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Signal power distribution based modulation format identification for coherent optical receivers

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ABSTRACT

A simple modulation format identification (MFI) technique based on extracting features from the statistical distributions of normalized signal power is proposed for cognitive coherent optical receivers. The proposed MFI technique requires no prior training and is independent of phase noise or frequency offset. Furthermore, it also performs good identification of the polarization-multiplexed (PM) M-QAM signals even after insufficient equalization of the constant modulus algorithm (CMA). Simulation results demonstrate successful MFI among PM-QPSK, PM-8-QAM, PM-16-QAM, PM-32-QAM and PM-64-QAM signals within OSNR range of practical system. Experimental verification using PM-QPSK/16-QAM/64-QAM signals also confirms the feasibility of the proposed MFI technique after long distance fiber transmission.

1. Introduction

The utilization of coherent detection and digital signal processing (DSP) has dramatically increased the capacity and transmission distance of optical fiber communications in the past few years [1–4]. However, only increasing the transmission capacity is not enough for the future bandwidth-desired optical network, because the current dense wavelength division multiplexing (DWDM) network with fixed wavelength grid cannot be fully utilized due to lack of spectrum flexibility. To properly address these challenges, cognitive optical networks (CON) [5] with flexible transceivers and network elements have recently attracted a lot of interest. In the CON, reconfigurable transmitters are capable of signal generation with arbitrary modulation formats to adapt to real-time network conditions and data rate for a given traffic demand [6]. Therefore, prior knowledge of the modulation formats of the incoming signals at a receiver unit will no longer be guaranteed. As a result, it may become necessary for a digital coherent receiver to identify the modulation format of incoming signals at the physical layer before appropriate modulation-format-dependent signal processing is employed.

Modulation format identification (MFI) has been studied to a certain extent for wireless communication systems and has become an important component for software-defined radio (SDR) and military applications [7]. However, most proposed MFI methods in wireless networks are not tolerant to oscillator phase noise as electronic oscillators have significantly better frequency and phase accuracy than local lasers used in coherent optical communications [8–10]. In addition, the majority of frequency offset estimation (FOE) and carrier phase estimation (CPE) techniques in digital coherent receivers are somewhat dependent on modulation format in the first place [11–12], rendering the knowledge of modulation format a must. As a result, it is desirable to derive an MFI technique independent of phase noise for future CONs. Several MFI techniques for optical communication systems were recently proposed in the literature [13–17]. In [13], a MFI scheme based on signal constellation and K-means algorithm has been proposed. However, this scheme has limited tolerance to the phase noise and thus requires modulation-format-transparent algorithms before MFI. MFI technique utilizing artificial neural networks has been presented in [14], which can achieve high identification accuracy in the presence of fiber dispersion. However, prior training is needed for this technique. In [15–17], MFI methods based on stokes space signal representation for digital coherent optical receiver have been demonstrated, which allow for MFI at a considerably earlier stage of the DSP module in the receiver and therefore relax the subsequent modulation-format-dependent algorithms. Also, those schemes do not need training or a constellation diagram to operate. However, iterated machine learning algorithms

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are required in these methods, which may increase the computation complexity.

Recently, we proposed a simple MFI technique described in [18] that studies the distribution of received normalized signal power after CD compensation, timing phase recovery and constant modulus algorithm (CMA) equalization, as shown in Fig. 1. The MFI technique requires simple computations, needs no prior training and is independent of phase noise. However, the CMA cannot give effective equalization for the multi-level polarization multiplexed (PM) M-QAM signals [19], which will have an impact on the correct identification of modulation format. Actually, no comments about these problems were talked about in [18].

As a result, in this paper, we expand on our previous work in [18] and mainly focus on the MFI of PM-M-QAM signals after CMA pre-convergence. It is found that the correct MFI can be realized among PM-QPSK, PM-8-QAM, PM-16-QAM, PM-32-QAM and PM-64-QAM signals if the identifying features and decision thresholds are carefully chosen, even though the PM-M-QAM signals are insufficiently equalized by using the CMA. Note that 128-QAM and higher order modulation formats are not considered in the proposed MFI technique, since they are rarely utilized in practical systems due to their strict requirement to frequency and phase accuracy of the coherent optical receivers. Analytical models under additive Gaussian noise channel are built and successful MFI is realized within the range of OSNR starting from the theoretical minimum for 7%-overhead forward error correction (FEC) thresholds. Proof of concept experiments are also carried out for PM-QPSK, PM-16-QAM and PM-64-QAM signals, which confirms the feasibility of our proposed MFI technique in the dual-polarization long-distance fiber transmission systems.

