Signal Processing for Optical Communication System Assisted by Computer Vision Techniques

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***Abstract*—We review the recent progress on the application of image processing techniques to optical communication systems. The focus is placed mainly on the implementation complexity and performance of the techniques for optical performance monitoring and the compensation of common phase error. We also briefly introduce several applications where machine learning algorithms could be beneficial to fiber-optic transmission system.**

Keywords-digital signal processing; image processing; optical communications

I. INTRODUCTION

Digital signal processing (DSP) is one of the key enabling techniques in modern optical communication systems. It is not only used for the modulation and demodulation of high-speed optical signals, but also employed for the compensation of linear and nonlinear impairments of fiber-optic transmission system. As DSP modules are becoming essential parts of commercial optical transceivers, the research interest has evolved into finding advanced DSP technology to support elastic and intelligent optical network, and to lower the cost and power consumption of the current DSP technologies. [1]

Recently, there have been substantial efforts to apply the image processing techniques to optical communication systems [3-18]. Some examples are optical performance monitoring, blind identification of modulation format, and the compensation of fiber nonlinearities [16]. In these applications, excellent performance has been demonstrated by using the machine-learning algorithm, which is one of powerful tools for image processing in the area of computer vision. Here, it is worth noting that the image processing techniques should not be regarded as 'more advanced' than the conventional DSP techniques, but they might be understood as new viewpoints on the classical problems for the possibility of reducing the implementation complexity and/or power consumption. Meanwhile, we believe that it is indispensable for the image processing techniques to be compatible with current DSP structures implemented by using the state-of-the-art circuits and CMOS process when being migrated into optical communication systems.

In this paper, we review the current progress on the use of image processing techniques for optical communication systems. In particular, we focus on the techniques that facilitates the optical performance monitoring and compensation of common phase error (CPE) in optical communication systems. These techniques have long been developed for computer vision, and could be implemented in cost-effective and efficient manners. We show that they can reduce the implementation complexity, while achieving comparable performance to the conventional DSP algorithms. Besides, we briefly review other interesting image processing techniques which can be applied to fiber-optic communication systems.

II. IMAGE PROCESSING TECHNIQUES FOR OPTICAL PERFORMANCE MONITORING

The architecture of optical networks are becoming more complicated, transparent and dynamic inherently along with the continuously increased capacity of optical communication systems. Hence, modern optical performance monitoring is highly indispensable for providing the reference information for the control plane in an elastic optical network [2]. Here, we focus on current progress based on using image processing techniques to recognize the modulation format, which proposes to be a key feature in future cognitive transceivers.

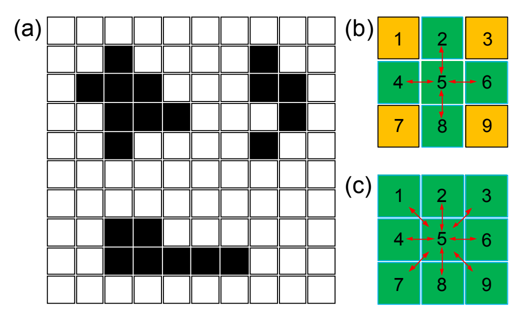

Figure 1. (a) An example of binary image with connected components; (b) 4-connectivity; (c) 8-connectivity.

The connected component analysis (CCA) is the essential enabling technique used for image processing. This technique facilitates the detection of the connected regions in a binary image, and it is usually integrated into an image recognition system. Fig. 1(a) shows a binary image with three connected areas. In general, there are two types of definition of connectivity specified for different applications, namely 4-connectivity and 8-connectivity. The difference between them is the number of neighbors that are treated as "connected". For example, under the 4-connectivity definition, there are two connected area in the upright corner

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of Fig. 1(a), while only one connected area will be counted under the 8-connectivity definition. In the subsequent CCA-based modulation format recognition algorithm, 8-connectivity is employed to have better tolerance against noise.

