A Packet-Based Photonic Label Switching Router for a Multirate All-Optical CDMA-Based GMPLS Switch

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***Abstract*—A novel packet-based photonic label switching router for a multirate all-optical switch using generalized multiprotocol label switching is proposed. The idea is based on using optical code-division multiple access (OCDMA) as multiplexing technique and treating OCDMA codes as labels. The system can coexist with current wavelength division multiplexing systems on the same infrastructure. The concept of switch fabric is introduced. Label processing and label swapping functionalities of the switch are discussed. In-depth analyses are made for spectrally phase-encoded OCDMA (SPE-OCDMA) due to its capabilities of supporting high data rates, large code cardinality, and its secure transmission. Packet loss rate for a multirate SPE-OCDMA system is derived. Some performance metrics are derived for a typical network via simulation, and the results are discussed.**

***Index Terms*—All-optical switch, label processing, label swapping, multirate generalized multiprotocol label switching (GMPLS), optical code-division multiple access (OCDMA), packet-based photonic label switching router (PPLSR), spectrally-phase-encoded.**

I. Introduction

THE information and traffic explosion in ubiquitous Internet-based communication networks with essentially different characteristics and requirements are behind the emergence of enabling technologies for ultra high speed communication systems. As such, the enormous capacity of fiber-optic medium makes optical networks a major candidates for core networks and an interesting choice for future access networks [1].

As growing optical technologies make optical systems faster, limited speed of electronic modules along the path of optical networks becomes the limiting factor, hence leading to the idea of all-optical networks (AONs). At the same time, power consumption has emerged as one of the most prominent obstacles in the way of expanding routers' capacity. The hope was to alleviate this problem by introducing optical technology into routers, but optical-to-electrical-to-optical conversion, as a highly power-consuming process, makes it ineffective. Today, there is a tendency toward all-optical networking for future reliable, high speed, high-quality networks. In an AON, the limiting processes of optical-to-electrical-to-optical conversions are eliminated, and key processing functions are established in optical domain. Therefore, all-optical processing becomes the major challenge confronting all-optical networking. Although optical processing is a powerful tool from a theoretical point of view, difficulties in design and fabrication of fundamental devices make the realization of the aforementioned ideas, by today's technology, difficult if not impractical [2]–[4]. Therefore, a system can emerge as successful if it can implement the features of all-optical networking in a simple and efficient manner.

A major challenge in all-optical networking is routing. Internet traffic is doubling every year while router capacity per unit volume is doubling every 18 months [5]. Today, main limitations in increasing routers' capacity are dynamic RAM (DRAM) access time, which limits the number of address lookup per unit time [6], and power dissipation [7]. Almost 50% of power is consumed by optical-to-electrical-to-optical conversion and chip-to-chip communication.

To address these problems along with the desire of service providers to gain more control over the traffic that passes through their networks, label switching emerges as an attractive solution. There is a variety of generalized multiprotocol label switching (GMPLS) proposals in which label is mapped into optical domain [8]–[11].

Recent demonstrations of several multiuser, multigigabits per second optical code division multiple access (OCDMA) systems [12]–[15] showed the capability of OCDMA technique as a multiple access scheme in several gigabits per second systems. Also, the demonstration of wavelength division multiplexing (WDM) compatible OCDMA [16], [17] suggested the possibility of implementing OCDMA systems on WDM infrastructure. Furthermore, requirements for future AONs and the potential of OCDMA in satisfying them such as all-optical processing, simplified and decentralized network management, inherent consistency with bursty traffic, improved spectral efficiency [13], and enhanced security [18] have attracted increased attention to this advanced and fundamental multiple-access technique.

In this paper, we propose a novel GMPLS-based switch that uses OCDMA codes as labels. In this system, multiple-access scheme is also based on OCDMA technique. Switch fabric mainly consists of passive OCDMA en/decoders, optical hard limiters (OHL) [19], [20], optical cross connects (OXC), and optical amplification blocks. Add-drop functionality is implemented by passive decoding and encoding the desired signal. Dynamic devices are configured in path setup phase. After path setup phase, switching will be done with no further

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processing (or more precisely, by optical processing); therefore, it is established almost instantaneously and at the bit level, i.e., every single bit is switched separately. These features are essential for bursty data traffic and delay/jitter-sensitive multimedia transmissions [21]. Also, utilization of multirate OCDMA [22] overcomes the granularity issue in an efficient manner and offers support for different classes of service at the physical layer.

