Chirp-Dispersion Interaction-enabled Uneven Optical PAM-4 based on Dual-drive MZM for 5.9-dB SNR Gain in Digital RoF Fronthaul with Quantizer Compatibility

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Abstract: We theoretically model and explain the dispersion-induced eye closure/open in dual-drive MZM-based system and leverage the effect for uneven optical PAM-4 digital radio-over-fiber fronthaul. We evaluated two quantizers and 5.9-dB SNR gain is experimentally achieved.

1. Introduction

With the exponential growth of Internet traffic, the requirement of dense deployment of base stations has increased dramatically, leading to the cell area reduction. Wireless communications and optical transport networks are intersected more tightly, which is bridged by the mobile fronthaul. In fronthaul, centralized or distributed units (CU/DUs) transmit the wireless signals to the radio units (RUs) through fibers [1]. Then the signals are transmitted to various end users by radio. In this scenario, multi-level digital radio-over-fiber (D-RoF) becomes attractive for both academia and industry, aiming to achieve larger bandwidth and higher fidelity [2].

Due to the low cost and consumption, intensity modulation and direct detection (IM-DD) has been widely adopted for short-reach optical communication systems. In IM-DD systems, 4-level pulse amplitude modulation (PAM-4) is a simple and promising format, which has been chosen as a standard format for 400-G Ethernet [3]. However, when using a dual-drive Mach-Zehnder modulator (DD-MZM) to generate optical PAM-4 signals, the frequency chirp occurs and causes phase rotations of the symbols. This distortion interplays with fiber chromatic dispersion (CD), leading to inter-symbol interference (ISI) and bit error rate (BER) performance degradation. In [4], the frequency chirp effect in DD-MZM-based PAM-4 transmission has been investigated, which shows that positive and negative chirps occur when symbols change. These chirps result in the change of relative amplitudes, which enlarges the specific eyes and narrows the other eyes in eye diagrams. In [5], eye closure caused by CD-induced rotation of optical constellation is reported. However, the quantitative relationship between eye closure and phase rotation is not fully revealed.

In this work, we study eye closure/open caused by chirp-CD interaction in DD-MZM-based PAM-4 transmission and leverage it to enhance the SNR in D-RoF fronthaul, as shown in Fig. 1(a). We theoretically deduce the relationship between eye closure/open and the rotation of optical constellation. Combining the uneven spaced amplitudes with bits interleaving, uneven PAM-4 method is naturally formed, which offers protection on the significant bits and improves the SNR in the low received optical power (ROP) region, as depicted in Fig. 1(b). In this scheme, high-order bits are assigned to the first bits of PAM-4 symbols and the Euclidean distance between the middle constellation points is enlarged, as shown in Fig. 1(c). Compared to the outer constellation points, a lower error probability in the middle or high-order bit is achieved, introducing lower quantization noise [6]. In the DD-MZM based system, instead of trying to remove the change of eyes' scales, we take advantage of the dispersion-induced uneven PAM-4 and achieve fidelity enhancement. To further improve fidelity, we use μ-law and Lloyd-Max algorithm-based quantizers to make better use of the finite quantization bits considering Gaussian-like distributed wireless waveform [7].

