Label Coding Techniques for All-Optical MPLS Networks

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Abstract: In this paper, a short overview and comparison of label coding techniques is given. Particularly, different all-optical label processor implementations based upon optical code correlation are shown and investigated. The code families suitable for the all-optical MPLS are compared concerning the correlation properties and provided label lengths. The optical code label processor implementations are investigated by means of numerical simulations and relating to the supported label lengths and permitted node-interconnection distances.

1 Introduction

Future networks should carry several types of traffic in a dynamical manner. Predominantly, optical networks could provide sufficiently high bandwidth for future bandwidth-intensive applications. In particular, label switching has been pointed out as an effective and promising technique, which should move toward the goal of a dynamical, high-capacity optical network with capability to carry heterogeneous network traffic and provide several quality-of-service (QoS) classes.

Recently, several implementations of photonic label switching techniques have been proposed [1 - 5]. The first one is an Internet Draft [1] that concentrates on the multi-protocol lambda switching (MPλS) approach, which combines multi-protocol label switching (MPLS) traffic engineering control with optical crossconnects. In MPλS networks, wavelength paths in a WDM physical network are established using WDM links (lightpaths) and optical cross-connect (OXC) nodes according to upper layer protocols (e.g. IP). In an interconnecting fiber, a wavelength is identified as a label by an OXC. Thereby, number of wavelengths limits the scalability and granularity of an MPλS network. In order to solve the granularity problem and make possible much larger networks, electrical nodes incorporating SDH mapping and IP routing functionalities are needed.

Photonic packet switching [2 - 8] provides a finer granularity and much better scalability, thereby allowing high-speed switching and forwarding without the need for O/E conversion. In an all-optical MPLS network, labels are attached to each data packet. Consequently, switching in the optical layer can be performed in both the wavelength and time/space domain. Moreover, very large networks are possible by choosing large enough labels. An example of a core label-switched router (LSR) incorporating photonic label switching without wavelength conversion is shown in Fig. 1. As it can be seen from this figure, the wavelengths λ_1 to λ_M are separated at the input ports using WDM demultiplexers and then forwarded to the output ports on a packet-by-packet basis by *M* photonic label-switched routers (PLSR). An incoming packet on a particular wavelength can be forwarded to each output fiber depending on the packet's label.

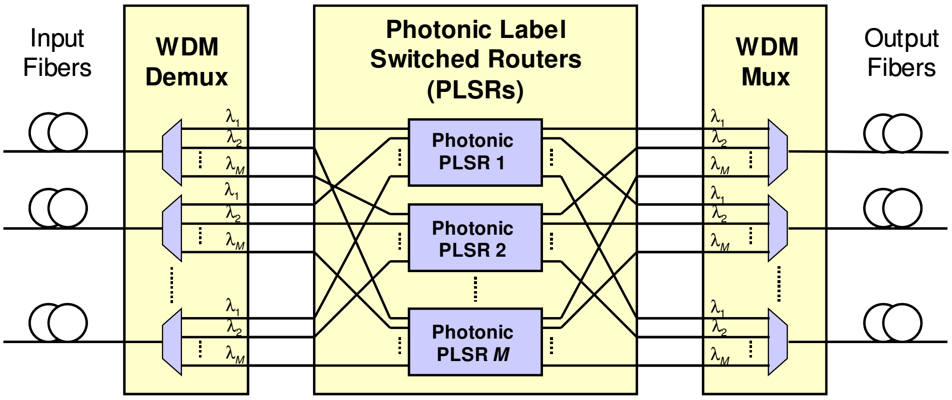

Figure 1: WDM core photonic label-switched node

PLSR consists of an all-optical label processor, a label swapper and a photonic switch fabric (Fig. 2). The labels are first extracted from the incoming packets and processed by the label processor. The photonic switch fabric is set to the appropriate state by the switch control unit, while the new label is generated corresponding to the label-swapping forwarding algorithm (LSFA) and added to the outgoing data packet. The adding of new labels can occur either before or after the switch fabric. In Fig. 2, both label swapping and writing are performed before the switch fabric because the switch can only be set after the LSFA is performed. Note that the photonic switch fabric should also be equipped with optical buffers to avoid packet collisions at the output ports.