The rest of this paper is organized as follows. The architecture of the proposed switch and system's characteristics are described in Sections II and III, respectively. Performance analysis is presented in Section IV. Concluding remarks are given in Section V. An appendix is devoted to detailed mathematical analysis of packet loss rate (PLR) for the proposed multirate spectrally-phase-encoded (SPE) OCDMA needed to support the result of Section IV.

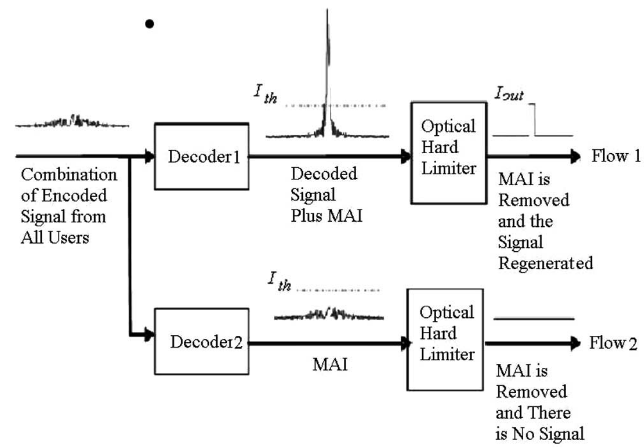

Fig. 1. Separating different flows by label processing.

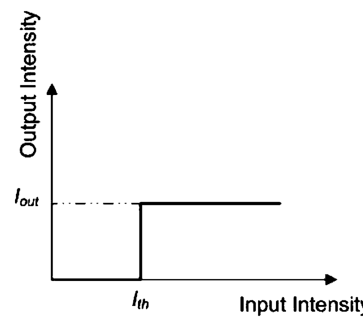

Fig. 2. An ideal OHL input–output characteristic.

II. Architecture

In the proposed system, communications between network nodes are via on–off keying (OOK)–OCDMA technique [20], [23], [24]. Multiple data streams can be transmitted simultaneously on the same fiber link using different OCDMA codes. The code corresponding to each flow is also considered as its label. These codes (labels) can be altered as the flow travels through the GMPLS domain.

In a multiple-access GMPLS system, a switch must establish three essential functions: 1) separating a desired flow from a group of flows coming from an input port by using its label (label processing), 2) routing the flow according to its label and input port, and 3) labeling the outgoing flow with appropriate label (label writing). On the other hand, as in an OCDMA system, performance is mainly limited by multiple-access interference (MAI) [20], [25]. Performance will degrade significantly if MAI from the input port travels through the switch and adds up with other sources of MAI at the output port. Therefore, a fourth functionality is needed in this switch. The switch must block MAI; in other words, regenerate the data in optical domain. These functionalities are described in the sequel.

Fig. 1 shows the concept of label processing functionality in the proposed system. Consider an arriving encoded signal to an input port. The signal is primarily duplicated into N signals, where N is the number of employed codes in each input port ($N = 2$ in this figure), which, then, are fed into N decoders. Each decoder is matched to the code of a certain user (flow). A short intense pulse is generated at the output of a decoder when the corresponding user transmits "1." The output remains a low-intensity MAI when the corresponding user transmits "0." In the next step, MAI is removed by OHL. OHL is a block that has an input–output characteristic as shown in Fig. 2. A "1" sent by a user produces a decoded signal at the output of the corresponding OHL and no signal or MAI at other outputs. Here, OHL acts as a thresholder that regenerates the signal in optical domain. Assume that the threshold of the OHL, $I_{\rm th}$, is the minimum intensity for which a "1" is declared. If the decoded signal goes above this threshold, OHL observes the signal, and a pulse will appear at its output. It means that a bit "1" is recognized by the switch and will be transmitted through the proper output port. On the other hand, if the intensity at the input of the OHL is below the minimum, there is no output signal, i.e., a "0" has been transmitted. In order to transmit the signal to the next node, the signal is routed to the desired port and encoded using a predetermined code (label writing). This is established by passing the short intense light pulse through an OXC to OCDMA encoder.

