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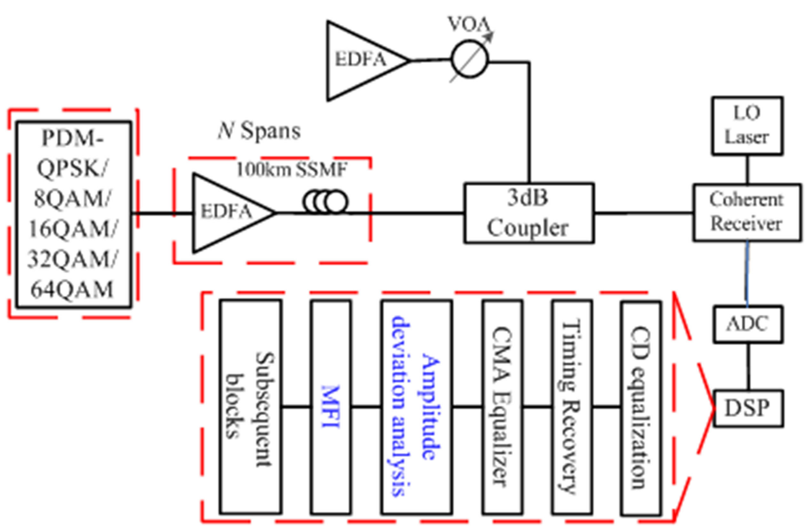

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A Modulation Format Identification Method Based on Amplitude Deviation Analysis of Received Optical Communication Signal

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Abstract: Modulation format identification (MFI) is necessary for future elastic optical networks. We propose an MFI scheme based on the amplitude deviation analysis of the received optical communication signal. In our method, for a received optical signal, two values of normalized average amplitude deviation with reference to amplitude of ideal polarization-division multiplexing (PDM) QPSK and 16 quadratic-amplitude modulation (QAM) are computed, respectively, and the ratio of the two values is used to identify the commonly used formats like PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM, and PDM-64 QAM. The results demonstrate that the modulation format can be identified with the required optical signal-to-noise ratio not higher than the forward error correction (FEC) threshold. The advantage of our method is that it is not sensitive to phase noise, frequency offset, and nonlinearity in optical fiber communication systems. The proposed method needs no training samples or additional hardware, so it is simple and cost-effective. Meanwhile, we also discuss the influence of the residual chromatic dispersion on our proposed scheme.

Index Terms: MFI, coherent optical communications.

1. Introduction

The next-generation fiber-optic communication networks are envisioned to be flexible in nature, which will be capable of dynamically implementing data signal of different modulation formats (MFs), data rates, and error correction protocols, according to network operating demands [1]. Thus, blind and flexible MFI for digital coherent receivers in heterogeneous EONs appeals attention because it can adaptively identify the MFs of received signals and provide the MF information to subsequent digital-signal-processing (DSP) blocks [2].

In past few years, a number of MFI techniques for digital coherent receivers have been proposed. Signal cumulant and signal power distribution-based techniques, which assume prior information about the optical signal-to-noise ratio (OSNR) of the received signal, have been proposed in [3],

TABLE 1
Feature Quantity of Different MFs

R	Result
$R\leq 1.7$	QPSK
$1.7<R\leq 1.9$	8QAM
$1.9<R\leq 2.15$	32QAM
$2.15<R\leq 2.6$	64QAM
$R>2.6$	16QAM

[4]. S. M. Bilal *et al.* have reported a method based on evaluation of peak-to-average-power ratio (PAPR) of received data samples, which needs additional hardware components, such as filters and power meters [5], [6]. Stokes space representation and variable Bayesian expectation maximization (VBEM) algorithm-based technique employs an iterative framework for the optimization of certain set of parameters and requires considerable computation time [7]–[12]. A digital frequency-offset loading technique is proposed for the MFI, and additional pilot signal is required at the transmitter. Recently, several machine-learning techniques are used to extract format sensitive features to identify the signal types, such as the methods based on artificial neural networks (ANNs), principal component analysis (PCA), convolutional neural networks (CNNs) and deep neural networks (DNNs) for signal pattern recognition [13]–[17]. The deep learning methods require a great amount of signal samples for extensive training.