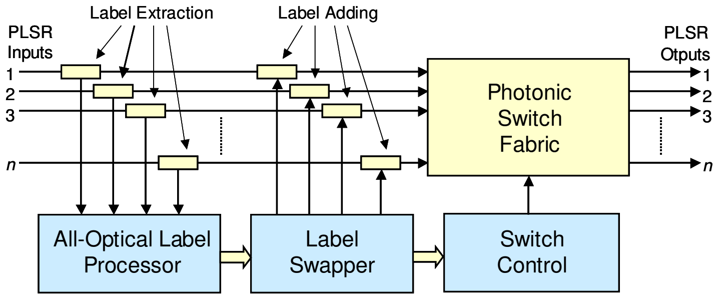

Figure 2: Photonic label-switched router (PLSR) architecture

The implementation of the label processor, thus the switching performance of a PLSR, depends heavily on the selected label coding technique. In the next Section, a short overview on label coding techniques is given.

2 Label Coding Techniques

There are several methods for coding the control information (header or label) on the optical medium in photonic packet-switched networks. In general, these methods can be classified in three basic categories (see Table 1) including *time-domain coding* (TDC), *frequency-domain coding* (FDC) and *code-domain coding* (CDC).

TDC is the most utilized method [5, 6, 7, 8], where the control information is transmitted on the same wavelength as the payload, thereby using the same modulation format (ASK) for both data and label. The label and the packet data are transmitted consecutively in a serial manner. *Optical pulse interval* (OPI) coding is structured in such a way that the data rates of the label and the payload section are the same. Alternatively, if the label is transmitted at a lower bit-rate than the payload, it is called *mixed rate* (MR) coding.

Implementation of the MR method is easier and cheaper than the OPI because the label-processing unit can be implemented in electronics. Moreover, optical transparency can also be achieved by the provision of bit-rate variable payloads and a label with fixed lower bit-rate. However, due to the low bit-rate of the label, the processing overhead and node latency are usually large. At high bit-rates, OPI can only be realized by employing all-optical signal processing. The implementation of an all-optical label processor in the time domain is still difficult and usually restricted in terms of supported label lengths. However, this technique can significantly reduce node latency and label processing time.

Label Coding Techniques								
FDC (Frequency-Domain Coding)			CDC (Code-Domain Coding)				TDC (Time-Domain Coding)	
SCM	MW	DW	Incoherent		Coherent		OPI	MR
			DS	OFH	Binar	Quadrature		

Table 1: Label Coding Techniques

In FDC, the control information is transmitted on a frequency band separate from the frequency on which the data are transmitted. Using the sub-carrier multiplexing (SCM) technique, the payload and the label are encoded as radio frequency (RF) sidebands on the optical carrier, each at a distinct sideband frequency [2]. In the network nodes, the label is separated from the packet by easily filtering the sidebands from the optical carrier. Then, the recovered control information can be processed electronically in the label-processing unit. However, the bit-rate of the data is limited by the sub-carrier frequency, thereby making this technique impractical in ultrahigh-speed photonic networks. In the multi-wavelength (MW) approach, control information is transmitted in a bit-parallel manner on N wavelengths. The time-skew between the parallel bits on different wavelengths caused by the group velocity dispersion (GVD) can seriously limit the achievable transmission distance in MW coding. Moreover, N transceivers have to be deployed at each node, thereby making the implementation expensive. Another approach is the serial MW coding, where the label pulses are transmitted on W separate wavelengths in a serial manner [3]. Both serial and parallel MW coding require a very large number of wavelengths (large bandwidth) for coding a label, thereby limiting the number of data-channels in the system. Dual wavelength (DW) coding is similar to the SCM approach, with the slight difference that instead of two RF sidebands, two separate wavelength channels are dedicated to carry of payload and control information. That is, the label is transmitted on a separate wavelength channel in parallel with the payload. Consequently, the label-processing overhead can be reduced even for a lower bit-rate of the label. A lower bit-rate implies an easier implementation of the label processor in electronics, thereby making the node realization cheaper.

