# Experimental Demonstration of 200 Gb/s/λ Coherent PON with a Low-Complexity Receiver and a Multi-purpose Neural Network

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**Abstract:** We experimentally evaluate a single-BPD-based polarization-insensitive coherent receiver for 200 Gb/s/λ PON. A neural network is used as a joint equalizer and Alamouti decoder. A 29 dB power budget is achieved with 20 km transmission. 

## 1. Introduction

Driven by emerging services such as 5G X-haul, extended reality, cloud gaming and ultra-high-resolution streaming, the demand on access network bandwidth will keep increasing and impose great challenges on future passive optical network (PON) evolution. In April 2021, the standardization organization ITU-T fulfilled and passed its newest generation PON recommendation (G.9804) targeting 50 Gb/s/λ (downstream). The basic physical layer transmission scheme for 50G PON will be the same as its precedent generations, i.e. intensity modulation/direct detection (IM/DD). But digital signal processing (DSP) is for the first time expected to play an important role to compensate for severe signal distortions and achieve PON's stringent power budget requirement. A recent flexible-PON field trial demonstrated the feasibility of further scaling IM/DD technology up to 100 Gb/s with the help of advanced signal processing [1]. But it also shows the fact that IM/DD is approaching its performance limit and can hardly be further scaled beyond 100 Gb/s/λ for future PON generations.

Coherent PON, although having been proposed and studied for some time, is gaining more attention recently due to its superior receiver sensitivity advantages over IM/DD schemes. However, the cost and power consumption of current coherent transceiver products are still too high to be practically used in PON. Many simplified coherent detection schemes have been designed with the expectation of lowering down the cost of coherent optics [2]. In this paper, we particularly focus on one of the most hardware-efficient approaches [3-5] which only uses a 2x2 optical coupler or hybrid, a single balanced photodetector (BPD), and one analog-to-digital converter (ADC). At the core of this approach, Alamouti polarization-time block coding is used to save half of the hardware components, and heterodyne detection is employed to save another half of the resources at the cost of higher analog bandwidth. Since the wavelength of the local oscillator (LO) at the receiver side is different from the downstream carrier wavelength (heterodyne), the LO may be split and reused as the upstream laser source.

There have been some reported experiments with such a simplified coherent PON setup [4, 5], but few have reached capacity over 100 Gb/s/λ. On the other hand, neural networks (NN) have been extensively studied in recent years and demonstrated to be an effective tool to implement signal equalization in optical systems [6]. In this paper, we use a complex-valued neural network in the Alamouti heterodyne receiver's DSP to achieve both dispersion compensation and Alamouti decoding. With the aid of the DSP, bit error rate (BER) performances for different modulation formats and baud rates are experimentally investigated using off-the-shelf discrete components. To the best of our knowledge, this is the first experimental demonstration of such a single-BPD-based coherent receiver achieving capacity up to 200 Gb/s/λ with a 29 dB power budget.

## 2. Operation Principles

The system architecture (with only downstream concerned) and main function blocks are illustrated in Fig. 1. The optical line terminal (OLT) maps binary data to quadrature amplitude modulation (QAM) symbols and applies 2x2 Alamouti polarization-time block coding. The coded signals are then modulated onto two polarizations using a classical dual-polarization coherent modulator [3-5]. To relax the analog bandwidth requirements of the components as much as possible, Nyquist pulse shaping is applied to the digital waveform before digital-to-analog conversion (DAC). On the optical network unit (ONU) side, an LO mixes with the received signal in a 2x2 optical coupler (or optical hybrid), after which a single BPD converts the mixed optical signal to electrical domain with an intermediate frequency (IF). Then the signal is sampled by an ADC and processed by the subsequent DSP stack. The DSP functions include IF down-conversion, symbol alignment, IF offset and phase correction, equalization, Alamouti decoding, and QAM symbol de-mapping.

