Net 4×500Gb/s IM/DD Optical Interconnects with Interleaved PDM and Probabilistic Shaping

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Abstract *We propose an interleaved PDM WDM IM/DD scheme avoiding carrier fading with only one optical filter and one photodiode per polarization. With probabilistic shaping, we demonstrate 4×500Gb/s IM/DD interconnects of WDM PDM PS-PAM-16 signals with net spectral efficiency 3.60 b/s/Hz. ©2023 The Author(s)*

Introduction

An insatiable demand for broadband applications such as artificial intelligence and metaverse has propelled the optical interconnects to operate at 200 Gb/s and beyond. Due to the low cost, power efficient and small footprint, intensity modulation and direct detection (IM/DD) scheme has been dominated in intra-data-centre applications.

However, IM/DD systems are limited by their ability to perform only 1-D modulation and detection, which restricts their spectral efficiency (SE) or system capacity. Polarization, a fundamental characteristic of light waves, is commonly used in coherent optical communication systems to double the SE. The polarization division multiplexing (PDM) in IM/DD is limited by the carrier fading obstacle and previously relies on either polarization-tracking techniques [1-3] or Stokes vector receivers (SVRs) [4-6]. The former is faced with challenges when tracking the states-of-polarization (SOP) of the received signal with low instantaneous polarization mismatch. The latter is capable of detecting all the polarization states in Stokes space but at the expense of high hardware complexity.

Alternatively, orthogonal offset carriers can be used in PDM single-sideband (SSB) systems to avoid the carrier fading without sacrificing SE. For each polarization signal detection, only one optical band-pass filter (OBPF) and one photodiode (PD) is required, leading to a simpler polarization rotation-invariant receiver[7, 8].

In this paper, we propose an interleaved PDM wavelength division multiplexing (WDM) IM/DD architecture to further boost the system capacity by using the rate-adaptable probabilistic shaped pulse amplitude modulation (PS-PAM) signals. With the aid of a nonlinear equalizer, the IM/DD based optical interconnects of net rate 2.0 Tb/s WDM PS-PAM-16 signal is demonstrated. The net SE is 3.60 b/s/Hz excluding the forward error correction (FEC) overhead.

Principle of interleaved PDM WDM IM/DD architecture

Fig. 1 illustrates the generation and reception of the proposed interleaved PDM WDM IM/DD systems. At the transmitter (Fig. 1(a)), the optical carrier frequency $f_{i,y}$ in Y polarization of the *i*-th channel is set to have an offset f_{offset} respect to the carrier frequency $f_{i,x}$ in X polarization. Without sacrificing SE, we can set the offset f_{offset} to be half of the WDM channel spacing Δf to

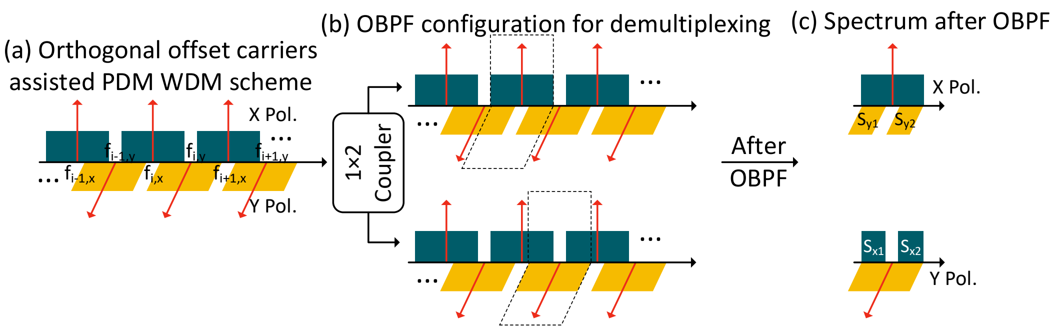

Fig. 1: (a) Interleaved WDM PDM IM/DD scheme. (b) OBPF configuration for WDM and PDM demultiplexing. (c) Spectrum after OBPF. Pol.: polarization.

minimize the residual carriers after the opposite polarization filtering.

The received signal is firstly split into two copies to enable simultaneous detection of both polarizations. After the OBPF configured as shown in Fig. 1(b), the unwanted carrier on the opposite polarization is removed. Then we can get the output photocurrents (I_1 and I_2) of the two polarizations after DD.

$$\begin{aligned} I_1 &= \left|C_x + S_x\right|^2 + \alpha\left|S_{y1} + S_{y2}\right|^2 \\ &= \left|C_x\right|^2 + 2\mathrm{Re}\left\{S_x \cdot C_x^*\right\} + \left|S_x\right|^2 + \alpha\left|S_{y1} + S_{y2}\right|^2 . \end{aligned} \quad (1)$$

$$\begin{aligned} I_2 &= \left|C_y + S_y\right|^2 + \alpha\left|S_{x1} + S_{x2}\right|^2 \\ &= \left|C_y\right|^2 + 2\mathrm{Re}\left\{S_y \cdot C_y^*\right\} + \left|S_y\right|^2 + \alpha\left|S_{x1} + S_{x2}\right|^2 . \end{aligned} \quad (2)$$

Here the 1st term on the right side of Eq. (1) or Eq. (2) is a direct current (DC) component and can be removed. The 2nd term is the desired linear beating term. The 3rd and the 4th terms correspond to the intra-polarization signal-signal beat interference (SSBI) and inter-polarization SSBI. The coefficient α denotes the residual proportion of the signal in the opposite polarization, which is dependent on the channel spacing of the WDM system. Owing to the high carrier-to-signal power ratio (CSPR) in IM/DD systems, the SSBI terms are much smaller than the linear term. Therefore, we can separately detect each polarization without digital polarization de-rotation and complex multi-input-multi-output (MIMO) equalization.

