Spectrally-Efficient Direct Detection of QAM Signal by Orthogonal Carrier Interleaving

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Abstract: We propose and numerically demonstrate a scheme that enables the direct detection of QAM signals by a single photodetector. 40-Gb/s 16-QAM signal over 22-km fiber transmission is recovered without sacrificing optical spectral efficiency.

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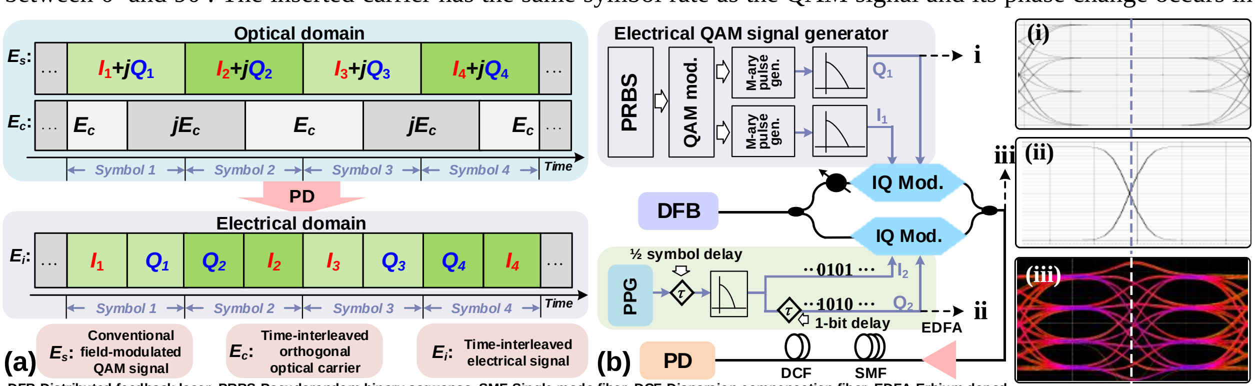
1. Introduction

Ever-increasing bandwidth demand driven by multimedia service and high-definition video has imposed a stringent spectral efficiency (SE) requirement on optical networks [1-3]. High-order quadrature amplitude modulation (QAM), which provides an improved SE with a reduced hardware complexity, has been widely investigated in both long-haul and short-reach scenarios [1,2]. However, in practical implementations, a high-cost and sophisticated coherent receiver is usually employed to recover the phase-diversity signal [3], which may not be preferable for cost-sensible short-reach applications. In order to simplify the receiver architecture, various schemes have been proposed such as block-wise phase switching [4], dual-band transmission [5], and signal carrier interleaving [6]. Although the single-photodetector (PD) detection schemes were achieved in [4,5], they used as twice acquisition time or bandwidth as required by a coherent receiver, which results in a halved optical SE.

Here, we propose a spectrally-efficient direct detection scheme for the transmission of high-order QAM signal in short distance, which remains the same optical SE as a coherent-receiver architecture. For a coherent receiver, the in-phase (I) and quadrature (Q) parts of a signal are projected onto different PDs. By contrast in our scheme, the two parts are temporally separated by a single PD with a doubled bandwidth. For that, a time-domain orthogonal phase-interleaved signal is inserted to a QAM signal at a transmitter, the I and Q parts can thus be separated in function of the phase state of the carrier. Benefiting from a relatively long and flat eyelid of the electrical QAM signal, which is often expected in the transmitter, a ½ symbol delay of the two signals makes it possible to project the I and Q parts of a QAM symbol onto two time slots in one symbol time. The reduction of optical SE by half due to repetitive detection [4] or dual-band detection [5] can therefore be avoided, and the optical SE remains the same as a coherent-receiver architecture. By this means, a single PD can be used to recover the I and Q information. The feasibility of the scheme is verified by a system simulation where a 40-Gb/s 16-QAM signal is successfully detected under 20% forward error correction (FEC) threshold. Simulation results prove our scheme as a possible solution to simplify the receiver architecture for low-cost short-reach scenarios without sacrificing the optical SE.

2. Operation principle

The direct detection of field-modulated QAM signal is based on the temporal separation of its I and Q parts, whose schematic diagram is shown in Fig. 1. A QAM signal is transmitted with an optical carrier that interleaves its phase between 0° and 90°. The inserted carrier has the same symbol rate as the QAM signal and its phase change occurs in



DFB-Distributed feedback laser, PRBS-Pseudorandom binary sequence, SMF-Single mode fiber, DCF-Dispersion compensation fiber, EDFA-Erbium doped fiber amplifier, PPG-Pulse pattern generator.

Fig. 1 (a) Schematic illustration of the principle for the proposed spectrally-efficient direct detection of QAM signal based on orthogonal carrier interleaving. (b) Block diagram of the simulation setup. Insets (i)-(iii) depict the eye diagrams of the filtered electrical PAM-bit stream signal, and ideally detected signal, respectively.

