Biploar Optical Labeling with Spectral Amplitude Coding Scheme for Packet Switching over GMPLS Network

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***Abstract*—Generalized multi-protocol label switching (GMPLS) is a promising technique to implement all-optical core networks. In this paper, we propose a new optical code labeling (OCL) based on optical code- division multiple access (OCDMA) techniques for packet switching. To improve the efficiency of label-recognition and network throughput, bipolar label coding is employed in the proposed scheme. Label switching capabilities in packet loss probability (PLP) is greatly enhanced since our proposal enlarges the Hamming distance of the star diagram of the decoded label signals. The proposed label mapping mechanism is achieved through spectral amplitude coding (SAC) in the physical layer. In performance analysis, we present a numerical simulation of PLP to quantify the switching efficiency. Results show the proposed bipolar coding technique reduces PLP in switching process, resulting in an extension of label switching path (LSP) in GMPLS core network.**

Keywords-generalized multi-protocol label switching (GMPLS); optical code labeling (OCL); spectral amplitude coding (SAC); optical code-division multiple access (OCDMA).

I. INTRODUCTION

From its combination with the existing Internet Protocol (IP) layer and the control paradigm over multiple routing domains, one can realize the maturity in Generalized Multi-Protocol Label Switching (GMPLS) in practical application and deployment [1]. After being standardized by Internet Engineering Task Force (IETF), great effort in investigating the inter-operable GMPLS network has been taken by numerous researchers. Much attention to GMPLS protocols comes from the integration across network layers [2]. This advantage is a fundamental principle of designing a reliable system and reduces the complexity in network control for operators.

Optical Code Labeling (OCL), mapping the packet address onto the label through optically encoding, is proposed as a labeling procedure in GMPLS networks [3]. This labeling scheme is modified from a multiplexing technique known as Optical Code-Division Multiple Access (OCDMA). Optical code is used as a label to switch different data flows to the desired path without Optical-to-Electrical (O/E) conversion [4]. Spectral Amplitude Coding (SAC) system has a cost-effective de/encoder due to the rapid development of filter components [5], such as Array Waveguide Grating (AWG) and Fiber Bragged Grating (FBG). Furthermore, the code chips are encoded on the spectrum slices, without compressing the time waveform. The electronic devices in the codec could operate at a low speed of bit-rate instead of high chip-rate. Meanwhile, coded signals from different users can be transmitted over the same wavelength band without the impact of Multiple Access Interference (MAI). From above reasons, we adapt the SAC codec for the label generating and processing units in GMPLS network.

In this paper, we modify the node structure in GMPLS so that it could fit for the proposed bipolar OCL. With the moderate complexity of node architecture, label space is enlarged while keeping the short processing time. Compared to On-Off Keying (OOK), the packet is switched in a more secure environment since label of each packet is represented by one of two distinct codes, according to the payload bit [6]. Another advantage of bipolar OCL is a higher measured Signal-to-Noise Ratio (SNR) at the decoder end, due to the larger Hamming distance between levels of bit “0” and “1”. Therefore, the system performance has a huge advance in Packet Loss Probability (PLP), achieving a longer transmission distance in Label Switching Path (LSP).

This paper is divided into five main sections. Section I provides some background information about GMPLS network and the label generating and processing schemes for packet switching. Section II outline the design of the proposed bipolar OCL scheme in GMPLS network. Section III describes the architecture of Edge Node (EN) and Core Node (CN) with the function of bipolar OCL. Sections IV presents the system performance analysis and shows the improving results of PLP. Finally, section V draws the conclusion.

