Demonstration of PAM4-OCDM system with electrical amplitude-level pre-tuning and post-equalization for data centers applications

TAKAHIRO KODAMA,1,* TATSUYA MIYAZAKI,1 MASANORI HANAWA,1 AKIHIRO MARUTA,2 NAOYA WADA,3 GABRIELLA CINCOTTI,4 AND KEN-ICHI KITAYAMA3,5

1Graduate Faculty of Interdisciplinary Research, University of Yamanashi, 4-3-11, Takeda, Kofu, Yamanashi 400-8511, Japan
2Department of Electrical Electronic, and Information Engineering, Osaka University, 565-0871 Osaka, Japan
3Ultrafast Photonic Network Group, National Institute of Information and Communication Technology, 184-8795 Tokyo, Japan
4Engineering Department, Roma Tre University, V. Volterra 62, I-00146 Rome, Italy
5Graduate School for the Creation of New Photonics Industries, 1955-1 Kurematsu-cho, Hamamatsu, Shizuoka 431-1202, Japan
*tkodama@yamanashi.ac.jp

Abstract: A PAM4-OCDM system with optical multi-/demultiplexing and electrical pre-/post-processing is proposed for short-reach applications. We experimentally demonstrate, for the first time, a power-efficient 4 OC x 10 GSymbol/s PAM4-OCDM system. The four PSK-OCs are simultaneously generated using a single light source and a passive multiport optical encoder and received by a single optical decoder and cascaded DSP. The effectiveness of the electrical-domain amplitude level pre-tuning and post-equalizer are demonstrated, considering different values of shot and beat noises.

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1. Introduction

Scaling transmission capacity per optical transceiver has an enormous impact on both capital expenditure (CAPEX) and operating expenditure (OPEX) of intra- and inter-data center connections, within a range of a few hundred meters up to several tens of kilometers [1]. In the internet of the things (IoT) context, cloud infrastructures require high performance and suitable optical modules. In fact, a huge number of optical terminals and end-users are needed, that induce aggressive cost and energy consumption. Power and cost efficiency are the key issues in many short-range systems, and they can be improved using advanced modulations and detection techniques based on low-power, low-cost and integrated optical modulators.

Recently, four-level pulse amplitude modulation (PAM4) has been demonstrated to be a valid approach to upgrade the transmission capacity in power-efficient data center connections, also in relation to the IEEE standardization of Ethernet interfaces at 40 and 100 Gbps [2–6]. In addition, PAM4 enables legacy systems for 56Gbps / link and yields a better spectral efficiency, with respect to on-off keying (OOK) modulation, even though it is more susceptible to physical layer degradation effects, such as chromatic dispersion.

Wavelength division multiplexing (WDM) system can further enhance the transmission capacity, by increasing the number of wavelengths [7]. However, an initial frequency setting and frequency monitoring/tuning of the light sources are required for keeping a satisfactory signal quality. These issues can be simultaneously overcome using an broadband light source, such as an optical comb source, in the place of multiple independent lasers [8].
As an alternative to WDM systems based on optical combs, optical code division multiplexing (OCDM) can provide another dimension, beyond time and wavelength [9,10]. In addition, the combined use of WDM and OCDM allows us to largely increase the bandwidth granularity and the system flexibility.

Code characteristics of time-spread (TS), spectral spread (SS) or hybrid orthogonal optical codes (OC) have been studied for scaling the number of simultaneously available OCs. In particular, TS-OCs have superior code performances and better spectral utilization efficiency, with respect to SS-OCs [11–13].

More than ten years ago, we have developed a multiport encoder/decoder (E/D), that has the unique capability of simultaneously generating and processing multiple phase shift keying (PSK) OCs, for a cost-effective use in OCDM systems [14,15]. Each PSK-OC is equivalent to a Fourier subcarrier, and the their orthogonal property stems from the fact that the subcarriers have almost nonoverlapping frequency spectra, to reduce crosscorrelation effects. A quadrature amplitude modulation (QAM) OC generated by the convolution of two different PSK OCs using multiport E/D and phase modulator can drastically reduce crosscorrelation effects [16].

The multiport E/D has been used in several OCDM experimental demonstrations, as well as to generate codes in packet switching systems. The combined use of OCs and WDM have been also already experimentally demonstrated, reaching the record capacity of 2.56 Tb/s [17]. Different modulation formats, such as differential phase shift keying (DPSK), code shift keying (CSK) and M-ary have been also reported, also to increase the data confidentiality [18–20].

The multiport E/D has been also used in all-optical orthogonal frequency division multiplexing (OFDM) systems, which are characterized by synchronous subcarrier multiplexing transmission [21]. In this case, the multiport E/D operates both the optical discrete Fourier transform and the subcarrier multiplexing/demultiplexing. Both synchronous OFDM and asynchronous OCDM systems can independently handle various types of IoT signals, in the context of next generation optical short-reach networks.