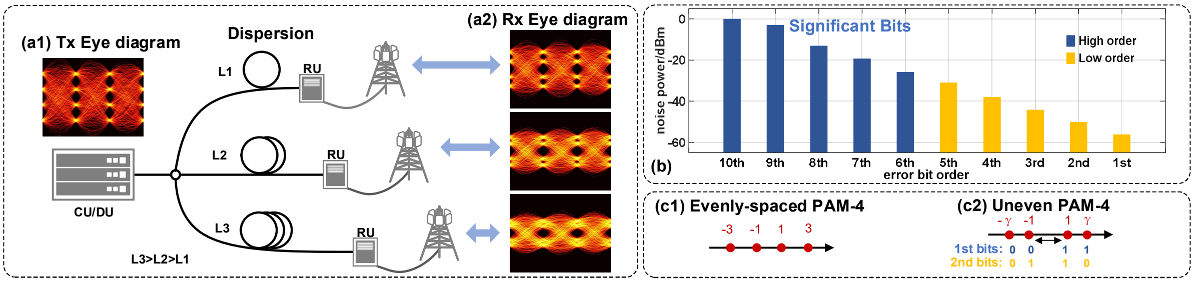

Fig. 1. The architecture of D-RoF fronthaul and the uneven PAM-4 method. (a1) Eye diagram of PAM-4 at the transmitter. (a2) Eye diagrams at receivers after transmission over different fiber distances. (b) Quantization noise versus the position of quantization bit. (c) Constellations of evenly-spaced and uneven PAM-4. CU/DU: centralized or distributed unit; RU: radio unit.

2. Principle

When MZM is used for PAM-4 signal modulation by two different binary signals, the relationship between output and input fields is shown in Eq. (1). Here $V_1(t)$ and $V_2(t)$ are driving voltages from different binary sequences with different peak-to-peak voltages (Vpp). The DD-MZM is biased at the quadrature point. In this configuration, the Vpp of $V_1(t)$ is two times or half of $V_2(t)$ to generate the symbols of PAM-4 and we take the former in this work for an example. The latter one follows similar mechanism and also provides SNR gain. Note that the output of DD-MZM not only has the amplitude part but also the phase part, which causes frequency chirp to IM.

$$E_{out} = E_{in} \cdot cos \frac{\pi}{2V_\pi}(V_1(t) - V_2(t) + \Delta Bias) \cdot \exp\left(j \cdot \frac{\pi}{2V_\pi}(V_1(t) + V_2(t))\right) \quad (1)$$

After fiber transmission, uneven spaced amplitudes occur due to the effect of CD, as shown in Fig. 1(a2). Through simulation, we observe that as the transmission distance increases, the position of each constellation point on the complex plane will change due to the CD-induced ISI, as shown in Fig. 2(a). Each cluster rotates and spreads. At the receiver, the signal is converted to photocurrent through square-law detection at the photodiode (PD) and the direct-current (DC) component is subtracted. We focus on the centers of clusters by parallel axis theorem, which is shown in Eqs. (2) and (3). I_s represents the average intensity of each symbol type, while I_c represents the average relative intensity to their centroid. r_i is the amplitude of every symbol, which can be converted to the distance to the origin of coordinates, and $r_i{'}$ is the distance to the centroid. For each symbol type, I_c is approximately equal since the shape and quantity are almost identical. After PD, the I_c part is removed as a DC component. Then problem is simplified as finding the trajectories of centroids.

$$I_s = I_c + |CO|^2 \quad (2)$$

$$I_s = \sum_{i=1}^{n} r_i{}^2 /n, \;\; I_c = \sum_{i=1}^{n} r_i{'}^2 /n \quad (3)$$

The proportion between symbol amplitudes can be converted to the proportion between square differences as shown in Eq. (4) and Fig. 2(b). $\overrightarrow{OP}^2$ represents the average intensity of all symbols, which is the DC component. Due to the large enough horizontal component, $|OC_1 + OP|$ and $|OC_2 + OP|$ are approximately equal and their directions can be considered as horizontal. The amplitude proportion is finally converted to the proportion between the horizontal projections. As shown in Fig. 2(c), 4 centroids rotate around different points. Due to the effect of CD, projections of the middle centroids relatively increase, compared to the outer centroids, which explains eye closure/open.

$$\frac{\overrightarrow{OC_1}^2 - \overrightarrow{OP}^2}{\overrightarrow{OC_2}^2 - \overrightarrow{OP}^2} = \frac{(\overrightarrow{OC_1} - \overrightarrow{OP})(\overrightarrow{OC_1} + \overrightarrow{OP})}{(\overrightarrow{OC_2} - \overrightarrow{OP})(\overrightarrow{OC_2} + \overrightarrow{OP})} \approx \frac{|\overrightarrow{C_1{'}P}|}{|\overrightarrow{C_2{'}P}|} \quad (4)$$