II. BIPOLAR OCL SCHEME IN GMPLS NETWORKS

We present an edge-core-edge transmission in GMPLS network with the proposed labeling scheme. Hadamard codes are used as optical labels for the network, to achieve all optical switching by constructing the code switching layer among network nodes. Hadamard codes, obtained by selecting the rows of Hadamard matrix as code vectors, were originally used for Two-Code Keying (TCK) in SAC-OCDMA systems to enhance system performance [7]. In that scheme, user sends Hadamard code vector $\boldsymbol{C_m}$ for data bit "1" and its complement $\overline{\boldsymbol{C}}_{\boldsymbol{m}}$ for bit "0". The correlation properties of Hadamard codes are [7]:

$$\boldsymbol{C_m} \odot \boldsymbol{C_n} = \begin{cases} N/2, & m = n \\ N/4, & m \neq n \end{cases} \quad (1)$$

$$\boldsymbol{C_m} \odot \overline{\boldsymbol{C}}_{\boldsymbol{n}} = \begin{cases} 0, & m = n \\ N/4, & m \neq n \end{cases} \quad (2)$$

where the symbol $\odot$ is the dot-product operator and N is the code length. Based on the following two properties, Hadamard codes can be adapted for TCK without the MAI by performing the correlation subtractions:

$$\boldsymbol{C_m} \odot \boldsymbol{C_n} - \boldsymbol{C_m} \odot \overline{\boldsymbol{C}}_{\boldsymbol{n}} = \begin{cases} N/2, & m = n \\ 0, & m \neq n \end{cases} \quad (3)$$

$$\overline{\boldsymbol{C}}_{\boldsymbol{m}} \odot \boldsymbol{C_n} - \overline{\boldsymbol{C}}_{\boldsymbol{m}} \odot \overline{\boldsymbol{C}}_{\boldsymbol{n}} = \begin{cases} -N/2, & m = n \\ 0, & m \neq n \end{cases} \quad (4)$$

Adapting bipolar OCL for packet switching increases the efficiency of packet processing, with a moderate degree of complexity at CN. To append optical labels on a packet, edge node (EN) performs label mapping and generating. Each path connected between nodes is assigned two code labels, a Hadamard code, and its complement, as shown in Fig. 1. For instance, the path between CN1 and CN2 corresponds to code $\boldsymbol{C_1}$ and $\overline{\boldsymbol{C}}_{\boldsymbol{1}}$. The reason for this assignment is to support bipolar OCL, as well as to expand the label space. Figure 1 also shows the demonstration of label stacking. The data flow along LSP of (CN1-CN2-CN3) is switched by CNs according to the two-level label, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$. Edge node EN1 performs the integration of distinct code labels before the packet traffics the node-to-node path.

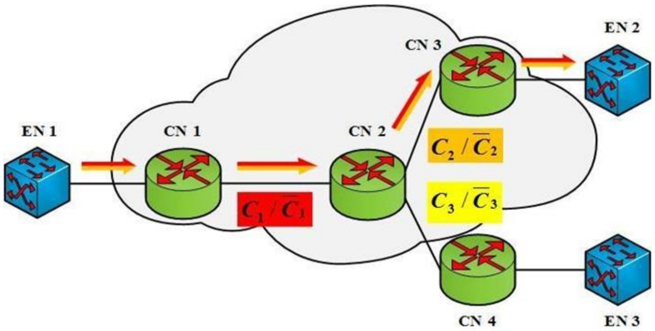


Figure 1. Node-to-node transmission in GMPLS with bipolar OCL.

The LSP in Fig. 1 includes two path segments of codes $\boldsymbol{C_1}/\overline{\boldsymbol{C}}_{\boldsymbol{1}}$ and $\boldsymbol{C_2}/\overline{\boldsymbol{C}}_{\boldsymbol{2}}$. Table I illustrates the bipolar OCL scheme with Hadamard coded label of length 4. For payload bit "1", $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$, matching wavelength bins of (λ_1, 0, λ_3, 0) and (λ_1, λ_2, 0, 0) are selected. On the other hand, for the case of bit "0", the edge node transmits $\overline{\boldsymbol{C}}_{\boldsymbol{1}}$ = (0, λ_2, 0, λ_4) and $\overline{\boldsymbol{C}}_{\boldsymbol{2}}$ = (0, 0, λ_3, λ_4) to the network. Since all labels are spectrally coded on the same wavelength band λ_1~λ_4, the combined signal is the summation of the coded spectrum, $\boldsymbol{S_1}$ = (2 λ_1, λ_2, λ_3, 0) for bit "1" and $\boldsymbol{S_0}$ = (0, λ_2, λ_3, 2λ_4) for bit "0". Table II shows the packet switching process at CN1 and CN2. The label summation of $\boldsymbol{S}$ is correlated with $\boldsymbol{C_1}$ and $\overline{\boldsymbol{C}}_{\boldsymbol{1}}$, indicating the path between CN1 and CN2. The result of correlation subtraction for bit "1" is 2-unit power, and CN1 establishes a link to CN2 as a part of LSP. At CN2, the correlated results for bit "1" with $\boldsymbol{C_2}$ and $\boldsymbol{C_3}$ are 2 and 0-unit power, respectively. Thus, CN2 switches the packet to CN3 along the path matching $\boldsymbol{C_2}$. Note that for bit "0," the CN does not set up any connection due to the negative correlation value, and the packet is blocked for a bit interval.