Previous experiments of OOK-OCDM systems have demonstrated an increasing number of simultaneously available OCs [22,23]. However, in OOK-OCDM systems, the number of LiNbO₃ intensity modulator (LN-IM) and photodiodes (PD) required is the same as the OC number. On the other hand, PAM4-OCDM system can halve the number of LN-IMs and PDs, with respect to OOK, and it can be considered as an efficient solution for short-reach transmission [24]. In addition, the multiport E/D is a fully passive optical device, that can be integrated with LN-IM and PDs, in low-cost, low-power optical modules.

In the present paper, we experimentally demonstrate for the first time an asynchronous 4 OC x 10 GSymbol/s PAM4-OCDM system using multiport E/D, over a 20 m single mode fiber (SMF) link. Moreover, we also validate the effectiveness of amplitude level tuning at the transmitter, as well as optical-domain bandwidth optimization of PAM signals.

2. System architecture

Figure 1 describes the PAM4-OCDM architecture, using a broadband light source, a LN-IM array and a pair of multiport E/Ds at transmitter and receiver sides. A short-pulse stream is generated by a single broadband light source, and is optically encoded by a multiport encoder, to simultaneously generate a set of OCs. The device is a direct-sequence spread spectrum (DS-SS) encoder, and the OCs are generated and processed in the time domain [15]. Assuming that all the optical chip pulses have the same amplitude, the impulse response at the port $k'$ of the multiport E/D can be expressed as

$$h_{k'}(t) = \sum_{n=0}^{N-1} e^{-2\pi i nk'/N} \delta \left( t - \frac{n}{C} \right) \quad k' = 0, 1, \ldots, N-1$$
where $j = \sqrt{-1}$ and $\delta(t)$ is the Dirac delta function. We use a $N = 16$-port optical E/D with free spectral range $C = 200$ GHz.

Each independent data signal, encoded on a different OC, is modulated by the LN-IM array. The maximum number of the IoT context signals coincides with the number of the E/D ports, and a pre-filtering is inserted to equalize OSNR for all OCs and eliminate the out-of-band noise. In the short-reach application of Fig. 1, we consider point-to-point topology and synchronous transmission. However, the detection timing for different OCs may vary, due to fiber length and group velocity differences after the multiport E/D. Therefore, the system performances have been evaluated in the worst-case scenario, with the largest values of beat noise at the receiver and maximum crosstalk, that occurs when the peaks of the crosscorrelation and autocorrelation signals overlap, as shown in Fig. 2.

![Fig. 1. Schematic diagram of the PAM4-OCDM system.](image1)

![Fig. 2. Temporal waveform of the detected OC, in the worst-case scenario.](image2)
3. Experimental setup and results

Figure 3 outlines the experimental setup and results of the 4 OC x 10 GSymbol/s PAM4-OCDM system. Two 16-port E/Ds are allocated at the transmitter and receiver sides, respectively. The erbium-doped fiber amplifiers (EDFA) are used to compensate the insertion losses. The sampling rates of the arbitrary waveform generator (AWG: Tektronix, 7122C) and digital sampled oscilloscope (DSO: Keysight, DSAX96204Q) are 10 GSa/s and 80 GSa/s, respectively.

A mode locked laser diode (MLLD) with 10 GHz repetition rate and 1550 nm central wavelength is used to generate a 2.4 ps optical pulse stream, as shown in Fig. 3(a). Power-level optimized PAM4 signal with a 100000-symbol was modulated by the LN-IM. Four 16-chips (200 GChip/s), PSK OCs are simultaneously generated at the outputs #1, #5, #9 and #13 of the 16-port E/D. Each encoded signal has equal power, random bit phase and same polarization and it is assigned to a different IoT context data. The multiplexed signal is shown in Fig. 3(b).

At the receiver side, the signal is decoded by the 16-port E/D, and the spectra at the four matched ports are shown in Figs. 3(c)-3(f). After the PD, with 7.5 GHz at 3 dB bandwidth, the received signals are sampled and quantized by the DSO. The output signals are offline processed, to equalize the inter-symbol interference (ISI), due to the radio frequency band limitation of the analog devices. We used a training sequence similar to the data pattern used to measure the bit error rate (BER). A least mean square (LMS) algorithm has been used to equalize the bandwidth limitation of digital-to-analog and analog-to-digital converters. The LMS and training sequence were used to set the tap coefficient of a finite impulse response (FIR) filter with 161 taps. The temporal waveforms at −5 dBm of the received OC #9 with equalization is shown in Fig. 4(a). When the four OC#1, #5, #9 and #13 are simultaneously transmitted, the equalized signal shown in Fig. 4(c) presents a slight eye-opening, compared to the non-equalized signal shown in Fig. 4(b).

Finally, the system performances are evaluated by BER measurements, varying the PD input power, using variable optical attenuators (VOA).

