Analysis of an Optical Burst Switching Network with Code-Based Label Processing

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Abstract—In this paper an optical burst switching (OBS) architecture with optical orthogonal codes (OOC) label processing is analyzed. Just-enough-time (JET) signaling is considered as a higher performance option in relation to other protocols. We demonstrate that a decrease in burst loss probability and a gain in processing time are obtained when optical label processing is used as compared to conventional electronic processing. It is also demonstrated that bursts with short length that would be blocked with electronic processing will be transmitted with optical processing. These results suggest that bufferless optical processing may be used to increase network capacity and to upgrade OBS network performance, in a cost-effective solution.

Index Terms—Just-enough-time, optical orthogonal codes, optical burst switching.

I. INTRODUCTION

Internet protocol (IP) over wavelength-division multiplexing (WDM) is a promising framework to support the bandwidth and flexibility requirements of the next generation of networks. It is expected to reduce complexities and overheads associated with the asynchronous transfer mode (ATM) and synchronous optical network/synchronous digital hierarchy (SONET/SDH) layers [1]. In fact, the evolution of WDM optical network towards all-optical networks (AON), which eliminate the core optical-to-electrical-to-optical (OEO) conversion, allows for unprecedented transmissions rates. One kind of AON that has been intensively analyzed is optical burst switched (OBS) network [2]. In OBS networks, data packets with a common destination arriving at the same ingress node are aggregated into bursts, each being all-optically switched through the network. A header, which may be just a label or a separate control packet [3], precedes the burst payload transmission and attempts to reserve required switching and transmission resources at each output link port and node switch along the
route. The burst is sent with or without acknowledgement, according to the specific protocol being used.

Pioneering OBS proposals, such as just-enough-time (JET) and just-in-time (JIT) [3], operate without acknowledgement, i.e., one-way reservation. The common trend is the elimination of round-trip waiting time before the information is transmitted (the so-called tell-and-go approach). Thus, OBS networks combine the best of circuit and packet switching in the optical realm, because it has an intermediate granularity when compared to the circuit and packet switching network and could be implemented with mature technology [1][4][5]. Furthermore, conventional electronic processing of labels, due to opto-electric-optical conversions becomes limited in speed, and tends to become the main bottleneck as data bit rates go higher.

In order to increase network utilization and to overcome some limitations of OBS, studies have been done in techniques like optical buffering in fiber delay lines (FDL) [5], grooming [7], deflection routing [8], and burst assembly [9]. However, these approaches lack cost-effectiveness [6]. In another promising approach, optical label processing is proposed [10] to increase the speed of label processing and, as a consequence, to improve network utilization; in this case, labels are codified by phase and intensity, as coherent codes scheme [11]; these labels optically processed in the networks nodes, reducing the burst loss probability and increasing the network utilization by a factor as high as 2.5 (250%) [12]. We define here a network utilization gain as the ratio between burst loss probability using conventional electronic processing and burst loss probability using optical processing. Despite their performance gain, coherent codes present a high implementation complexity; therefore, from a practical perspective, the use of incoherent codes [4], which are codified only in intensity, becomes attractive because they could be implemented with the presently available optical technologies.

In this context, the present work analyzes the performance of an OBS network architecture that uses code labels based on incoherent codes, such as orthogonal optical codes (OOC) [14], with JET signalization [15]. The performance metric used here is based on burst loss probability, network utilization gain and optical buffer size requirements, considering both electronic and optical label processing. This paper is organized as follows. In Section II, the architecture of utilized OBS network is illustrated. In Section III, the methodology utilized to analyze the performance of proposed architecture is derived. In Section IV, the main results are presented and finally, in Section V the conclusions of this work are discussed.

II. NETWORK ARCHITECTURE

In the following topics some relevant characteristics of OBS networks will be presented, the architecture analyzed in this work will be explained and some details about the OOC codes will be discussed.