CDC is well suitable for easy and fast all-optical detection of high-speed labels [4, 9]. The code sequences can be easily assigned to the labels in a label-switched network. Consequently, the label processing can be fully accomplished optically in an OCDM decoder only by the detection of the autocorrelation peak. In general, there are two types of CDC coding techniques, namely *incoherent* and *coherent* CDC. Incoherent techniques comprise *direct sequence* (DS) *coding* and *optical frequency hopping* (OFH). The first one uses the *on-off-keying* (OOK) pulse code sequences, where control information is coded in the time domain using sequences of short pulses called chips [10, 11]. The second one is a frequency or a time-frequency domain approach, where short-duration wide-band pulses are encoded/decoded using specially designed optical filters e.g. chirped moiré gratings [12] or a cascade of filters (an array of uniform FBGs) [13]. OFH-CDC uses unipolar codes, where the i-th pulse is coded in frequency domain according to a set of discrete frequencies $S = \{f_1, f_2, \ldots, f_q\}$ placed around the carrier frequency f_c:

$$f_j = h(j)\frac{B}{q}, \qquad j = 1,2,\ldots N; \qquad 1 \le h(j) \le q \,, \tag{1}$$

where B denotes the available frequency bandwidth, $h(j)$ is the placement operator and q represents the number of available frequencies.

Coherent CDC techniques provide a larger ratio of the central autocorrelation peak to the side lobes resulting in a better code detection [14]. Here, the control information is coded not only in time, magnitude or frequency but also the phase of the optical signal is modulated. If the phase is changed in discrete manner using two values ($\varphi = \pi$ or $\varphi = 0$), the coding is named *binary coherent* coding, while codes incorporating a change of carrier phase between four values ($\varphi = 0, \pi/2, 3\pi/2$ or π) are called *quadrature coherent* codes [15]. Note that in binary coherent CDC, the coherence length of the light source has to be greater than the chip length. Moreover, the difficulties associated with the coherent transmission have to be taken into account.

3 Optical Code Label Processor (OCLP)

In an OCLP, the control signals for the label swapper and switch control are generated depending on the label matching in the look-up table consisting of $m \times n$ OCDM decoders (all-optical code correlators). The all-optical CDM en-/decoder architectures that are investigated in this paper are shown in Fig. 3. The first one (a) is a parallel structure, which can be used as an incoherent DS correlator if the phase shifters are left out or as a coherent one when the optical gates are not deployed. The second architecture (b) is an all-serial structure, which requires a smaller number of optical components and has lower optical loss than the parallel structure. It is more suitable for implementation of 2^n codes and can also build both incoherent and coherent en-/decoders depending on whether phase shifters or optical gates are deployed. The third architecture (c) based on multiple bragg gratings is used for implementing the OFH correlators.