In this paper, we propose a MFI method based on amplitude deviation analysis of the coherently received signal. By analyzing the average amplitude deviation from the standard amplitude distribution of ideal PDM-QPSK and PDM-16 QAM formats, five most commonly used formats in optical coherent transmission systems, PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM and PDM-64 QAM can be identified. The proposed method is not sensitive to the phase noise caused by Laser linewidth and the frequency offset between the transmitter Laser and local oscillator (LO) Laser, and can tolerate the fiber nonlinearity. Furthermore, our method needs no training samples or additional hardware, so is simple and cost effective. The total time complexity of the proposed method is *O(n)*, better than many other MFI methods. The influence of the residual chromatic dispersion is also discussed in the paper.

2. Amplitude Deviation Analysis of Received Optical Signal

It is assumed that the electric field for an ideal PDM-QPSK symbol is expressed by $E_{QPSK}(\mathrm{k}) = \mathrm{A}\exp(\mathrm{i}\phi_k)$, where $\phi_k = \frac{(2m-1)\pi}{4}$, $\mathrm{m} = 1, 2, 3, 4$. The electric field for an ideal PDM-16 QAM symbol can be expressed by $E_{16QAM}(\mathrm{k}) = a_k + \mathrm{i}b_k$, where $a_k, b_k = 1, 3$. If the possible symbols for PDM-QPSK or PDM-16 QAM format distribute uniformly, the normalized amplitudes for ideally PDM-QPSK and PDM-16 QAM are $\tilde{A}_{QPSK}(k) = \frac{|E_{QPSK}(\mathrm{k})|}{\sqrt{E[|E_{QPSK}(\mathrm{k})|^2]}} = 1$ and $\tilde{A}_{16QAM}(k) = \frac{|E_{16QAM}(\mathrm{k})|}{\sqrt{E[|E_{16QAM}(\mathrm{k})|^2]}} = \sqrt{\frac{1}{5}}, 1, \sqrt{\frac{9}{5}}$ respectively. Here E[x] denotes the expected value of x. If one sampled point per symbol is considered, the amplitude of a received symbol can be expressed by r_k. The average normalized amplitude deviation of received symbols from the closest amplitude of ideally PDM-QPSK and PDM-16 QAM are defined $e_I = E[|r_k - \tilde{A}_{QPSK}|]$ and $e_{II} = E[min|r_k - \tilde{A}_{16QAM}|]$ respectively. Since ideal PDM-16 QAM signal has three possible amplitudes, the normalized amplitude deviation of a received symbol from the closest amplitude is obtained by calculating the minimum value among $|r_k - \sqrt{\frac{1}{5}}|, |r_k - 1|, |r_k - \sqrt{\frac{9}{5}}|$. In order to maximize the difference in the MFs $R = \frac{e_I}{e_{II}}$ is used as the feature quantity. Different modulation formats have different R values, which can be distinguished by particular thresholds. In this paper, we set the threshold values of R as 1.7, 1.9, 2.15 and 2.6 to identify PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM and PDM-64 QAM formats. The identify results are detailed in Table 1 and the corresponding decision flow charts for format identification are shown in Fig. 1.

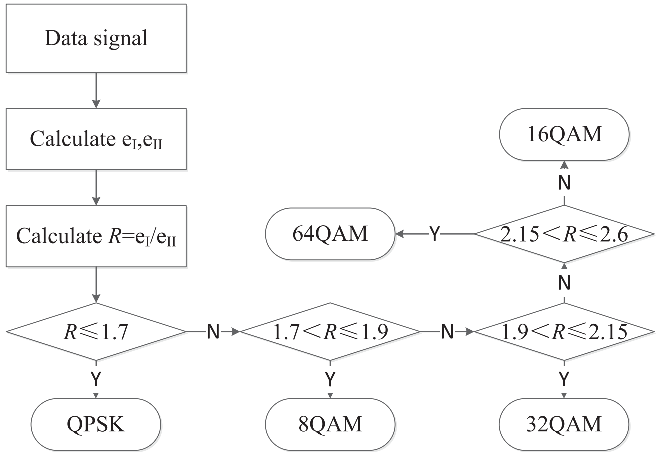

Fig. 1. Flowchart of MFI method based on amplitude deviation analysis.