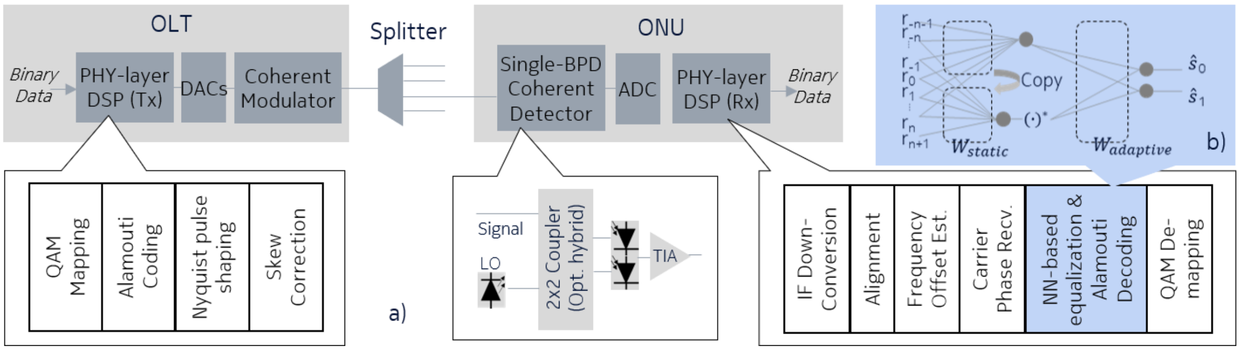


Fig. 1. a) A polarization-insensitive coherent PON system (downstream only) with the single-BPD-based receiver and b) the multi-purpose neural network in the receiver DSP, in which $(\cdot)^*$ means conjugation

In this work, we use a simple but multi-purpose complex-valued NN to achieve QAM signal equalization (including at least chromatic dispersion- and bandwidth limitation-induced inter-symbol-interference cancelation) and Alamouti decoding simultaneously. In its simplest form, the NN can only contain two layers with each layer having two linear neurons, just like depicted in Fig. 1b. Functionally, the first layer acts as a parallel equalizer. It equalizes a two-symbol pair at a time. Each two-symbol pair corresponds to one Alamouti code block. Then, one of the neurons' outputs is conjugated, after which the second layer performs a linear transformation to the two equalized symbols. When properly trained, the NN will output estimations of the original QAM symbols as complex numbers. In practical operations, the NN training has two phases. First, when the ONU is powered up, the NN is trained normally using enough pilot symbols. Then, the first layer's weights ($\boldsymbol{W}_{static}$) are frozen because the fiber dispersion and the component bandwidths are stable channel properties. The second layer neurons' weights ($\boldsymbol{W}_{adaptive}$) are updated periodically based on reference symbols to realize real-time polarization tracking. Phase-drift is also handled adaptively by the second layer neurons because the phase correction term is automatically included within $\boldsymbol{W}_{adaptive}$ in the reference-signal-based training process. Note that $\boldsymbol{W}_{static}$ can be regarded as a filter's tap coefficients, and the input layer neurons are two parallel filters that share the same coefficients. Therefore, only one set of weights $\boldsymbol{W}_{static}$ is updated during initial training and all the input neurons always copy the same weight values.

In the following experiments (Section 3), we use the 2-layer linear NN with the input size set to 40. For each inference, we feed 20 oversampled symbols into the NN and get 2 equalized & decoded symbols at the output. Without nonlinear activation functions, the NN is mathematically equivalent to the classical least mean square (LMS) equalizers working in a cascaded manner. But in principle, by extending the layers with more neurons and non-linear activation functions, it is feasible to also mitigate nonlinear distortions in the system at the cost of higher computing load. Nevertheless, it requires additional tricks to guarantee that the training procedure converges properly and efficiently, which are out of the scope of this paper and will be left for future work.

## 3. Experiment and discussion

### *3.1. Testbed setup*

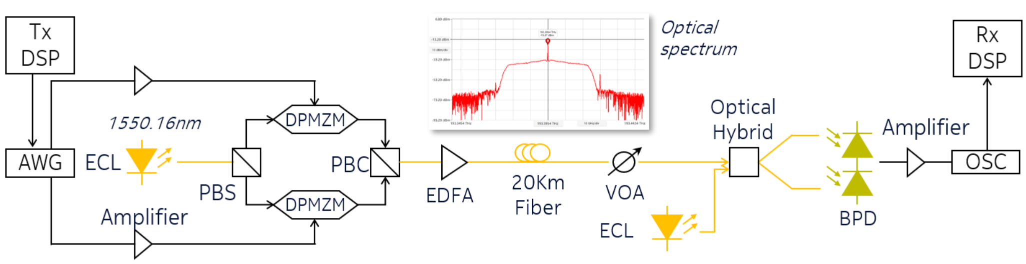


Fig. 2 Experimental setup (inset shows optical spectrum of a 50 Gbaud 16QAM signal). PBS: polarization beam splitter; DPMZMs: dual-parallel Mach-Zehnder modulators; PBC: polarization beam combiner.