In optical communication system, we propose to use this CCA-based technique for recognizing the modulation formats blindly [3]. In the Stokes space, the polarization-multiplexed signals have unique patterns of symbol distribution for each modulation format. Thus, the number of clusters can be a simple but unique metric to distinguish between modulation formats.

Traditional solution treats this as a clustering problem, and the famous K-means clustering algorithm is utilized to count the number of clusters in the three dimensional (3-D) space [4]. However, this algorithm handles the data set in 3-D space, and thus it usually takes tens of iterations to obtain the convergence result. Alternatively, given the image from projecting the 3-D distribution into 2-D planes, non-iterative connected component analysis can achieve similar performance in terms of successful recognition rate, after a series of pre-processing techniques that are comprised of density-based filtering, converting data into binary image, and average-smoothing [5]. A brief block diagram of the pre-processing techniques is shown in Fig. 2. The CCA will output the number of connected areas, which is employed as the input for the subsequent recognition algorithm. Compared with the K-means based clustering algorithms, the computation complexity can be significantly reduced by using the CCA-based algorithm. Here, CCA is performed within a binary image, thus the computational complexity of CCA itself is very low. In addition, the binary image does not exhaust much memory, and thus can reduce the resources required in implementation [5]. This provides the feasibility of applying more processing in the image to secure a higher successful recognition rate. As proposed in [6], the symmetry of square constellation diagram enables the quadrature rotation and superposition of the binary image to compensate for the missing of certain constellation points, thus making the recognition more robust to noise and limited number of samples with negligible increase in complexity.

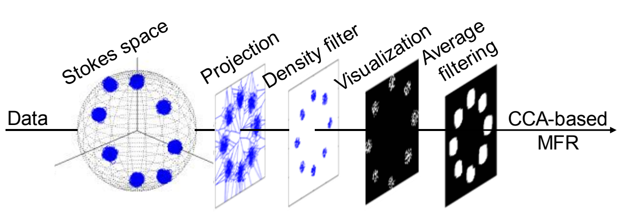

Figure 2. Procedures of the CCA-based modulation format recognition for a polarization-multiplexed 8-PSK signal.

III. Image Processing Techniques for the Estimation of Common Phase Error

The bounding box is also a popular tool in image processing. It is usually defined as the minimum rectangle in the horizontal and vertical direction (axis-aligned) or in any direction (best-fit) that covers all the pixels of the graph, as illustrated in the inset of Fig. 3. It is widely used in the correction of a skewed image and object locating in computer vision. In optical communications, such a bounding box can be employed to correct the CPE in coherent optical orthogonal frequency-division multiplexing systems (OFDM) systems. Due to laser's phase noise and relatively long duration of OFDM symbol, all subcarriers in each symbol suffer from a common phase rotation, which is known as CPE. Conventionally, CPE is corrected by inserting several pilot subcarriers in each OFDM symbol, but it reduces the spectral efficiency. From computer vision's point of view, the common constellation rotation among a certain number of subcarriers that are modulated by data with square constellation shape can be modeled as an image-skewing problem. A typical solution is to find the bounding box of this 'image' and correct its skew angle.

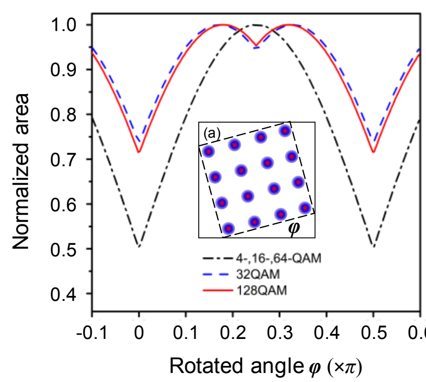

Figure 3. Normalied area as a function of the rotated angle. Inset (a): axis-aligned bounding box (solid line) and best-fit bounding box (dashed line).