We define the amplitude proportion of the upper/lower eye and the middle eye as γ. As shown in Fig. 2(d), γ increases with transmission distance and baud rate, while the counterclockwise trajectories remain unchanged. Combining with bit interleaving method as shown in Fig. 2(e), the change of amplitude proportion forms uneven PAM-4, which protects significant bits.

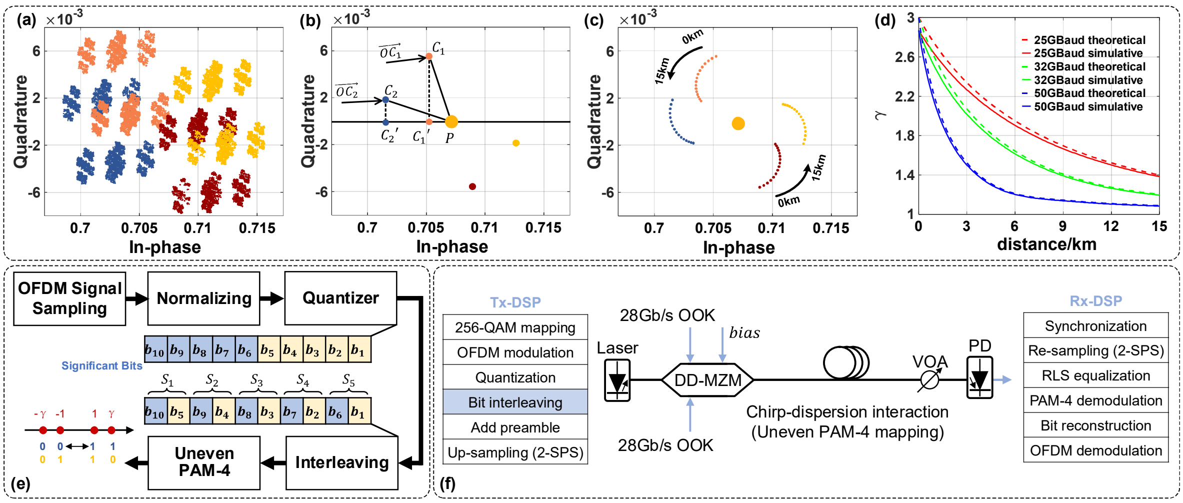

Fig. 2. The explanation of eye closure/open, the principle of uneven PAM-4 and the experimental setup. (a) Each type of symbols after 10km transmission. (b) The conversion of proportion. (c) Trajectories of centroids from 0 to 15km. (d) The amplitude proportion versus the distance and the baud rate. (e) The schematic diagram of uneven PAM-4 and bit interleaving methods. (f) The experimental setup and the DSP stacks. VOA: variable optical attenuator; PD: photodiode; Tx: transmitter; Rx: receiver.

3. Experiment

The experimental setup is shown in Fig. 2(f). We use a C-band DD-MZM (Fujitsu 7937EZ) to generate 28-GBd PAM-4 signal. Two binary signals are generated from a 56-GSa/s arbitrary waveform generator (AWG, Keysight M8195A). After 5/10-km single-mode fiber transmission, a variable optical attenuator (VOA) and a 40-GHz PD are employed. Finally, a 100-GSa/s real-time oscilloscope (RTO, Tektronix DPO75902SX) captures the signal with 8-bit resolution.