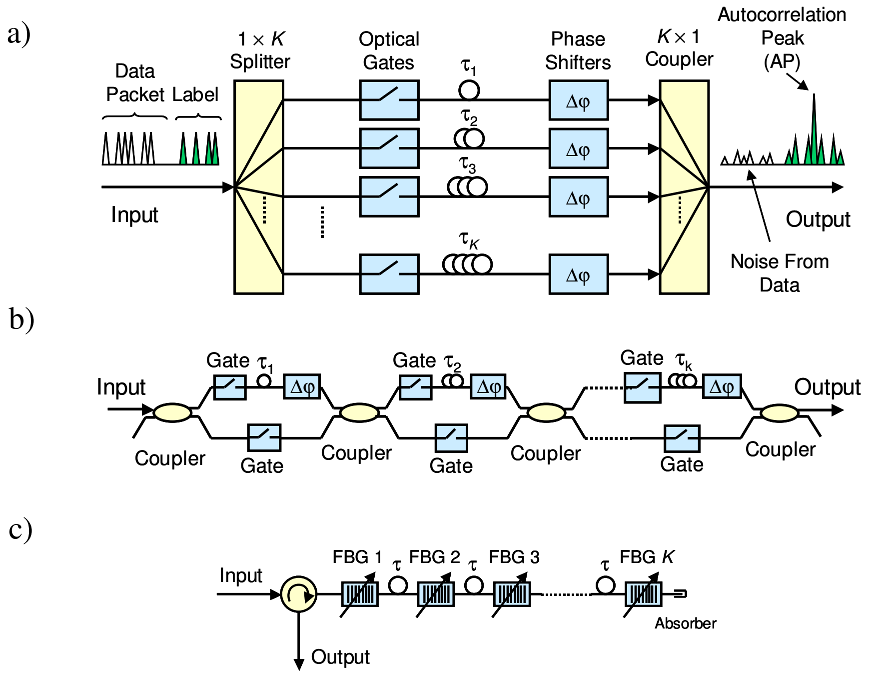

Figure 3: All-optical code correlator implementations

4 Comparison of OCLP Implementations

4.1 OCDM Code Selection

Generally, in OCDM systems, the users' codes should be chosen to satisfy the following conditions: first they should maximize the peak of the autocorrelation function, the second condition is to minimize the side lobes of the autocorrelation function, and finally, the cross-correlation function of each pair of code sequences should be minimized. The correlation function between two unipolar codes $c_X = [\ c_{x,1}\ ,\ c_{x,2}\ ,\ c_{x,3}\ ,\ldots,\ c_{x,N}]$ and $c_Y\ = [\ c_{y,1}\ ,\ c_{y,2}\ ,\ c_{y,3}\ ,\ldots,\ c_{y,N}]$, is:

$$R_{X,Y}(p) = \sum_{i=0}^{N} c_X(i) \cdot c_Y(i-p) \qquad ; \qquad -N+1 \le p \le N-1 \ , \tag{2}$$

where $c_{x,j}$, $c_{y,j} \in \{0,1\}$ and N denotes the code length. $R_{X,Y}$ represents the autocorrelation function if $c_X = c_Y$; otherwise $R_{X,Y}$ is the cross-correlation function.

In the detection of the optical CDC labels, the correlation process is not affected by the multiple-user interference (MUI) because only one label is transmitted on a particular wavelength at a particular time. Therefore, the effect of the MUI and thus the noise produced by MUI is not taken into account. Three parameters can be considered to compare the codes concerning the correlation properties and the number of supported labels (i. e. code cardinality). The first two parameters are defined as the differences between the autocorrelation peak (AP) and the maximum autocorrelation sidelobe (AS) as well as between AP and the maximum cross-correlation peak (CP). They reveal how precise the threshold has to be set for detecting a label in an asynchronous mode. The third parameter is the code cardinality that indicates how many labels can be supported in the network.

It is quite evident that the autocorrelation peak in an incoherent OCDM decoder employing unipolar codes is w, where w denotes the number of chips taking value "1", also called the code weight, while the maximum cross-correlation peak is $(w - 1)$. In a binary coherent CDC system, the optical correlation is performed coherently on condition that the light source has a coherence length greater than the pulse length. Here, the optical phase of the pulses is coded in a discrete manner (π or 0), thus the codes $c_{x,j}$, $c_{y,j} \in \{1, -1\}$ are bipolar codes and the number of chips set to "1" equals the code length (i.e. $w = N$). Because of $w = N$ and taking into account that the pulses are summed up coherently, the amplitude of the autocorrelation peak is now N^2 [16], while the maximum cross-correlation value is $(N-1)^2$.

In the past, various unipolar pseudo-orthogonal optical codes have been proposed and investigated [17]. An example of such a code is the *prime sequence code* family with a set of code sequences of length $N = p^2$, where p is a prime number also determining the number of allowed users. The autocorrelation peak of this code family is p, and the cross-correlation is 2. The drawback of the prime codes is low cardinality as well as the high max. autocorrelation sidelobe (AS), which can be as high as $(p - 1)$. The *extended quadratic congruence* (*eqc*) codes have much better AS value (AS = 1), but the code cardinality is very low (p-1). The prime/hop and *eqc/prime* codes are hybrid codes suitable for the OFH-CDC systems, which provides better correlation properties, thereby allowing much a larger set of labels. The coherent 4-ary codes proposed in [18] allow larger code cardinality than the hybrid codes as well as very good correlation characteristics. Fig. 4 shows a comparison of the codes mentioned above. It can be seen that the hybrid OFH codes (prime/hop and eqc/prime) and the coherent codes (PSAB) show better performance than incoherent prime and eqc codes because they provide better correlation properties and a larger number of supported labels.

