Optical Fiber Technology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Non-data-aided joint bit-rate and modulation format identification for next-generation heterogeneous optical networks

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ARTICLE INFO

Article history:
Received 23 July 2013
Revised 5 November 2013
Available online xxxx

Keywords:
Bit-rate and modulation format identification
Heterogeneous fiber-optic networks
Optical performance monitoring
Artificial neural networks
Fiber-optic communication

ABSTRACT

A novel and cost-effective technique for simultaneous bit-rate and modulation format identification (BR-MFI) in next-generation heterogeneous optical networks is proposed. This technique utilizes an artificial neural network (ANN) in conjunction with asynchronous delay-tap plots (ADTPs) to enable low-cost joint BR-MFI at the receivers as well as at the intermediate network nodes without requiring any prior information from the transmitters. The results of numerical simulations demonstrate successful identification of several commonly-used bit-rates and modulation formats with estimation accuracies in excess of 99.7%. The effectiveness of proposed technique under different channel conditions i.e. optical signal-to-noise ratio (OSNR) in the range of 14–28 dB, chromatic dispersion (CD) in the range of −500 to 500 ps/nm and differential group delay (DGD) in the range of 0–10 ps, is investigated and it has been shown that the proposed technique is robust against all these impairments.

1. Introduction

Future fiber-optic communication networks are anticipated to support a wide variety of data traffic resulting from the advent of a plethora of applications with different data rate requirements [1,2]. Therefore, in contrast to legacy single line-rate (SLR) networks with predefined modulation formats, future fiber-optic networks are envisaged to be heterogeneous in nature encompassing multiple modulation formats and mixed line-rates (MLR) (such as 10/40/100 Gbps) [3]. Since bit-rates and modulation formats may vary dynamically across neighboring wavelength-division multiplexed channels in heterogeneous fiber-optic networks, the digital receivers as well as the intermediate network nodes in future optical networks must be fully capable of recognizing the transmitted signal's bit-rate and modulation format autonomously [2]. Joint BR-MFI is crucial at the intermediate network nodes due to the fact that the optical performance monitoring (OPM) techniques employed at these nodes (for enabling continuous and real-time information about the extent of various transmission impairments) may be bit-rate/modulation format dependent [4,5]. The real-time information about the signal's bit-rate and modulation format, obtained through BR-MFI, can empower the OPM devices installed at the intermediate network nodes to adopt a monitoring technique most appropriate for the identified signal type. Similarly, the critical information provided by BR-MFI can be effectively exploited by the carrier recovery modules in digital coherent receivers. Particularly, the need for non-data-aided BR-MFI in future optical networks arises due to the following two reasons (1) The data-aided BR-MFI may be difficult to realize at the intermediate network nodes because these nodes can only permit limited complexity. (2) The data-aided BR-MFI approach may significantly increase the system overhead.

Non-data-aided modulation format identification (MFI) has a long history in wireless radio networks where it was initially used for several military applications such as signal surveillance and interference detection [6]. With the emergence of multiple standards in modern wireless communication networks as well as with the advent of flexibility and cognition in these networks, the digital receivers are expected to handle multiple modulation formats and data rates. Therefore, MFI is now considered an essential feature of emerging software-defined radio (SDR) and cognitive radio [7]. A plethora of MFI techniques has been proposed for wireless networks in the last decade and a comprehensive review of these techniques is given in [8–10]. As fiber-optic communication systems are also embracing diversity in terms of bit-rates and modulation formats, non-data-aided BR-MFI in future fiber-optic networks is becoming an important issue. However, real-time identification of bit-rates and modulation formats in high-speed optical networks is much more complicated as compared to that in wireless networks. This is due to the fact that the data rates involved in fiber-optic networks are much higher. Therefore, the

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1068-5200/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yofte.2013.12.001

detection of signals and subsequent recognition of bit-rates and modulation formats without any prior information from the transmitters is quite challenging especially at the intermediate network nodes which can only allow limited complexity.

Non-data-aided joint BR-MFI in fiber-optic communication networks is a relatively unexplored area of research. Gonzalez et al. [11] and Borkowski et al. [12] have demonstrated MFI in digital coherent receivers for a few modulation formats. However, these techniques may not be suitable for MFI at the intermediate network nodes due to high complexity of a coherent receiver. Another drawback of these techniques is that they are limited to MFI and cannot perform joint BR-MFI. Recently, we proposed a technique for non-data-aided MFI in heterogeneous fiber-optic networks by using an ANN in combination with asynchronous amplitude histograms (AAHs) [13]. However, since an AAH is generated from amplitude samples acquired through one-tap asynchronous sampling, it lacks the timing/slope information essential for distinguishing between various bit-rates of the signals [14]. Consequently, that technique is also constrained to just MFI.