A. Optical Burst Switching (OBS)
In OBS networks, information data is collected in the input node and aggregated in bursts according to characteristics like destination, class of service (CoS) and quality of service (QoS), and client profiles [2][9]. The input nodes are responsible for establishing the connection mechanisms of signaling, routing and wavelength assignment [5]. Signaling is used to set up and tear down the reserved connection lightpaths. Routing is utilized to define the path of burst through the OBS network, whereas wavelength assignment (or allocation) determines which wavelength to transmit the burst. In the adopted JET signaling the time interval between the label and burst transmissions is the offset time. In fact, it has been demonstrated that JET and other predictive reservation schemes have a positive effect in decreasing the overall burst loss probability in comparison with others protocols [15][16][17]. In Fig. 1 the timing chart of resource reservation applying electronic processing of labels based on JET protocol is illustrated. It should be noted that the burst label is processed in every node of OBS network.

![Fig. 1. Time chart of resource reservation for label and burst transmission applying JET signaling and label electronic processing.](image)

### B. Optical Burst Switching (OBS) with OOC labels

Considering that the average burst length is strongly related to the performance of the OBS control channel [23], we will apply optical code labels and optical processing to make the JET signaling at the OBS control channel. Fig. 2 illustrates the internal architecture of optical burst switching node. The optical processing consists basically of the optical correlation of the OOC labels that arrive in the OBS node, and is performed as follows.
OOC labels in control wavelength arrive in the OOC decoder where the correlation with a copy of routing table entries is carried out; this correlation can be done with tapped lines or Bragg gratings [6]. The signal with high correlation is extracted and part of optical power of this signal is optoelectrically (OE) converted and electronically processed to send information to set the specific optical switch port configuration. Finally, part of the power of optical signal is sent to optical code converter, where label swapping is performed according to generalized multiprotocol label switching (GMPLS) information [18].

C. Optical Orthogonal Codes (OOC)

Among incoherent codes we find optical orthogonal codes (OOC), prime codes and M-sequence [19][20]. Here, an optical code division multiplexing OCDM with OOC is adopted because of its technological maturity and auto- and cross-correlation values [14]. In this case, each bit is divided up into \( n \) time periods, called chips. The total number of illuminated chips in the code is called the (Hamming) weight \( w \). The encoder of each transmitter represents each bit 1 by sending the code sequence; however, a bit 0 is not encoded and is represented using all-zero sequence. The set of signature sequences OOC is characterized by \( (L, w, \lambda_a, \lambda_c) \), where \( L \) is the length, or the number of total chips in the sequence and \( \lambda_a, \lambda_c \) are the maximum values of the auto-correlation and cross-correlation, respectively. By designating two sequences in an OOC by \( x \) and \( y \), the auto-correlation (1):
and cross-correlation (2) are defined [14], respectively by,

\[
\sum_{l=0}^{L-1} x_l x_{l+\tau} = \begin{cases} 
  w, & \text{for } \tau = 0 \\
  \leq \lambda_w, & \text{for } 1 \leq \tau \leq L-1 
\end{cases}
\]  

\( (1) \)

\[
\sum_{l=0}^{L-1} x_l y_{l+\tau} \leq \lambda_c, \quad \text{for } 0 \leq \tau \leq L-1
\]  

\( (2) \)

where \( \tau \) is the relative delay between two sequences \( x_l, y_l \in \{1,0\} \). Considering the correlation restrictions given by (1) and (2) and the number of sequences in OOC families with same weight, the possible lengths are given by [14],

\[
L \geq L_{\text{min}} = \left[ C \cdot w \cdot (w-1) + 1 \right]
\]  

\( (3) \)

where \( C \) represents the number of sequences in the OOC family with same weight. Some techniques of OOC implementation are designed to increase the number of simultaneous users supported by this kind of code [19][20].

D. Photonic Buffering

An objective of this work is to illustrate that OBS networks with electronic label processing require optical buffers with various sizes to reach the same performance of the optical label processing. The utilization of photonic buffers at the OBS switch has been analyzed to improve the OBS network throughput and to reduce burst loss probability [5][23][26]. Optical buffering is implemented via extended fiber delay lines (FDL) with lengths equal to a multiple of a burst length [4]. Photonic buffers were demonstrated and can be placed into two categories, called feed-forward and feedback [26]. The feed-forward buffer is structured with multi-stage 2×2 switch elements containing FDL; the feedback buffer utilizes fiber re-circulating loop, which employs optical amplifier inside the loop to compensate the round-trip loss.