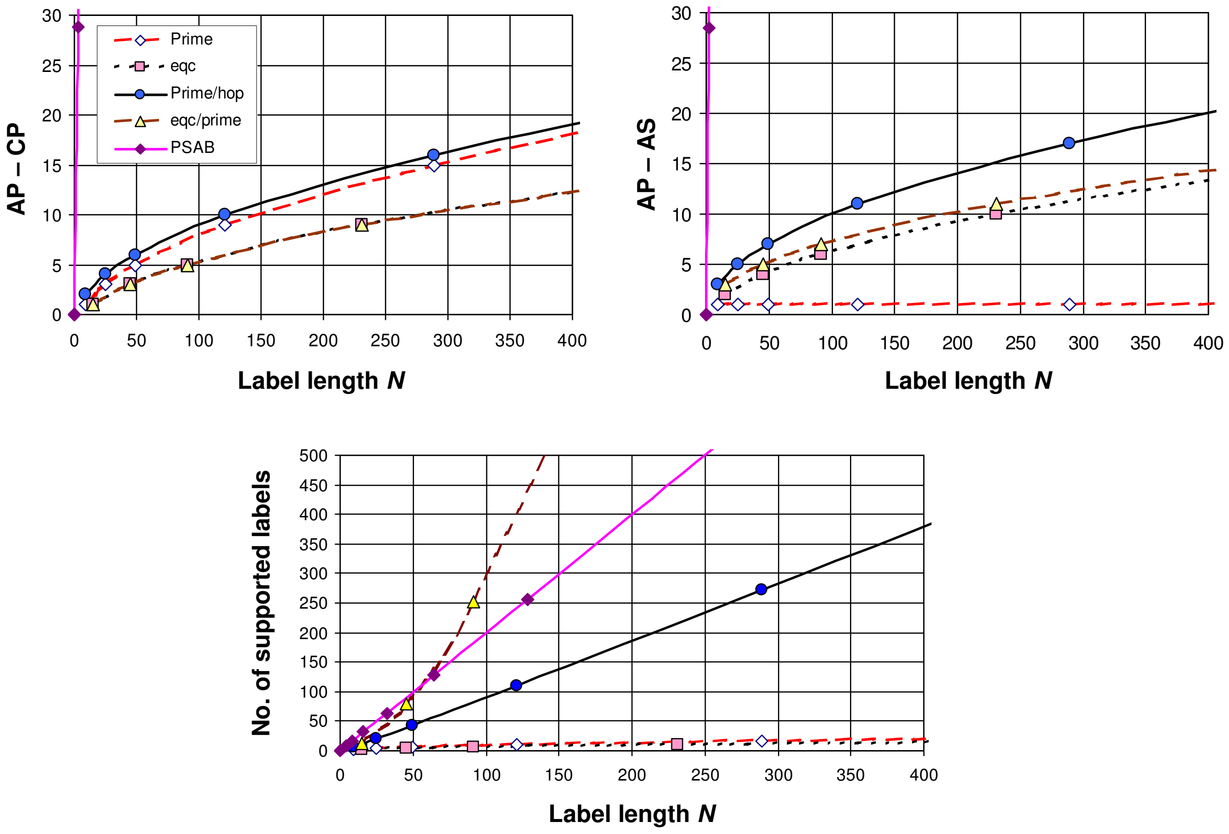

Figure 4: Comparison of several optical codes

4.2 Allowed transmission length

Numerical simulations are performed in order to investigate the allowed transmission length for coherent binary, incoherent DS and OFH correlators. For this purpose, 8-bit labels with a bit separation of τ = 12.5 ps are generated in an OCDM encoder using 4 ps wide pulses. The labels are attached to the 100 Gbit/s data packets and transmitted over a pre-compensated fiber span as shown in Fig. 5. Two OCDM decoders (one matched and one not-matched) are deployed in the receiving node to measure AP, CP and the noise due to the residual data at the output (see Fig. 3). Note that the label pairs used in the comparison have the worst AP to CP ratio.