Probabilistic Shaping for Short Reach Interconnects

The probabilistic shaping (PS) technology is proposed to close the gap between the channel capacity and the Shannon limit by adjusting the probability of the constellation points. It has been widely applied to amplified coherent optical transmissions under average power constraint. In short reach IM/DD systems with a peak power constraint [9], the shaping gain can also be obtained due to the very sharp pulse shaping and the severe system bandwidth constraint. Besides, the transmission rate can be fine-tuned according to the channel condition by changing the rate parameter in the Maxwell-Boltzmann (MB) distribution.

For all results, we use the normalized general mutual information (NGMI) as the performance metric, which is independent of the modulation format. Assume a concatenated FEC with a total code rate R_c of 0.826 is used, the threshold of NGMI is 0.857 [10]. Then the net bit rate of PS-PAM-M/PAM-M signal per polarization can be calculated as

$$\text{Net Rate} = \left[\text{Entropy} - (1 - R_c)\log_2 M\right] \times \text{Baudrate} \quad (3)$$

Fig. 2 (a) shows the used probability distribution of the PS-PAM-16 signal with an entropy of 3.19 bits/symbol.

Experimental Setup and DSP Stack

Fig. 2(b) shows the experimental setup. At the transmitter, the WDM channels of X and Y polarizations are sourced by 8 external cavity lasers (ECL 1~4 for X pol. and ECL 5~8 for Y pol.) with ~100kHz linewidth. The polarization-maintaining erbium-doped fibre amplifier (PM-EDFA) in each polarization branch is employed to compensate for the insertion loss (~13 dB) of the 16×1 polarization-maintaining optical coupler (PM-OC). An arbitrary waveform generator (AWG, Keysight M8194A) operating at 120GSa/s generates 100GBaud baseband PS-PAM-16 signal with different entropies. After amplified by a pair of electrical amplifiers (EAs) with 50GHz bandwidth, the waveforms from AWG are used to drive the two Mach-Zehnder modulators (MZMs) (3-dB bandwidth of ~25 GHz) in orthogonal polarizations. The MZMs are biased at quadrature point. Then the signal of two polarizations are combined through the polarization beam combiner (PBC).

At the receiver, a variable optical attenuator (VOA) is employed to adjust the received optical power (ROP). Then the signal is split into two copies for X- and Y-polarization detection, respectively. In our experiment, one OBPF is used to emulate the simultaneous reception of

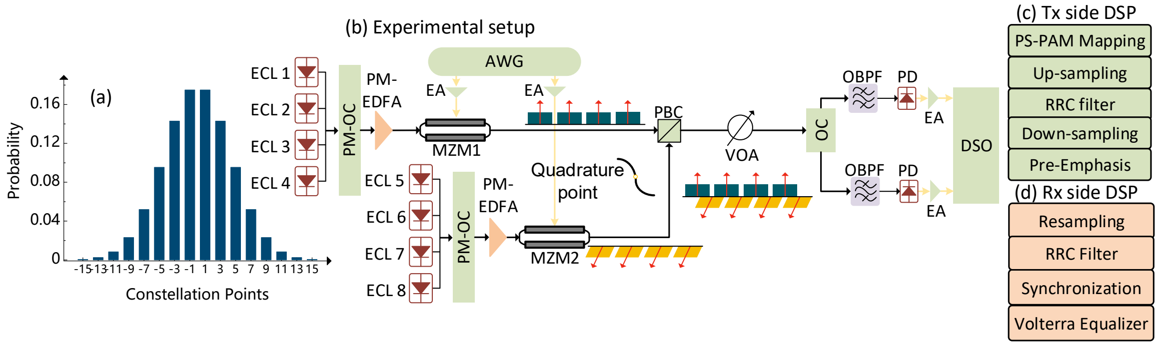

Fig. 2: (a) The probability distribution of the constellation points of PS-PAM-16 signal with 3.19 bits/symbol. (b) Experimental setup. (c) Transmitter side DSP. (d) Receiver side DSP.

each polarization signal by suppressing the unwanted carrier. The edge roll-off of the OBPF (EXFO XTM-50/W) is 500 dB/nm. The filtered signals of two polarizations are respectively detected by two PDs and subsequently amplified by EAs. Finally, the received signal is captured by a real-time digital storage oscilloscope (DSO) (Keysight UXR0594AP) with a 256-GSa/s sampling rate and 59GHz bandwidth for offline processing.