TABLE I. BIPOLAR LABEL STACKIGN FOR LSP OF CN1-CN2-CN3.

Path Segment	**Hadamard Code Vector**	**Spectral Label for Bit "1"**	**Spectral Label for Bit "0"**
CN1-CN2	$\boldsymbol{C_1}$= (1,0,1,0)	(λ_1, 0, λ_3, 0)	(0,λ_2, 0, λ_4)
CN2-CN3	$\boldsymbol{C_1}$= (1,1,0,0)	(λ_1, λ_2, 0, 0)	(0, 0, λ_3,λ_4)
CN2-CN4	$\boldsymbol{C_1}$= (1,0,0,1)	(0, 0, 0, 0)	(0, 0, 0, 0)
Summed Label Stack		(2 λ_1,λ_2,λ_3,0)	(0, λ_2, λ_3, 2λ_4)

TABLE II. PACKET SWITCHING PROCESSES AT CN1 AND CN2.

<table>
<tr><th>Node No.</th><th>Correlation Subtraction for Bit "1"</th><th>Correlation Subtraction for Bit "0"</th></tr>
<tr><td>CN1</td><td>$\boldsymbol{S_1} \odot \boldsymbol{C_1} - \boldsymbol{S_1} \odot \overline{\boldsymbol{C}}_{\boldsymbol{1}}$
=| (2,0,1,0) | - | (0,1,0,0) |
= 2</td><td>$\boldsymbol{S_0} \odot \boldsymbol{C_1} - \boldsymbol{S_0} \odot \overline{\boldsymbol{C}}_{\boldsymbol{1}}$
=| (0,0,1,0) | - | (0,1,0,2) |
= -2</td></tr>
<tr><td rowspan="2">CN2</td><td>$\boldsymbol{S_1} \odot \boldsymbol{C_2} - \boldsymbol{S_1} \odot \overline{\boldsymbol{C}}_{\boldsymbol{2}}$
=| (2,1,0,0) | - | (0,0,1,0) |
= 2</td><td>$\boldsymbol{S_0} \odot \boldsymbol{C_2} - \boldsymbol{S_0} \odot \overline{\boldsymbol{C}}_{\boldsymbol{2}}$
=| (0,1,0,0) | - | (0,0,1,2) |
= -2</td></tr>
<tr><td>$\boldsymbol{S_1} \odot \boldsymbol{C_3} - \boldsymbol{S_1} \odot \overline{\boldsymbol{C}}_{\boldsymbol{3}}$
=| (2,0,0,0) | - | (0,1,1,0) |
= 0</td><td>$\boldsymbol{S_0} \odot \boldsymbol{C_2} - \boldsymbol{S_0} \odot \overline{\boldsymbol{C}}_{\boldsymbol{2}}$
=| (0,0,0,2) | - | (0,1,1,0) |
= 0</td></tr>
</table>

III. DESCRIPTION OF NODE STRUCTURE WITH BCL FUNCTION

To make fully switching, there are *N* pieces of encoders for bipolar OCL in an EN, where *N* is the total path number in the network, as shown in Fig. 2. Broadband Light Source (BLS), which connects to an optical switch, is used as the encoder's input. The header processor sets up the connection between BLS and OCL encoder by firstly analyzing packet destination and deriving a specific LSP. Then, a control signal closes the switches linking to the corresponding label generators. Each OCL unit has two outputs: spectrally Hadamard coded signal C_m and its complement. The outputs of optical codes and their complementary codes from different encoders are combined respectively by power combiners. An optical switch selects the one of the two summed signals based on data bit "0" or "1". The chosen one is further sent into a fiber.