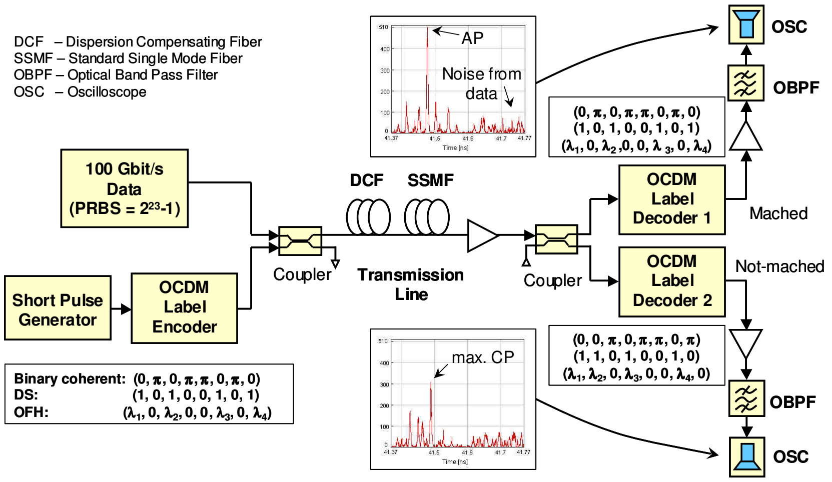

Figure 5: Simulation set-up

Fig. 5 shows the simulation results for three correlator implementations concerning the permitted transmission length. The label can be detected by setting an appropriate threshold value if both ratios AP to CP and AP to noise data are greater than 1. It can be seen that the binary coherent implementation shows the best performance in both cases. It allows label transmission with good correlation properties over a large dispersion-managed fiber span.

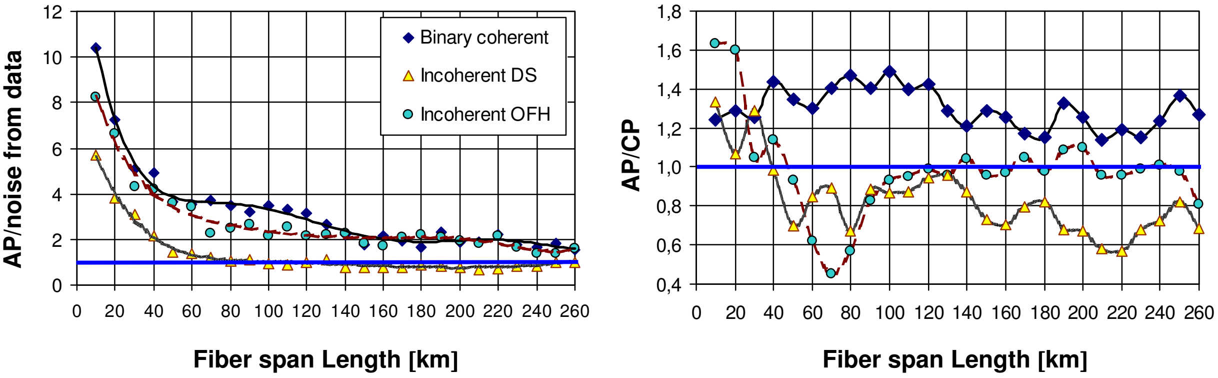

Figure 5: Allowed transmission length

5 Summary and Conclusions

Different optical code correlators that are candidates suitable for all-optical MPLS are investigated. Our simulation results show that the binary coherent all-optical correlator provides good correlation properties as well as data noise suppression even for larger transmission lengths. Thus, it can be concluded that the optical coherent codes are suitable for label coding in all-optical MPLS networks because they provide both the good correlation properties and a large set of supported labels for a given label length.

Acknowledgments

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