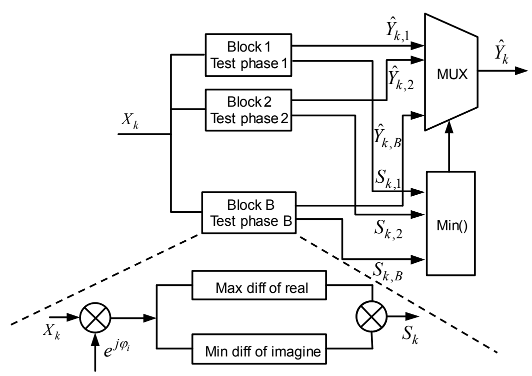

Figure 4. Block diagram of the axix-aligned bounding box algorithm. *X* is the input symbol, *Y* is the output symbol, and *B* is the number of test phases.

In [7], we proposed to correct the CPE by minimizing the area of the axis-aligned bounding boxes of the constellation diagrams generated by the data in each OFDM symbol. The basic principle of the proposed method is that the area of the axis-aligned bounding box of a square or quasi-square constellation diagram is a function of the skewed angle, and the minimum area is obtained when the skew is fully compensated. The dependency of skewed angles on the area of bounding boxes can be clearly seen in Fig. 3. Hence, a

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block-wise, feedforward phase searching method is used to estimate and correct the CPE in each frame, as illustrated in Fig. 4. Detailed experimental investigation and computational complexity analysis can be found in [8]. Compared with the conventional pilot-aided method, the bounding box methods have a comparable compensation performance, but a better spectral efficiency.

However, there are two drawbacks of the aforementioned axis-aligned bounding box based algorithm: (1) the accuracy of phase estimation is limited by the resolution of phase rotation; (2) rotating all points is a waste of computation resources as not all the constellation points contribute to the skew correction. These two problems can be solved simultaneously by employing the convex-hull-based best-fit bounding box algorithm [9]. Only the points on the convex hull of the constellation diagram are involved in the calculation and this method is free of the resolution limit. The additional complexity comes from the calculation of the convex hull, but fortunately there are several hardware-efficient algorithms developed for computer vision to alleviate this issue. Analysis shows the overall complexity is lower than the previously proposed bounding-box based algorithm, which makes room for using edge de-noising technique [9] to improve the performance further.

In additional to the CPE estimation algorithms based on bounding box, a recently proposed CPE estimation method utilizes the projected histogram of the constellation diagram [10] as a cost function, which can be traced to the skew estimation method based on projected histogram in computer vision as well. Besides, the bounding box of a constellation also finds its application in the channel estimation in OFDM system [11].

IV. Other Applications

Machine learning is a revolutionary technique to solve the traditional image processing problems such as pattern and face recognition in computer vision. It has also found broad applications beyond vision area and achieved great success in both research and engineering. In optical communication system, it has been demonstrated in various applications such as optical performance monitoring [12], signal equalization [13], optical sensing [14], and optical networking [15]. It shows either comparable or superior performance in comparison with the traditional approached. A comprehensive review about the machine leaning technique for optical communication can be found in [16].

Machine learning techniques are inherently suitable to predict the response of an intractable system such as highly complicated modern optical networks. However, these techniques should be justified in terms of complexity, power consumption and processing speed when they are applied to optical communications and networks. Until now, it is still questionable whether the current machine learning algorithms are beneficial to the signal processing in high-speed optical transmissions.

There are two additional interesting approaches utilizing images to aid the optical transmission system. In [17], the end-view images of optical connectors are processed to find the misaligned rotation angle of two segments of multi-core fiber. Besides, the image from the radiation pattern variations has recently been proposed to estimate the insertion loss in field-terminated connectors [18]. They are more engineering-oriented work thus we will not discuss them in depth here.

V. Summary

We have examined the applications of image processing techniques to enhance the digital signal processing in optical transmission systems. Their performance is comparable to the conventional digital signal processing algorithms, but their implementation complexity could be reduced significantly.

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