III. PERFORMANCE EVALUATION

In this section we analyze the relation between the optical label processing time and the minimum burst length transmitted by OBS network. We also analyze the network performance as a function of network available resources such as number of wavelengths and traffic characteristics (burst arrival rate – BAR, and mean burst length). In this analytical approach [9][16][17][28], the network burst traffic intensity is modeled by queue theory, and the burst loss probability is calculated for both
optical label processing and electronic processing.

The capacity of optical label processing is limited by the optical correlation time in the decoder utilized at the OBS node with architecture illustrated in Fig. 2. If this processing capacity is considered, the optical label processing time \( T_P \) is given by [21]

\[
T_P = \frac{1}{(L-1)/T_C}
\]  

(4)

where \( T_C = 1/BL \) is the chip period and B stands for the bit rate. Using (3), \( T_C \) may be written as:

\[
T_C = \frac{1}{B[C \cdot w \cdot (w-1)+1]}
\]  

(5)

Equations (4) and (5) indicate that the optical processing time depends on the bit rate, the number of codes and the code weight; thus, the optical code processing could affect the OBS network traffic characteristics such as the burst length. Following [23] the minimum burst length \( T_{Burst}^{min} \) that could be transported to the OBS network is given by

\[
T_{Burst}^{min} = N(k-k_C)T_P
\]  

(6)

where \( N \) is the number of fibers in the core router, \( k \) is the number of wavelengths that carry the data bursts and \( k_C \) is the number of wavelengths for control. In the rest of this work we consider one optical fiber pair per link.

To evaluate the OBS network performance as a function of time processing and burst length, a network utilization efficiency \( U \) parameter is used, which considers the network throughput when the burst loss is zero. It is defined by [22]

\[
U(\%) = \frac{T_{Burst}}{T_{Burst} + T_P} \times 100
\]  

(7)

where \( T_{Burst} \) is the burst length.

Let us now investigate the wavelength reservation scheme using the JET protocol and define a methodology to calculate burst loss probability as a function of traffic intensity. In order to determine the effective service time of a burst let us refer to Fig 3 below.
The first bit of Burst \(i\) arrives at the OBS node at time \(t_1\), and the last bit of the same burst leaves the switch at time \(t_2\). Here, we should recall that the OXC needs an amount of time equal to \(T_{OXC}\) to reconfigure its switching elements to perform a connection. The switch cannot accommodate a new burst on this wavelength until time \(t_3 = t_2 + T_{OXC}\) has passed; in fact, if a burst label had arrived at the switch in the time interval between \(t_2\) and \(t_3\), it would have been rejected by the switch scheduling algorithm. Therefore, we can think of a burst as occupying the channel not only during its transmission time (equal to its length), but also for an additional amount of time equal to \(T_{OXC}\). Consequently, the effective service time of a burst follows a general distribution with Laplace transform \(B^* (s) \exp(-s.T_{OXC})\) and mean \(T_{Burst} + T_{OXC}\). Based on this, an output port of an OBS node using JET behaves as an \(M/G/k/k\) loss system, where \(k\) is the number of wavelengths of the port. The traffic intensity (\(\rho\)) of the queue is:

\[
\rho = \lambda(T_{Burst} + T_{OXC})
\]  

where \(\lambda\) is the burst arrival rate (BAR) in bursts per second.

The burst loss probability is given by Erlang’s loss formula [16],

\[
P_b = \frac{1/! \cdot r^k}{\sum_{m=0}^{k} 1/m! \cdot r^m}
\]  

where \(r = \rho \cdot k\):

To calculate the buffer size in the OBS switches with electronic processing the system is modeled as \(M/M/k/D\). In this model \(D\) represents the buffer size that represents the number of bursts stored into the buffer. According to the \(M/M/k/D\) model, the loss probability is [16]
\[ p_{Buffer}^{b} = \frac{r^D}{k^{D-k} \cdot k!} \left( \sum_{n=0}^{\min\{k, D\}} \frac{r^n}{n!} + \sum_{n=k}^{D} \frac{r^n}{k^{n-k} \cdot k!} \right) \] (10)

At the optical FDL buffers, the buffering time is measured in units of the fiber line delays, and therefore only a finite set of delays can be set and achieved. Without loss of generality, we assume that an FDL unit is the burst length \( T_{\text{Burst}} \), then the buffer size \( D \) is determined by \( n \times T_{\text{Burst}} \), where \( n \) is an integer and positive number.