the middle of a QAM symbol by a carefully controlled ½ symbol delay. At the receiver, the photocurrents generated by the combined signal can be expressed as:

$$I_i = \left|E_s + E_c\right|^2 = \left|E_c\right|^2 + \left|E_s\right|^2 + 2\,\mathrm{Re}\left\{E_s E_c^*\right\}, \tag{1}$$

$$I_q = \left|E_s + jE_c\right|^2 = \left|E_c\right|^2 + \left|E_s\right|^2 + 2\,\mathrm{Im}\left\{E_s E_c^*\right\}, \tag{2}$$

where E_s and E_c denote the complex QAM signal and the optical carrier, respectively. In these Eqs., $|E_c|^2$ represents a constant, while $|E_s|^2$ is the signal-to-signal beating interference (SSBI), which can be neglected with a large carrier-to-signal power ratio (CSPR) [5]. When combined to an in-phase carrier, only the I part of the signal is detected, while the Q part is obtained by beating the signal with a 90° phase-shifted carrier. As shown in Fig. 1(a), the first and second half of a QAM symbol are aligned with two carriers of orthogonal phases, I and Q parts can therefore be projected alternatively in the two consecutive time slots within the symbol period. Here we assume that the QAM signal exhibits fast rise and fall edges, leading to obvious electrical level differences at both ¼ and ¾ symbol times of the eye diagram. Consequently, the optical QAM signal can be converted to intensity changes with a symbol rate that is multiplied by two, as shown in Fig. 1 (b). The optical SE remains unchanged as a coherent receiver scheme.

3. Numerical demonstration

We demonstrate the scheme by a system simulation and achieve direct detection of a 40-Gb/s 16-QAM signal by a single PD. The simulation setup is depicted in Fig. 1(b). Two I/Q modulators biased at null points are concurrently combined. The upper modulator is driven by an electrical 16-QAM signal, while the lower one is modulated by bit streams that enable the orthogonal carrier interleaving. In our simulation, a 40-Gb/s bit stream is first converted to 16-QAM, generating 2 channels of 4-ary pulse amplitude modulated (PAM) signals of 10 Gbd/s. 20-GHz Gaussian low-pass filters are employed to emulate electrical bandwidth limit. Inset (i) and (ii) show the eye diagrams of the filtered 4-PAM signal , respectively, where a ½ symbol delay is observed. The modulated light is amplified by an EDFA for 10-dBm launch power and sent to a 20-km SMF with a dispersion parameter of 16.75 ps/nm/km. Dispersion impairment is mitigated by a 2-km DCF. The signal is then detected by a 20-GHz PD. The BER is calculated by a Matlab component, including time synchronization, I/Q symbol decision, and error counting. Totally, over 1 million bits are taken into account. Inset (iii) gives the eye diagram of an ideally detected signal, which can be considered as a 20-Gbd/s 4-PAM signal. The eye width is halved, indicating that the I and Q parts are temporally separated.

Fig. 3(a) shows the BER curves as a function of CSPR for back-to-back (b2b) at an optical signal-to-noise ratio (OSNR) of 30 dB. As suggested by Eqs. (1) and (2), a low CSPR results in an enhanced SSBI, while a strong one leads to a less transferred signal energy [5]. The optimized CSPR ratio of 8 dB is found to reach the minimum BER, and this ratio is latter used for a fiber transmission. Fig. 3(b) shows the BER curves versus OSNR for b2b, and 20-km SMF with 2-km DCF transmission. The power penalty is ~1 dB at the FEC threshold (BER = 0.02). The eye diagrams are provided for given OSNRs of 30 dB and 31 dB, as shown in insets. The detected signals can be regarded as 20-Gbd/s 4-PAM signals with eight identifiable eyes observed in one QAM symbol period.

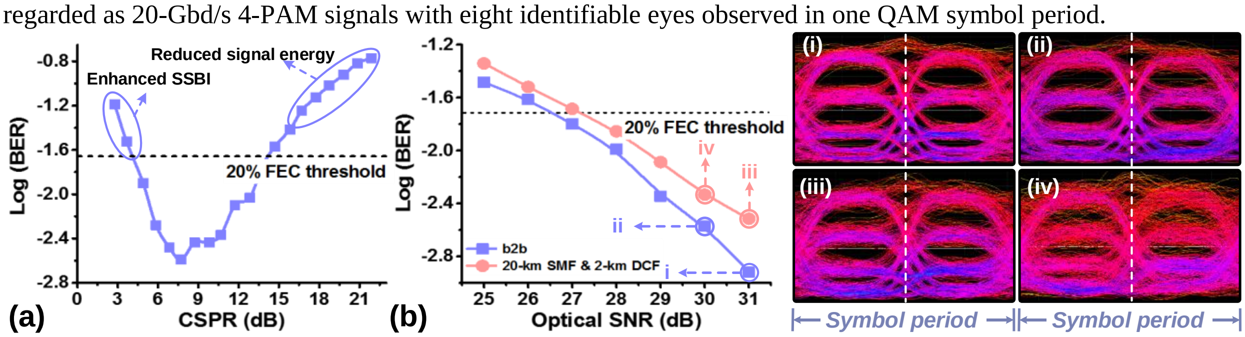


Fig. 2. (a) Calculated BER curve versus CSPR at 30-dB OSNR. (b) Calculated BER curves versus OSNR with 8-dB CSPR for b2b, and 20-km SMF with 2-km DCF transmission. Insets (i)-(iv) show the eye diagrams of the detected signals at 30-dB and 31-dB OSNRs.

4. Conclusion

By inserting an orthogonal phase-interleaved optical carrier in the transmitter, a spectrally-efficient direct detection scheme for high-level QAM signal by a single PD was proposed and numerically demonstrated. The feasibility was verified by a system simulation where a 40-Gb/s 16-QAM signal is directly detected over 22-km fiber transmission.

5. References

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