In this paper, we generalize our MFI technique proposed in [13] for the joint identification of bit-rates and modulation formats of the signals by using an ANN trained with the features of ADTPs. Since ADTPs contain distinct signatures of various modulation formats as well as information about the slopes of the signal pulses (which in turn depend on the bit-rate), the proposed technique using ADTPs with ANN can simultaneously identify the bit-rates and modulation formats of the signals. In order to investigate the applicability of the proposed technique, numerical simulations are conducted for various commonly-used bit-rates and modulation formats such as 10/20 Gbps return-to-zero (RZ) on–off keying (OOK), 40/100 Gbps polarization-multiplexed (PM) RZ quadrature phase-shift keying (QPSK) and 100/200 Gbps PM non-return-to-zero (NRZ) 16 quadrature amplitude modulation (16QAM) signals. The validity of proposed technique in the presence of various transmission impairments such as amplifier noise, CD and polarization-mode dispersion (PMD) is also investigated. The simulation results show that the proposed technique can simultaneously identify the bit-rates and modulation formats of all the signals with an overall accuracy of 99.95% and without requiring any information from the transmitters. Due to the fact that the proposed technique employs asynchronous delay-tap sampling (ADTS) after direct detection of signals, it can enable joint BR-MFI for several different signal types without requiring any hardware changes. Also, due to its implementation simplicity, it can facilitate non-data-aided BR-MFI in receivers as well as at the intermediate network nodes in next-generation heterogeneous fiber-optic networks.

2. Asynchronous delay-tap sampling

Asynchronous delay-tap plots are hailed as an alternative to the conventional synchronous eye-diagrams with the advantage that unlike the latter, the generation of ADTPs does not require timing/clock information [15]. In ADTS, the signal amplitude after direct detection is asynchronously sampled in pairs (p_i, q_i) having a known time delay τ between them called tap-delay as shown in Fig. 1. The sampling period T_{sampling} between two successive sample pairs has no relation with the symbol period T_{symbol} and can be several orders of magnitude longer. Generating the two-dimensional (2D) histogram of sample pairs (p_i, q_i) produces an ADTP or scatter plot. Hence, an ADTP is essentially a joint probability distribution of closely-located samples or in other words, distribution of signal waveform's slopes (for small τ values). The characteristic features of an ADTP depend on the signal pulse shape, its rise and fall times, symbol period T_{symbol} and the τ value used. Hence, for a fixed τ, ADTPs contain distinctive signatures of the signals' bit-rates and modulation formats, which can thus be utilized for joint BR-MFI purposes.

3. Operating principle

The concept of proposed technique is illustrated in Fig. 2 where ADTPs for three modulation formats at two different bit-rates are shown. Since the signal pulse shape after direct detection depends on the type of modulation format and since the signal pulse duration and rise/fall times (and hence slopes) depend on the bit-rate, the ADTPs for various modulation formats and bit-rates of the signals are unique for a given tap-delay, as obvious from first column of Fig. 2. In the presence of different link impairments for e.g. amplifier noise, CD, PMD etc., the signal pulses are distorted where the extent of distortion depends on the symbol rate as well as on the modulation format of the signal. Consequently, the features of ADTPs are also modified accordingly. However, ADTPs corresponding to different bit-rates and modulation formats of the signals still remain distinguishable as clear from second column of Fig. 2. The bit-rate and modulation format dependent features of ADTPs can thus be exploited for joint BR-MFI by employing the statistical pattern recognition techniques such as ANN-based classification methods.

Fig. 3 depicts various phases of the proposed ANN-based joint BR-MFI technique. In this method, we represent ADTPs (which are essentially 2D histograms having $A \times A$ bins) by $M \times 1$ vectors x (where $M = A^2$). Hence, the elements of vectors x represent the number of occurrences of sample pairs (p_i, q_i) in various bins of ADTPs, starting from the top-left corner. Similarly, for each ADTP, another $N \times 1$ binary vector y is also obtained. The vector y has only one non-zero element whose location i.e. argmax{y} signifies the actual bit-rate and modulation format of the signal. During the training phase of an ANN, numerous (x, y) vector pairs are presented to the ANN, as shown in Fig. 4, and its various parameters are optimized such that the analogue ANN output v can approach y. This is achieved when the mean-square-error (MSE) defined as $\|v - y\|^2$ is minimized for the training data set. During the ANN training phase, a validation process is also carried out to prevent

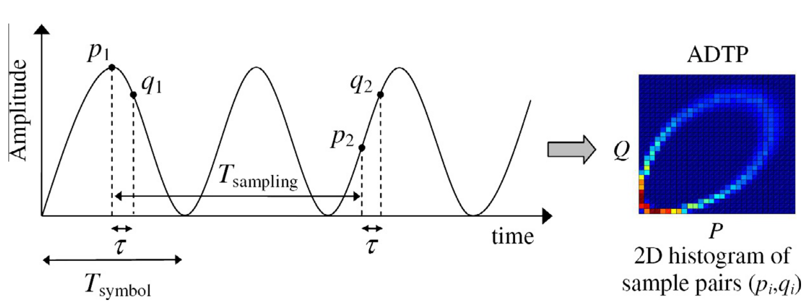

Fig. 1. Conceptual diagram of ADTS with tap-delay τ and sampling period T_{sampling}.

Please cite this article in press as: F.N. Khan et al., Non-data-aided joint bit-rate and modulation format identification for next-generation heterogeneous optical networks, Opt. Fiber Technol. (2014), http://dx.doi.org/10.1016/j.yofte.2013.12.001