IV. RESULTS

First we will analyze the results concerning the optical label processing time. These results are shown in Fig. 4, where optical label processing time versus the number of OOC is illustrated, considering bit rates \( B=1.0, 2.5 \) and \( 10.0 \) Gbps, and code weights \( w=3, 4 \) and \( 5 \). It can be seen that low processing times are obtained with optical label processing. We observe that the optical label processing time converges approximately to 1.0, 0.4 and 0.1 ns for bit rates of 1.0, 2.5 and 10.0 Gbps, respectively, independently of OOC number and code weight, as expected from (4). This occurs because the limitation of optical processing is the bit period that is the reciprocal of the bit rate, and the optical label processing time is very short compared with conventional electronic label processing (approximately \( 50 \mu s \) [24]).

The optical label time processing may also affect the traffic characteristics of OBS network, because the burst length accepted to be transported in the OBS network is a function of label time processing [23]. Table I summarizes these results for an OBS network with 64 wavelengths for optical burst data traffic per link and one wavelength for control.
Fig. 4. Processing time of optical label processing versus the number of OOC, for bit rates of 1.0, 2.5 and 10.0 Gbps.

<table>
<thead>
<tr>
<th>Code weight:</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing time (ns)</td>
<td>0.0</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Number of OOC's</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Table I. Minimum burst length for electronic and optical label processing

<table>
<thead>
<tr>
<th>Processing</th>
<th>Minimum burst length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0 Gbps</td>
</tr>
<tr>
<td>Optical (ns)</td>
<td>150</td>
</tr>
<tr>
<td>Electronic (μs)</td>
<td>16</td>
</tr>
</tbody>
</table>

From Table I we observe for a 10 Gbps bit rate that the minimum burst length accepted to be transported is 15 ns and 3.5 μs for optical label processing and electronic label processing, respectively. Considering that up to ~50% of IP traffic consists of packets smaller than 520 bytes [25], then for a system bit rate of 10 Gbps, we have packets with 0.417 μs duration; and 50% of these packets have a mean length of 33 ns. Then, by applying optical label processing, the OBS network will approach conventional packet switching network granularity, and the network utilization will thus be increased especially for small bursts composed by IP traffic.

In Fig. 5, the effects of bit rate and number of wavelengths on minimum burst length for transport by OBS network are presented, using (6), for both optical label processing and electronic processing. It is clearly shown that when optical label processing is utilized the minimum burst length decreases in comparison with electronic processing, for all numbers of wavelengths considered. It also shows, according to (6), that the minimum burst length increases when the number of wavelengths increases and the bit rate decreases.
Fig. 5. Minimum burst length versus bit rate for optical label processing and electronic processing as function of number of wavelengths.

Fig. 6 shows the utilization efficiency versus the burst length. It is considered for conventional electronic label processing a processing time of 50 μs [23], and for optical label processing time values 1.0, 0.4 and 0.1 ns for bit rates 1.0, 2.5 and 10.0 Gbps, respectively. It is seen that the utilization efficiency for optical label processing is higher than those for electronic processing. However, when the processing time is higher than the burst length the utilization efficiency decreases; on the other hand the utilization efficiency of optical processing is practically the same for the different bit rates. It should be noted that the network utilization efficiency considers the burst loss probability equal to zero. This is a good solution for adjusting burst length, and it does not depend on network resources like wavelength.
The burst loss probability as a function of the number of wavelengths for optical and electronic label processing is depicted in Fig. 7. Burst size was considered with mean length ($T_{\text{Burst}}$) of 1 ms, BAR of 3200 and 6400 bursts per second, $T_{\text{OXC}}$ of 1 ms, electronic processing time of 50 $\mu$s [23], and optical processing time of 0.4 ns, for a bit rate of 2.5 Gbps and network diameters of 500 and 1500 km.