The DSP stack is shown in Fig 2(c)~(d). At the transmitter, the data is mapped to PS-PAM-16 symbols first. After up-sampling, the signal is pulse shaped with a roll-off factor of 0.01. Then the signal is re-sampled to match the sampling rate of AWG. Before sending to AWG, a linear pre-emphasis is applied to compensate for the transmitter bandwidth limitation. At the receiver, the captured signal is first resampled, matched filtered and frame synchronized. Then the channel equalization is performed by 3rd-order Volterra nonlinear equalizer (VNLE). The 1st, 2nd and 3rd -order memory length of the VNLE is optimized to 140, 5 and 3, respectively.

Results and Discussions

Fig 3(a) shows the measured optical spectra at the transmitter and after applying OBPF. The OBPF effectively suppresses unwanted carrier power to a level that is approximately 50 dB lower, ensuring compliance with the condition to get Eq. (1~2). Considering the roll-off of the OBPF, the residual SSBI and SE, the channel spacing is optimized as shown in Fig. 3(b). A performance deterioration is observed when the channel spacing is reduced below 120GHz due to the poor suppression of unwanted carriers. We choose a 130GHz grid as a trade-off between performance and SE.

The measured NGMI versus the ROP of 100-GBaud PDM PS-PAM-16 signals with different entropies and PDM 100GBaud PAM-8 signal is demonstrated in Fig 3(c). The highest net data rates of 500 Gb/s can be achieved for 100GBaud 3.19-bits/symbol PDM PS-PAM-16 signals (ROP ⩾ 5 dBm), with the NGMI > 0.857. It is shown that around 1.0-dB receiver sensitivity gain can be obtained by the net 500Gb/s PDM PS-PAM-16 system, compared to the PDM 100GBaud uniform-PAM-8 signal.

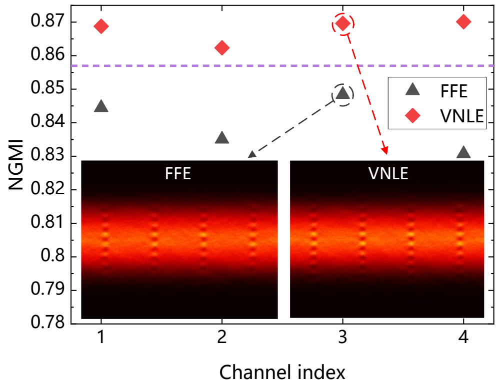

Fig. 4: The NGMI for all WDM channels with PS-PAM16 signal of net data rate 500Gb/s per channel using FFE or VNLE. The recovered eye diagrams are shown in insects.

Fig. 4 shows the measured NGMI for all WDM channels with PDM PS-PAM-16 signal of net data rate 500Gb/s. The NGMI values of all four channels are higher than the threshold of 0.857, resulting a total capacity of 2 Tb/s. Compared to feedforward equalizer (FFE), VNLE provide an obvious performance improvement for this high-order modulation format. Besides, insets show the recovered eye diagrams, the eye diagram with VNLE is clearer than that with FFE.

Conclusions

We experimentally demonstrated 4×500 Gb/s PDM IM/DD optical interconnects of PS-PAM-16 signal. The signals are detected using a polarization rotation-invariant receiver comprising of one OBPF and one PD for each polarization. Compared to the uniform-PAM-8 signal with a similar net rate, probabilistic shaping provides a receiver sensitivity gain of approximately 1.0 dB.

Acknowledgements

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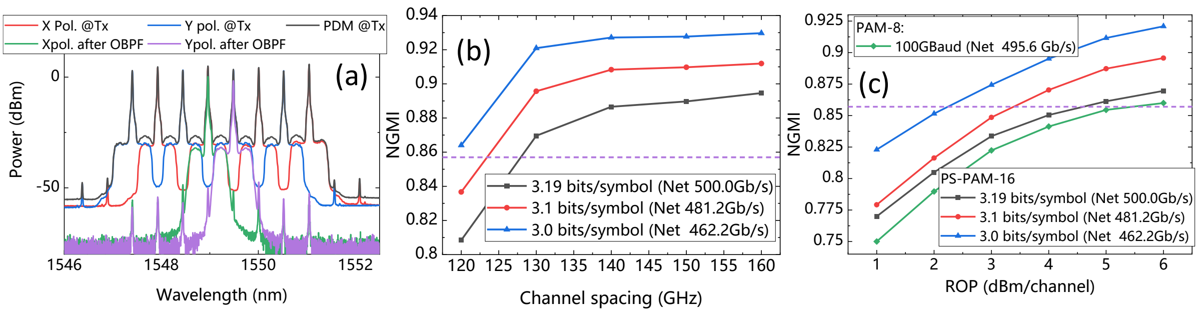

Fig. 3: (a) Optical spectra at the transmitter and after OBPF. (b) The measured NGMI versus the WDM channel spacing for 100-GBaud PS-PAM-16 with different entropies. (c) The measured NGMI versus ROP of 100-GBaud PAM-8 and 100-GBaud PS-PAM-16 with different entropies.

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