2. Operating principle

2.1. Identifying feature extraction

Fig. 2 shows the normalized power distributions of five common modulation formats including QPSK, 8-QAM, 16-QAM, 32-QAM and 64-QAM. Signals in presence of frequency offset and other phase impairments [shown in Fig. 2(b)] have the same normalized power distributions as that of the ideal constellations [Fig. 2(a)]. In a practical setting, the distribution can be obtained empirically from a block of received symbols if a sufficient symbol size is available. Clearly, different modulation formats have different power distributions, from which one can extract distinctive features for MFI. We propose to use ratios of probability of signal normalized power falling on different ranges as such decision metrics. Definitions of the three ratios R_1, R_2 and R_3 are shown in Table 1. If proper decision rules are chosen, QPSK and 8-QAM signals can be identified from other signals by using ratio R_1, 64-QAM signals can then be distinguished by utilizing ratio R_2, and at last the 16-QAM signal can be separated from 32-QAM signals based on ratio R_3 Table 2.

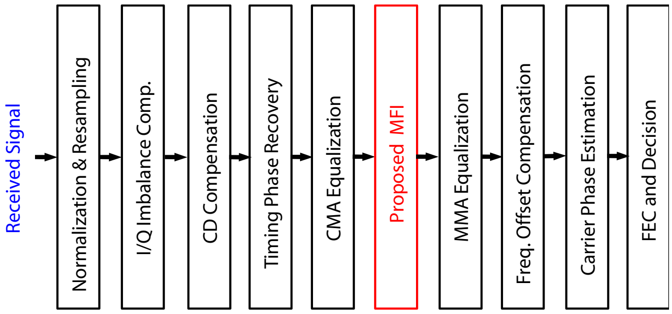

Fig. 1. Block diagram of digital signal processing algorithms in a digital coherent receiver supporting modulation format identification. CMA: constant modulus algorithm; MMA: multi-modulus algorithm.

2.2. Modulation format identification under additive Gaussian noise channel

Bononi et al. [20] showed that amplified spontaneous emission (ASE) noise as well as the fiber nonlinearity-induced noise can be approximated as additive Gaussian noise. As a result, the in-phase (I) and quadrature (Q) component of the received signal can be considered as independent Gaussian random variables with a variance of σ^2 and means μ_1 and μ_2, respectively. Then the probability density function (PDF) $f(x)$ of the normalized received power follows a non-central chi-squared distribution [21] given by

$$f(x) = \frac{1}{2\sigma^2} e^{-\frac{x+v^2}{2\sigma^2}} I_0\left(\frac{v\sqrt{x}}{\sigma^2}\right) \tag{1}$$

which has 2 degrees of freedom and $I_0(x)$ is the zero-order modified Bessel function of the first kind. The non-centrality parameter is

$$\frac{v^2}{\sigma^2} = \frac{\mu_1^2+\mu_2^2}{\sigma^2} \tag{2}$$

For the received signals with normalized power, the OSNR is given by

$$OSNR = \frac{1}{2\sigma^2}\cdot\frac{B}{12.5e9} \tag{3}$$

where B is the symbol rate. Hence values of the ratios are dependent on optical signal-to-noise ratio (OSNR) of the received signals. Based on this model, the theoretical values of the three ratios R_1, R_2 and R_3 of 28 GBaud signals under additive Gaussian noise channel within OSNR range from 12 dB to 36 dB are shown in Fig. 3(a), (c) and (e), respectively. It can be seen that successful MFI is achieved by selecting proper decision thresholds [see orange dot line in Fig. 3(a), (c) and (e)] within the practical OSNR range for each modulation format.

2.3. Modulation format identification in dual-polarization systems

In the dual-polarization fiber-optic systems, in addition to the Gaussian noise, another issue that should be considered is polarization crosstalk. The commonly used multi-modulus algorithms (MMA) [19,22], which are often utilized following the CMA for M-QAM polarization demultiplexing, are dependent on the modulation format, and thus the MFI, locating before MMA in the DSP module (see Fig. 1), will be affected by the inefficient equalization of CMA. Although the recently proposed stokes space based polarization demultiplexing (SS-PDM) technique is modulation format independent [23], it could not equalize the residual CD not fully compensated by the static CD compensation algorithms and its performance will degrade when polarization-mode dispersion (PMD) exists [24], which will subsequently increase the complexity of MFI. Compared with SS-PDM, CMA performs more effective equalization to CD and PMD [25]. As a result, in this section, study is focused on the MFI after CMA equalization.

Since PM-M-QAM signals cannot be fully equalized and demultiplexed using solely standard CMA [19,26], the insufficient equalization after CMA will have an impact on the normalized power distribution of the M-QAM signals when they work in the dual-polarization systems. A proof-of-concept dual-polarization simulation setup with additive Gaussian white noise (AWGN) channel model was built to facilitate the analysis of signal normalized power distribution after CMA pre-convergence. In the simulation, the polarization rotation angle was set to $\pi/6$, while the PMD