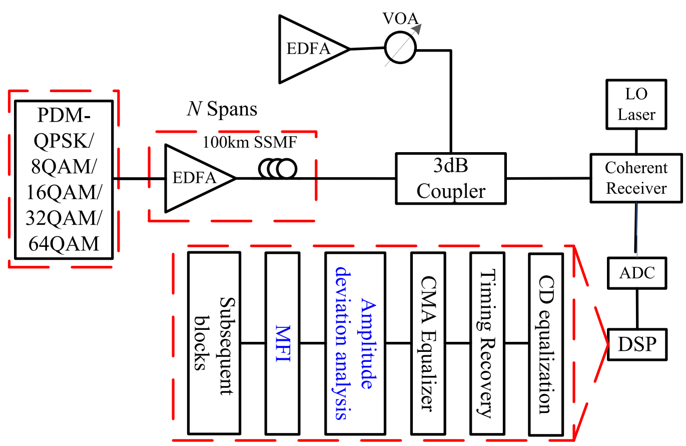

Fig. 2. The coherent optical fiber communication system setup to utilize the proposed method to identify the MFs.

3. Simulation Results

We set up the simulation system with the commercial software Virtual Photonics Inc. (VPI) Transmission Maker. The schematic diagram of proposed method based on amplitude deviation analysis for optical fiber transmission system is shown in Fig. 2. The optical signal of five widely used MFs, PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM and PDM-64 QAM, are transmitted to the fiber link. The symbol rate is 28 GBaud and the launched power is in the range of 0∼3 dBm. The wavelength of laser at transmitter is 1553.6 nm with a linewidth of 100 KHz. Each span has a 100 km standard single-mode fiber (SSMF) and an erbium-doped fiber amplifier (EDFA). The CD of SSMF is 16 ps/(km.nm) and equalizing polarization mode dispersion (PMD) parameter is set as 0.1 ps/$\sqrt{\text{km}}$. An EDFA and a variable optical attenuator (VOA) are used to vary OSNR of the optical signal input to a balanced detected coherent receiver in the range of 10∼36 dB with step of 2 dB. The linewidth of the local oscillator (LO) is 100 KHz. CD equalization and timing recovery are performed first. The system employs dual-polarization transmission, so the constant modulus algorithm (CMA) based equalizer is also performed for PMD before the MFI stage. After MFI, the modulation dependent subsequent blocks in DSP such as the adaptive equalizer, frequency offset estimator and carrier phase recovery are performed. 1000 symbols are enough for PDM-QPSK and PDM-8

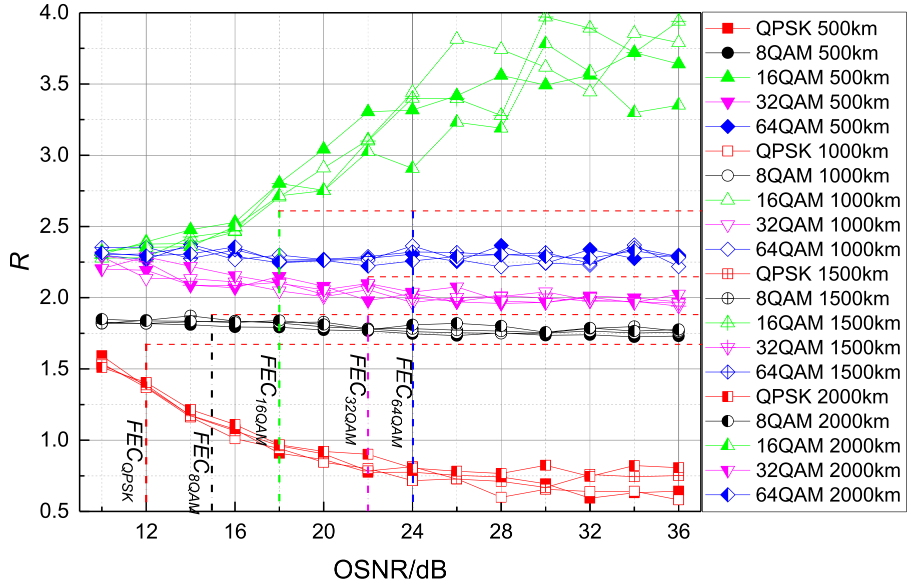

Fig. 3. The value of *R* varies with different MFs, OSNR and transmission distance. The symbol rate is 28 GBaud. The launched optical power is 0 dBm. The linewidth of Lasers is 100 KHz.