Figure 5 shows the measured BERs of the PAM4-OCDM signal for single OC and four OCs transmission over 20 m SMF link. In the case of single OC transmission, the 20% soft-decision forward error correction (SD-FEC) threshold (2.4 x 10^{-2}) is achieved for all the OCs. In the case of simultaneous transmission of four OCs, the optimal amplitude level was set at −6 dBm received optical power. The amplitude level optimization is described in the
following section. In this case, the measured BER reaches the 20% SD-FEC threshold only after equalization. A 10.4 dB power penalty at the FEC threshold is measured comparing the single and four OCs cases.

Figure 6 reports the tap coefficients used in the cases of single and four OCs transmission, that are quite similar. In fact, in the case of four OCs, the performances of detected signal are degraded by beat noise, as shown in Fig. 5. Since laser coherence time is quite small, the beat noise is a random Gaussian noise [25], and it does not affect the tap coefficients. The error-floor for the four OCs transmission is due to the beat noise, which represents the main limitation of PAM4-OCDM systems. The length of the FIR filter is a critical parameter that largely influences the complexity of the post-equalization process. To investigate the influence of the filter length to the system performance, we measure the BER as a function of the number of FIR filter taps, in the case in the four OCs and −4 dBm received power. From an inspection of Fig. 7, it is evident that a 31-tap FIR filter is sufficient to equalize at 8 times oversampling.

Figure 8 shows the power distribution of the PAM4-OCDM system. When the received power and the minimum power of $2.4 \times 10^{-2}$ are 0 dBm and −6 dBm, the 4 OC system can be operated with 6 dB power margin until 20% SD-FEC limit threshold.

![Fig. 4. Temporal waveforms at −5 dBm (a) OC #9 with equalization (b) four OCs without equalization and (c) four OCs with equalization.](image)

![Fig. 5. Measured BERs of PAM4-OCDM signal.](image)
4. Amplitude level optimization

Figure 9 shows the probability density function (PDF) of a received PAM4-OCDM signal. The shot and beat noises greatly affect the high amplitude levels of the PAM signal. The variances of shot $\sigma_{sh}$ and beat $\sigma_{beat}$ noises have the following expressions [25]:
\[ \sigma_{sh}^2 = 2eB_R \Re \left( E_{ac}^2 \right) \left( 1 + \sum_{i=1}^{N-1} \frac{E_{cc-i}^2}{E_{ac}^2} \right) \]

(2)

\[ \sigma_{beat}^2 = \frac{\Re}{\pi} \int_{1}^{N} \int_{0}^{2\pi} E_{ac}^2(t)E_{cc-i}^2(t)\cos^2\left( \varphi_{ac}(t) - \varphi_{cc-i}(t) \right) dt \]

(3)

\[ \sigma_{total}^2 = \sigma_{sh}^2 + \sigma_{beat}^2 \]

(4)

where \( B_R \) and \( \Re \) are the PD bandwidth and sensitivity, respectively, and \( e \) is the electron charge. \( E_{ac}(t) \exp[j\varphi_{ac}(t)] \) and \( E_{cc-i}(t) \exp[j\varphi_{cc-i}(t)] \) (\( i = 1,2,\ldots,N-1 \)) are the optical autocorrelation and crosscorrelation signals, respectively, and \( \overline{E_{ac}} \cdot \overline{E_{cc-i}} \) the average values; finally \( T \) is the symbol duration. Since the noise variances \( \sigma_{sh}^2 \) and \( \sigma_{beat}^2 \) depend on the PD input power, the total noise distribution slightly changes as PD input power increases. In the case of PAM4-OCDM signal, BER and ideal signal intensities \( s_j \) \( (i = 0,1,2,3) \) can be written as

\[ \text{BER} = \frac{1}{M} \sum_{i=0}^{M-1} \text{erfc} \left( \frac{Q_i}{\sqrt{2}} \right) \]

(5)

\[ Q_i = \frac{s_{i+1} - s_i}{\sigma_{i+1} + \sigma_i} \quad i = 0,1,2,3 \]

(6)

Here, \( M \) is the total number of amplitude levels. For an optimal amplitude level ratio that corresponds to the maximum BER, all the \( Q \) values are equal. Figure 10 shows the optimal power-level spacing as a function of PD input power, that has been numerically evaluated, as well as the experimental data. It is evident that the amplitude level optimization, considering a suitable noise variance for each amplitude level, can achieve better results. The optimum spacing ratio is set at \(-6 \text{ dBm}\) in the experiment.
5. Summary

We have demonstrated a power efficient 4 OC x 10 GSymbol/s PAM4-OCDM system at a single wavelength, using two passive optical multiport E/Ds and transceiver with DSP. This configuration allows us to upgrade the system capacity by increasing the number of codes and amplitude levels, without modifying the system architecture. The experiment also demonstrates the effectiveness of transmitter-side amplitude level optimization and receiver-side LMS-based equalization.

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