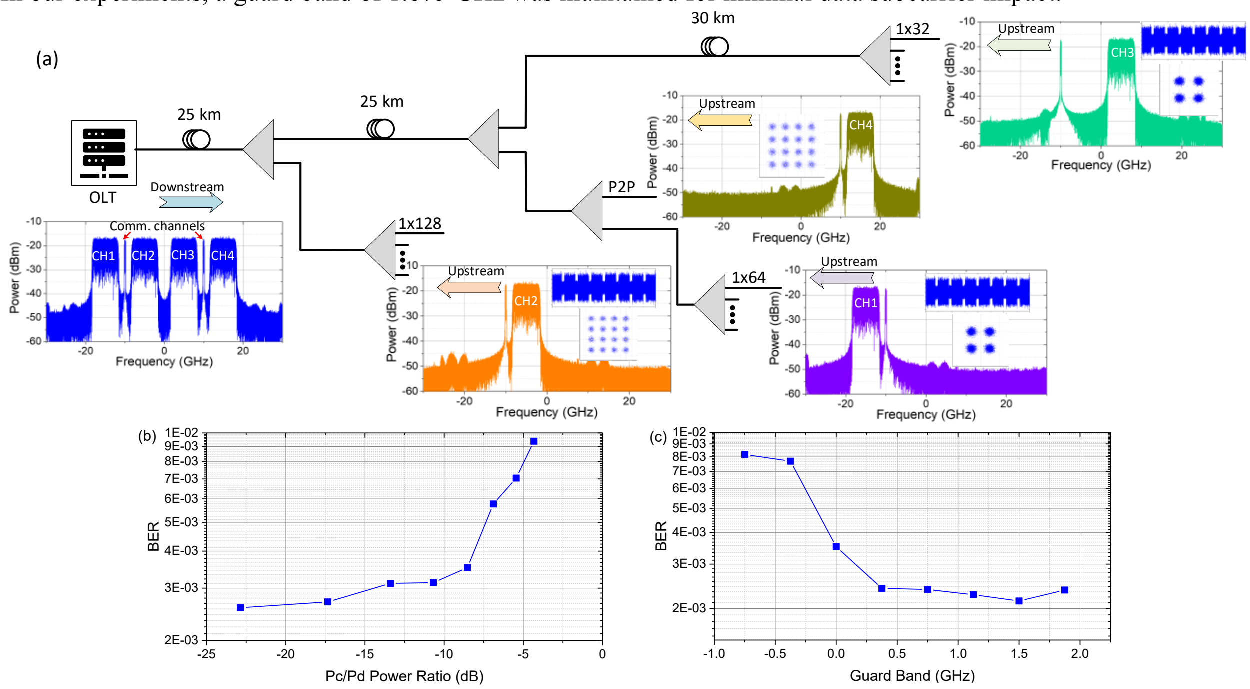


Fig. 3. (a) Experimental setup; (b) Subcarrier BER versus Pc/Pd power ratio; (c) Subcarrier BER versus guard band size.

Figures 4(a)-(d) assess the hybrid TFDM coherent PON's performance, covering continuous downstream and burst upstream transmission. Each TFDM subcarrier is individually analyzed for BER relative to received optical power (ROP), along with constellation diagrams. Figure 4(c) focuses on P2P services with continuous mode both downstream and upstream. Back-to-Back (B2B) BER vs. ROP results are included, along with thresholds for hard-decision and soft-decision FEC. These experiments confirm the versatility and effectiveness of the hybrid TFDM PON, accommodating various capacities, link budgets, and scenarios while ensuring robust system performance.

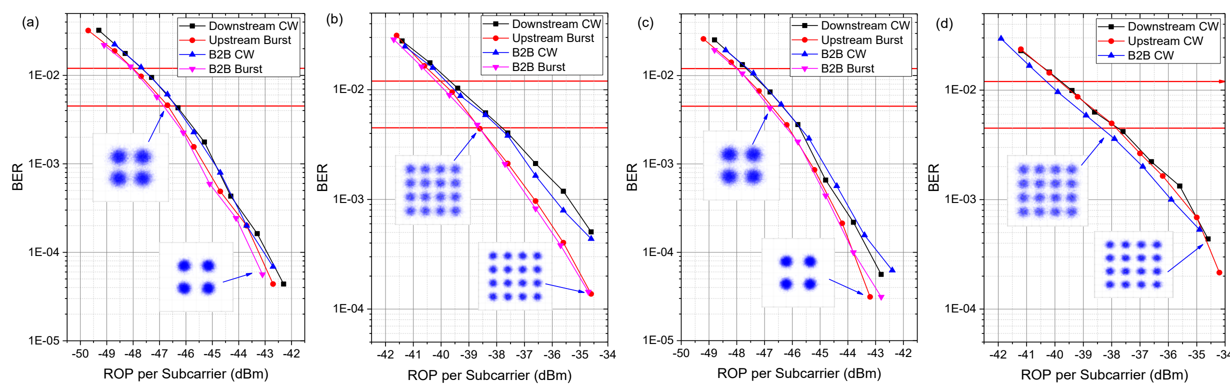


Fig. 4. Experimental results for downstream and upstream transmission: (a) BER versus ROP in subcarrier 1; (b) BER versus ROP in subcarrier 2; (c) BER versus ROP in subcarrier 3; (d) BER versus ROP in subcarrier 4.

## 4. Conclusion

We introduce and validate a novel hybrid TFDM coherent PON architecture, offering adaptable modulation formats across subcarriers and OTB communication channels for multiple application scenarios. Our experimental results show the flexibility to accommodate distributed splitting over various distances (25 km/128 split, 50 km/64 split, and 80 km/32 split) and a 50 km P2P link and the OTB subcarriers for dedicated management and monitoring connections between OLT and ONU. Downstream broadcasting and upstream burst transmission are also demonstrated.

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