The experimental setup is shown in Fig. 2. An external cavity laser (ECL) with 100 Hz linewidth at 1550.16 nm is employed as the light source. The light is modulated by a classical coherent transmitter (SHF 46215B) with about 23 GHz 3 dB bandwidth. The preprocessed Alamouti-coded Tx signal is output from an arbitrary waveform generator (AWG) (Keysight M8194A @ 120 GSa/s) after being digitally resampled and filtered. After modulation, the optical signal is amplified to 8 dBm by an erbium-doped fiber amplifier (EDFA) and launched into a 20 km fiber. At the receiver, another ECL, an optical hybrid, and a balanced photodetector (BPD) (Finisar BPDV3320R, 3 dB bandwidth of ~70 GHz) constitute the polarization-insensitive coherent heterodyne receiver. Note that the optical hybrid is interchangeable with a 2x2 coupler, but the LO input branch of the coupler should be polarization maintained to guarantee the receiver performance. As signals with different baud rates are tested, the receiver's LO wavelength is adjusted in such a way that the electrical IF, a.k.a, the LO wavelength difference between Tx and Rx, is about 2-GHz-higher than 1/2*baud rate. For example, IF is about 27 GHz for a Nyquist pulse shaped 50 Gbaud/s signal. A 55 GHz electrical amplifier (SHF S807C) is used to amplify the amplitude of the BPD's electrical output. At last, the signal is sampled by a real-time oscilloscope (Keysight UXR0592A) at a sampling rate of 256 GSa/s.

### *3.2. Results and discussion*

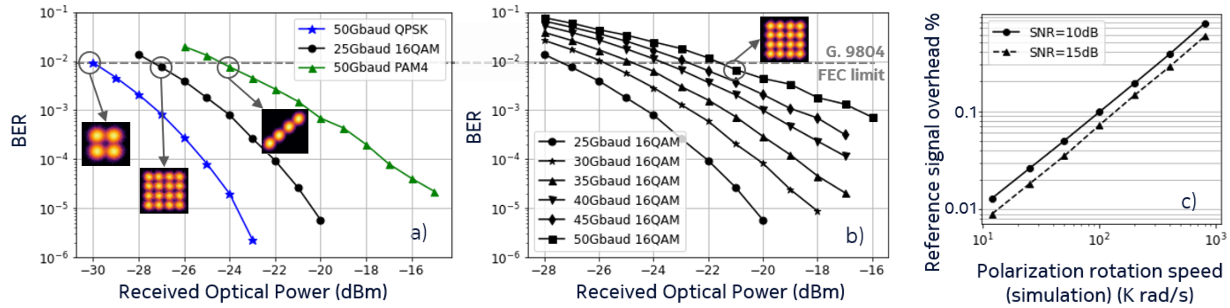


Fig. 3 a) Performance comparison of 100 Gb/s PAM4/QPSK/16QAM signals; b) BER performances of 16QAM signal with different baud rates up to 50 Gbaud/s; c) Minimum required reference signal overhead for $\boldsymbol{W_{adaptive}}$ training (simulation of 50Gbaud 16QAM).

First, we compare different modulation formats. Fig. 3a shows that QPSK has the best receiver sensitivity performance as a 100 Gb/s Alamouti heterodyne receiver. 4-level pulse amplitude modulation (PAM4), although having potential advantages of more simplified phase-insensitive DSP [4], is less favorable than 16QAM in our 100 Gb/s test, because it requires doubled bandwidth which reaches the components' bandwidth limits and leads to over 2 dB power penalty than 16QAM. Then, with 16QAM modulation format, different baud rates are tested (Fig. 3b), verifying that 29 dB power budget can be achieved up to 200 Gb/s/λ (8 dBm launch power, $10^{-2}$ BER).

Another aspect we concern about is the overhead of NN's adaptive training. We were not able to experimentally create fast polarization or phase drifting with deterministic speeds, thus simulations are used to investigate the required overhead of training $\boldsymbol{W_{adaptive}}$. First, we use 100 consecutive symbols periodically inserted in a 50Gbaud 16QAM signal as the training reference symbols as we confirmed that using a statistic gradient descent optimizer with proper learning rate the training always converges within about 30 iterations. Then, we simulate the signal's polarization rotation with a certain speed and find the corresponding maximum allowed interval between reference signals to retain < $10^{-2}$ BER. As expected, the result (Fig. 3c) shows that the overhead for $\boldsymbol{W_{adaptive}}$ training scales linearly with the signal's polarization rotation speed. Signal to noise ratio (SNR) also impacts the amount of overhead, because when the SNR degrades the training result of $\boldsymbol{W_{adaptive}}$ will be less accurate and the re-training frequency must be higher. With about 0.1% overheads, the system can tolerate polarization rotations up to hundreds of K rad/s which happen only in rare cases like nearby lightning strikes [7].

## 4. Conclusion

In this paper, we experimentally investigate the performance of the single-BPD-based Alamouti heterodyne coherent receiver, where an NN-based joint equalizer and Alamouti decoder recovers the signal in a polarization-insensitive manner with the ability of being adaptively trained. With 16QAM modulation, 200 Gb/s/λ can be achieved with a 29 dB loss budget at $10^{-2}$ BER, demonstrating that the simplified coherent receiver structure and NN-based DSP could be promising candidate solutions for future beyond-100G PON.

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## 5. Reference

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