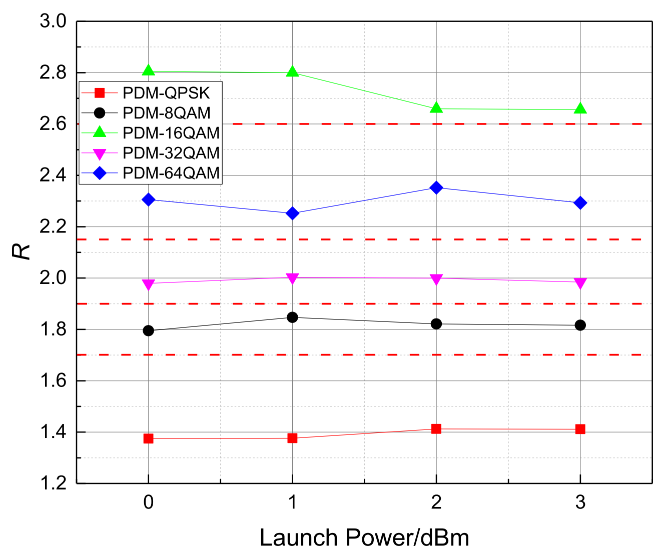

Fig. 4. The value of *R* varies with different MFs and launch powered when the OSNR of each MF is equals to the FEC threshold. The symbol rate is 28 GBaud. The linewidth of Lasers is 100 KHz.

QAM signals in each independent simulation. The PDM-16 QAM, PDM-32 QAM and PDM-64 QAM signals need 4000 symbols in each independent simulation owing to multi-amplitudes.

The value of *R* varies with different MFs, OSNR and transmission distance as shown in Fig. 3. We can see the value of *R* for PDM-QPSK can be distinguished from QAMs MFs clearly. The value of *R* for PDM-16 QAM increases as OSNR changes, and be distinguished from other MFs. For other QAM formats, like PDM-8 QAM, PDM-32 QAM and PDM-64 QAM, particular thresholds are given in Section 2 to distinguish them. The SD-FEC thresholds for 28 GBaud rate PDM system with PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM and PDM-64 QAM are illustrated by the vertical dash lines [4], [9]. It can be seen that the required minimum OSNR value of each MFs for

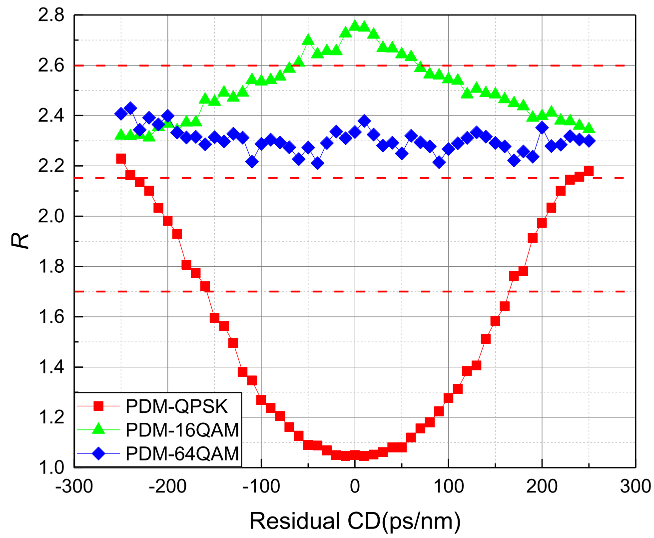

Fig. 5. The value of R varies with different residual CD when the OSNR of each MF equals to the FEC threshold. The symbol rate is 28 GBaud. The linewidth of Lasers is 100 KHz.

proposed MFI method is lower than their respective FEC thresholds. In addition, according to the variation of R values with OSNR, we believe that if the OSNR is higher than the FEC thresholds, different MFs can be separated with the threshold values of R.

It is well known that the fiber nonlinearity is the ultimate limiting factor for high symbol rate long haul optical fiber transmission system. The fiber nonlinearity is related to the launch power and fiber length. We investigate the impact of fiber nonlinearity on our proposed method. Figure 4 shows the effect of launched power on the R values of different MFs with the OSNR of each MF equaling to the FEC threshold. The fiber lengths are 2000 km, 2000 km, 1500 km, 1000 km and 500 km for QPSK, 8 QAM, 16 QAM, 32 QAM and 64 QAM signals respectively. It can be seen that the variation of R values remains in the range of respective threshold to identify each modulation format.

It is known that the residual CD after CD compensation in a practical optical fiber communication system affects the quality of received signal. In this paper, we also discuss the influence of residual CD on the value of R as shown in Fig. 5. The proposed method can tolerate a range of residual CD for PDM-QPSK systems ($-150\sim160$ ps/nm) and PDM-16 QAM systems ($-60\sim60$ ps/nm) without sacrificing performance.