It is observed that the burst loss probability for optical label processing is lower than electronic processing. For example, from Fig. 7 one can see that a burst loss probability of $1 \times 10^{-3}$ is approximately obtained for 33 and 57 wavelengths (with BAR=3200 and 6400 Bps, respectively) using conventional electronic processing; on the other hand, approximately, 29 and 49 wavelengths are necessary under the same conditions. This clearly shows an improvement in wavelengths usage of the OBS network, which in turn increases the network utilization gain (efficiency).
Fig. 7. Burst loss probability as a function of the number of wavelengths for optical label processing and electronic processing for burst arrival rate (\( \lambda \)) of 3200 and 6400 Bps; network diameter 500 km and 1500 km

To quantify the number of saved wavelengths when optical processing is used, it will be applied the parameter here defined as the economy of wavelength (SW).

\[
SW(\%) = \frac{W_{\text{Electronic}} - W_{\text{Optical}}}{W_{\text{Electronic}}} \times 100
\]  

(11)

where \( W_{\text{Electronic}} \) and \( W_{\text{Optical}} \) are the number of wavelengths utilized when applying conventional electronic processing and optical label processing, respectively. Utilizing the metric of SW we verify that for burst loss probability of \( 1 \times 10^{-3} \) there is a SW=12 and 14 %, for BAR of 3200 and 6400 Bps, respectively.

To illustrate the dependence between network performance and traffic characteristics we will show the burst loss probability as a function of the burst length for optical and electronic label processing. Figure 8 shows burst loss probability as a function of the burst length for network diameters of 500 and 1500 km, respectively. These results were obtained considering BARs of 3200 and 6400 Bps, \( T_{\text{OXC}} = 1\text{ms} \), electronic processing time of 50 \( \mu \text{s} \) [23], optical processing time of 0.4 ns, a bit rate of 2.5 Gb/s, and 32 wavelengths.
It is observed in Fig. 8 that the burst loss probability as a function of the burst length for optical label processing is lower than electronic processing. For conciseness, we have grouped the results for BARs of 3200 and 6400 Bps, and network diameters of 500 and 1500 km.

We observe that the burst loss probability difference for optical code and electronic label processing tends to be higher for short burst length; and that for a given BAR, the optical processing always outperforms the electronic processing. As previously discussed, the network diameter has low influence on the burst loss probability. However, considering that the burst loss probability for electronic processing increases with the network diameter this kind of processing could impose a further constraint for large networks.

In order to evaluate the network resources savings we have defined the figure of merit called network utilization gain (as the ratio of the burst loss probability for electronic processing and optical processing). Fig. 9 shows the utilization gain for the same parameters illustrated in Fig. 8. It is observed that the gain utilization tends to infinity for small length bursts. This behavior shows that the capacity of network resources liberation is very high and that short bursts could be transported with high network efficiency.
Another way to illustrate the advantages of the optical label processing utilization is by comparing their performance with the conventional electronic processing adding buffers at the OBS switch. This comparison is interesting because one of the main OBS design goals is the implementation of a bufferless network, where user data is transparently transmitted as a very high rate optical signal. Moreover, the number of FDLs is a critical system design parameter because it has an impact on optical hardware volume, switch size, and optical signal-to-noise ratio (OSNR) due to the transit of the optical signal in the FDLs.

It is shown in Fig. 10 the mean buffer size versus the mean burst length necessary to be included in to the OBS switches for the utilization of the electronic label processing to reach the same performance of optical label processing. The same parameters of Figs. 9 were utilized. One observes that the buffer size must be increased when the burst length increases. Also, the burst size increases when network diameter and burst arrival rate increase. Fig. 12 indicates that, for a BAR of 6400 Bps and a burst length of 0.1 s, an OBS network with electronic label processing would require a mean buffer size of 55 to achieve the same burst loss probability supported by optical label processing.
V. CONCLUSIONS

In this work, we proposed and developed a simple analytical methodology to analyze an OBS network architecture that utilizes JET signaling and optical processing of OOC labels. In comparison to the traditional electronic label processing, our results suggested that the optical label processing: a) decreases the label processing time, b) reduces the burst loss probability, c) increases the network efficiency utilization, and d) offers a gain utilization that rapidly increases with the decreasing of the burst length and which may be higher than $10^5$ even for bursts as long as 50 ms. We also showed that OBS networks with electronic label processing would require an impractically long FDL to provide the same burst loss probabilities than the ones achieved by optical label processing. For these reasons, we believe that the analyzed architecture could be strongly considered for implementing a cost-effective and high efficiency OBS network.

REFERENCES