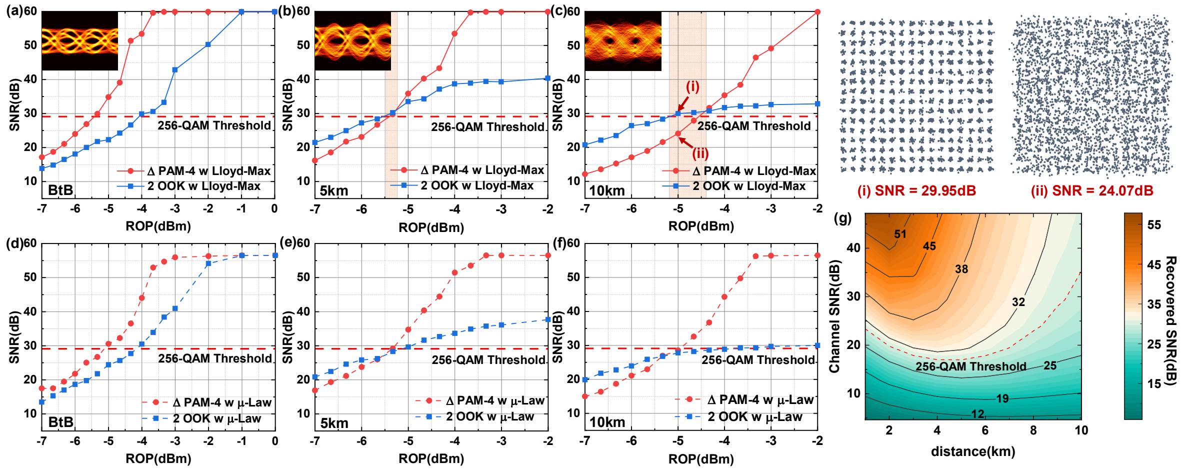

Fig. 3. The recovered SNR of differential-driven PAM-4 and 2 OOK signals systems with Lloyd-Max quantizer in different distance conditions: (a) BtB; (b) 5km; (c) 10km, and with μ-Law quantizer in different distance conditions: (d) BtB; (e) 5km; (f)10km. (g) Simulation result of recovered SNR versus transmission distance and channel SNR. ROP: received optical power; Δ PAM-4: differential-driven PAM-4.

We first experimentally compare our proposed uneven PAM-4 method generated by two 28-Gb/s binary signals with differential-driven PAM-4 signal generated by the same DD-MZM with equivalent output amplitude. Lloyd-Max algorithm-based quantizer is conducted in both methods. As depicted in Fig. 3(a)-(c), our proposed method achieves higher recovered SNR at low ROP conditions after 5-km and 10-km transmission. The eye diagrams indicate that the eye closure/open is aggravated with increased fiber lengths, while different degrees of uneven optical PAM-4 are shaped. In Fig. 3(c), our proposed method achieves the threshold of 256-QAM with 5.9-dB SNR gain. We further apply μ-law as the quantizer and repeat the above process, as illustrated in Fig. 3(d)-(f). The recovered SNR performance is slightly decreased in most cases compared with Lloyd-Max-based quantizer at the same condition, due to the greater quantization noise. With the μ-law quantizer, our proposed method still obtains gain at low ROP conditions. The results suggest the existence of optimal distance at a fixed ROP condition, due to the changing amplitude proportion with distance. As shown in Fig. 3(g), we further investigate the relationship between recovered SNR and channel SNR or transmission distance through simulation. With a fixed channel SNR condition, the optimal transmission distance is located on the ridge.

4. Conclusions

In this work, we establish a theoretical model for chirp and dispersion-induced eye closure/open in a dual-drive MZM-based PAM-4 IM-DD system. Analysis shows that the eye closure/open could explained by the optical constellation rotation on the complex plane and the amplitude proportion is decreased with increased distance or baud rate, which spontaneously forms the uneven PAM-4 method. We experimentally compared our proposed method with traditional chirp-free differential-driven PAM-4 modulation. With the help of the chirp-dispersion interaction-enabled uneven optical PAM-4, our proposed scheme achieves the threshold of 256-QAM with a 5.9-dB SNR gain.

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5. References

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