Subsequently, we also compare the time complexity of the proposed method with other MFI methods. The total time of our proposed method is $O(n)$ to compute the average normalized amplitude deviation of received symbols. Our method is more efficiently if compared with other methods, such as stokes space analysis method or KNN method, because the calculation time for these methods is on the order of $O(n^2)$ [9], [12].

4. Results of Proof Experiments

Subject to experimental conditions, we built a single-polarization system and measured experimental results for QPSK, 16 QAM and 64 QAM. The experimental configuration for Fig. 2 is as the following: the laser at the transmitter is 1550 nm with the linewidth of 5 kHz, and is modulated by an IQ modulator, with I and Q branches driven independently by two pseudo-random bit sequences (PRBS) produced by arbitrary waveform generator (AWG). Three MFs (QPSK, 16-QAM, 64-QAM) of 25 GBaud symbol rate are generated. The launched optical power to SSMF is 0.0 dBm. A real-time scope works as ADC to sample the coherent detected signal by 50 GSa/s sampling rate. The offline DSP performs CD equalization, resampling and MFI. Fig. 6 shows the experimental results

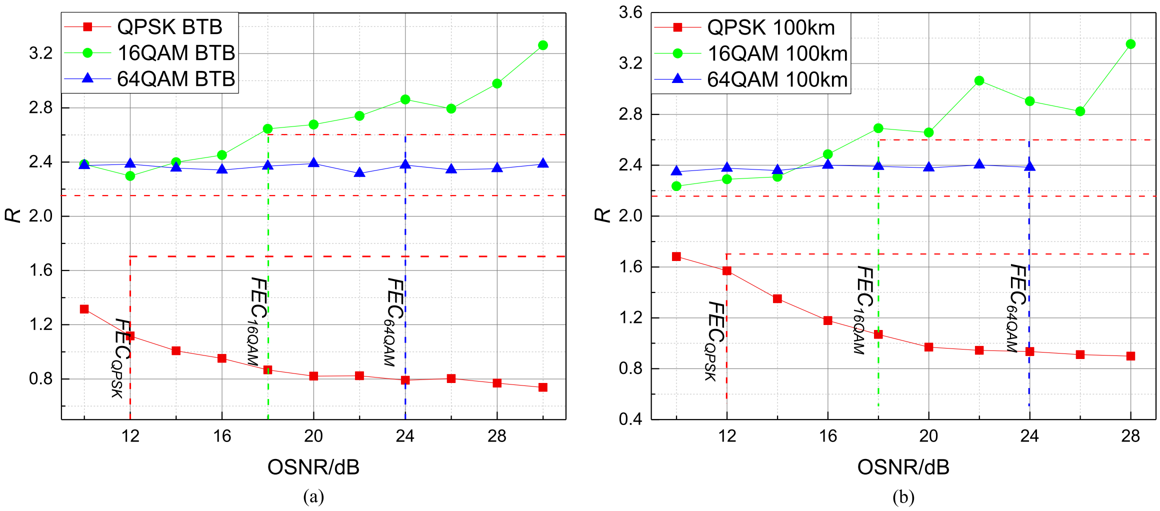

Fig. 6. The value of R for an experimental coherent communication system. (a) Back to back; (b) Transmission distance of 100 km.

for B2B optical communication system and transmission distance of 100 km. With two threshold values of R, 1.7 and 2.6, QPSK can be identified with OSNR higher than 10 dB in back to back system and 100 km transmission system. 16 QAM and 64 QAM can be identified with OSNR higher than 18 dB for both back to back system and 100 km transmission system. These results validate our method for MFI. Although limited by the experiment conditions, it is reasonable to predict by Fig. 3 that our method is applicable for longer transmission systems.

5. Conclusion

In this work, we propose a MFI scheme by analyzing the amplitude deviation of received optical from ideal PDM-QPSK and PDM-16 QAM normalized amplitude distributions. The ratio defining the extent of such amplitude deviation is utilized to distinguish five commonly used MFs, i.e., PDM-QPSK, PDM-8 QAM, PDM-16 QAM, PDM-32 QAM and PDM-64 QAM. The effectiveness has been verified via numerical simulations and experiments. Benefiting from the identification with amplitude analysis, the proposed method can tolerate the laser phase noise, frequency offset, and polarization mode dispersion. The minimum OSNRs of all the MFs required for this MFI method are below the FEC thresholds. In addition, the time complexity of the proposed method can be notably reduced compared with other methods. We believe that our simple and effective method would bring great convenience into future EONs.

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