CN executes the opposite decoding operation and switches packet to the proper path. In a CN, there are *M* pieces of OCL decoders similar to the encoders in edge node, where *M* is the number of output paths, as shown in Fig. 3. At first, a part of the incoming signal is split for label recognizing using a 1 by 2 power splitter. The tapped signal is distributed into different OCL decoders using a 1 by *M* power splitter. The outputs of decoders control the switching state of the *M* by *M* optical cross bar, which establishes a connection to the output path corresponding to the incoming label.

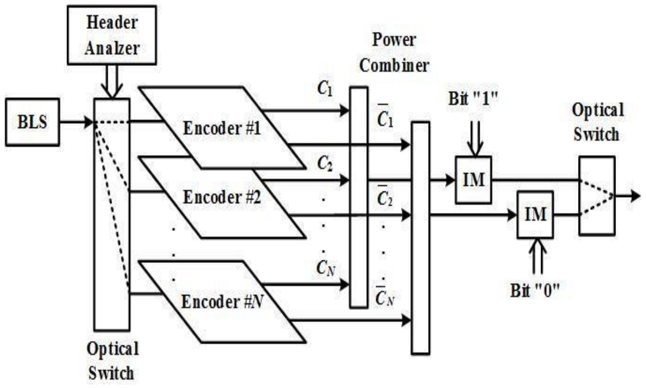


Figure 2. Architecture of EN with bipolar OCL.

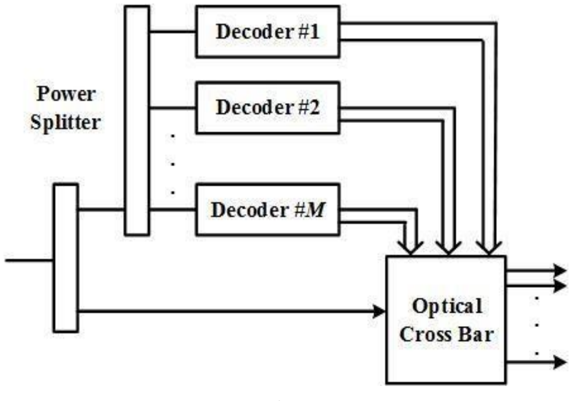
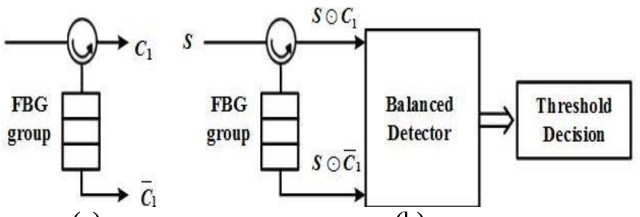


Figure 3. Architecture of CN with bipolar OCL.



(a) (b)

Figure 4. (a) FBG encoder for label generating; (b) FBG decoder for label recognizing.

Spectrally Hadamard-coded signal with length *N* and code weight *N*/2 is formed by a series of wavelength bins that match code chip "1" at the output of OCL encoder, as shown in Fig. 4(a). The coded label is generated from a group of *N*/2 copies of FBGs in the encoder. To transfer payload bit "1" or "0" into wavelength bins, the FBG-based encoder performs optical encoding by reflecting and transmitting wavelength bins. The FBG-based decoder, as shown in Fig. 4(b), rejects other uncorrelated labels or MAI and makes sure that the correlated one can be successfully recovered to the original data bit. Following the decoder is a balanced detector (BD), which outputs zero power if the summed signals do not include the matching label. To determine the initial payload bit, a quantizer restores the signals by threshold decision.

IV. PERFORMANCE ANALYSIS AND SIMULATION RESULT

In order to express the switching benefit of the proposed OCL, SNR shown at the label decoder is analyzed to quantify the system performance. We use the assumption for BLS characteristics and the mathematical deduction [8] to firstly derive the photocurrent, which is expressed as

$$I = RP_{\mathrm{sr}} / 2 \tag{5}$$

where P_{sr} is the received power at decoder and *R* is the responsivity of the photo-diode in the BD. Phase intensity noise and thermal noise are main degrading factor of SAC systems [9]. This paper only considers Phase Intensity Induced Noise (PIIN) since it is the dominant noise when optical signal is converted to electrical domain. The variance of PIIN is denoted as

$$\sigma^2 = R^2 P_{\mathrm{sr}}^2 BK(K+1) / 2v \tag{6}$$

where *B* is the electrical noise bandwidth, *v* is the spectral width of BLS and *K* is the number of stacked labels. By using Gaussian approximation, the PLPs of bipolar and unipolar label, $\mathrm{PLP_b}$ and $\mathrm{PLP_a}$ are expressed as:

$$\mathrm{PLP_b} = \frac{1}{\sqrt{2\pi}\sigma}\left\{\frac{1}{2}\int_{-\infty}^{0}\exp\left[\frac{-(x-I)^2}{2\sigma^2}\right]dx + \frac{1}{2}\int_{0}^{\infty}\exp\left[\frac{-(x+I)^2}{2\sigma^2}\right]dx\right\} \tag{7}$$

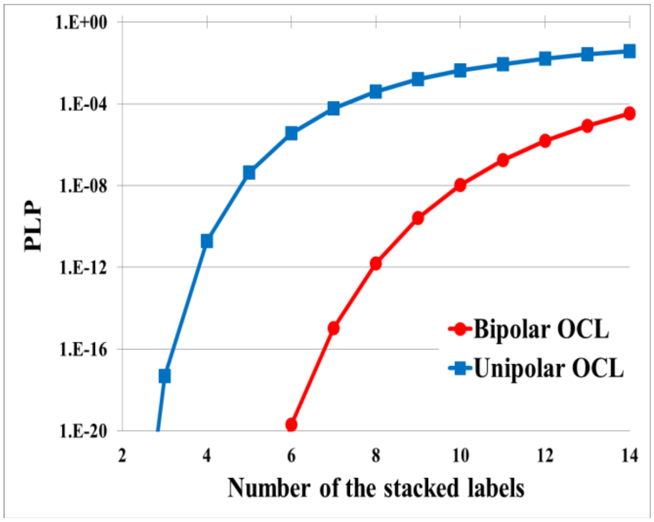


Figure 5. PLP comparison for the proposed bipolar OCL and the conventional unipolar OCL.

$$\mathrm{PLP}_{\mathrm{a}} = \frac{1}{\sqrt{2\pi}\sigma}\frac{1}{2}\int_{-\infty}^{I/2}\exp\left[\frac{-(x-I)^2}{2\sigma^2}\right]dx \tag{8}$$

The spectral width of BLS is 4.5THz and the electrical noise bandwidth is 10GHz. We use the Hadamard coded labels of *N* = 16 for simulation. In Fig. 5, packet with the proposed label performs better PLP than the one with the unipolar label. Under small number of the stacked labels, both types have relatively good results keeping the PLP under 10^{-9}. However, PIIN increasing with the label number degrades the system performance, when the number of stacked labels is large. For the bipolar label code, despite a larger PIIN variance, it still has a higher SNR value due to the doubled signal power. The stacked label number for bipolar OCL is 2 times of the other under PLP = 10^{-9}. This implies more labels can be attached to a single packet, resulting in an extension of LSP.

V. CONCLUSIONS

In this paper, we propose a bipolar OCL scheme in GMPLS network that enhances the switching efficiency by enlarging Hamming distance on the star diagram of the decoded labels. Reducing the PLP during label-recognizing procedure is a critical issue in GMPLS since it increases the distance of LSP in all-optical switching. The bipolar labeling is implemented based on the correlation and orthogonal properties of Hadamard codes. We adapt the FBG-based codec of OCDMA technique for modifying the node structure. A numerical simulation is conducted for the proposed scheming, proving the stacked label number is increased by utilizing the proposed bipolar label.

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