Fig. 3 shows a block diagram for the system in its entirety. Each input fiber is attached to N optical decoders by a $1 \times N$ optical splitter. Each decoder extracts its corresponding signal and via an OHL, MAI is removed and only the ultrashort light pulse remains. OXCs are used to route a signal to the appropriate optical encoder, connected to the desired output port. The optical encoders perform the label writing function by imprinting a label on the ultrashort lightpulse. After the optical encoder, an $N \times 1$ optical coupler is placed to combine all the signals coming from different optical encoders and leaving on the same fiber. This signal is, then, amplified and sent over the output port.

III. System's Characteristics

As can be observed from our discussion, no header processing is carried out for routing. Therefore, switching is almost instantaneous after path setup. After the path setup phase, consider a packet arriving at a label edge router (LER). An LER processes the destination path of this packet, and after encoding the signal with the proper code (label), transmits it to the desired output port. Following path setup, the packet travels with no further

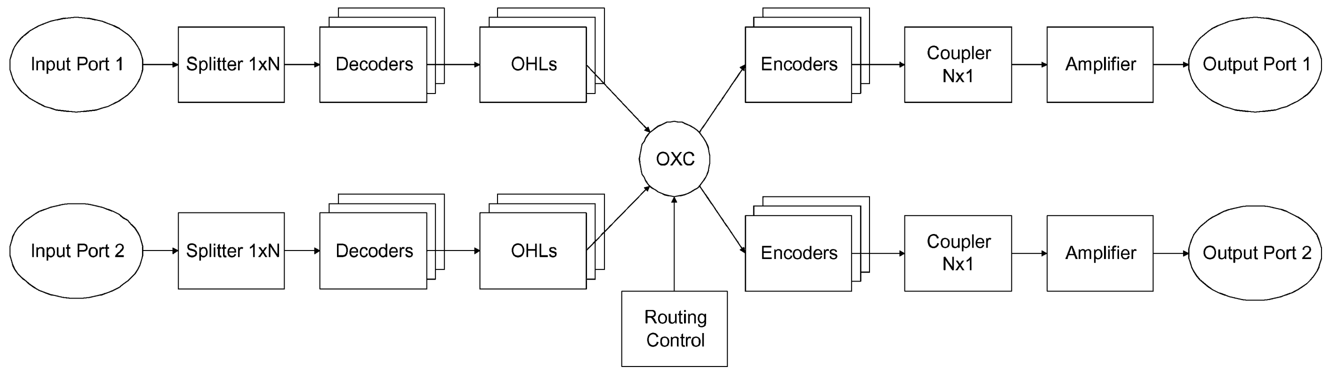

Fig. 3. Block diagram of the packet-based photonic label switching router (PPLSR).

processing. Until this path is dismissed, every other packet that uses the same path requires no processing except at the edge of the GMPLS domain.

Code spaces on each link are independent, i.e., any available code can be used on each link regardless of whether it is used on other links. In contrast to WDM-based GMPLS networks, in which the number of labels is strictly limited, a large number of codes can be obtained in OCDMA systems. Hence, when transmission between two LERs ends and the corresponding path becomes idle, as long as there are other available optical en/decoders and OHLs, there is no need to free the resources of this path to create new paths. These LERs can begin transmission again at any time, provided they do not cause an increase in MAI above a predetermined value on any link along the path. Therefore, the maximum number of active paths is determined by the endurable level of MAI. Also, the total number of active and idle paths may not exceed the number of en/decoders. Each of these limits may be dominant in different situations. For example, many low-rate optical label switching paths (OLSPs) can be blocked due to the limited availability of optical en/decoder. While a small number of high-rate OLSPs can be blocked because of the strong MAI they generate which causes the bit error rate (BER) to reach an unacceptable level.

While the total number of light paths is strictly limited by the number of en/decoders, MAI softly limits the number of active paths. If there are enough encoders and decoders, the system can utilize a soft limiting policy, i.e., can choose between blocking a request or allowing the request by tolerating some QoS degradation. But it, still, can be an interesting tradeoff for multimedia and data networks. For a more advanced design, error detection and retransmission can be considered at the edge of the GMPLS domain.

Due to the intrinsic nature of CDMA systems, bandwidth allocated to an OLSP is used only when data is being sent on the link and can be used by others when there is nothing to send. Utilizing multirate schemes proposed for OCDMA systems can support fine granularity [22]. In this paper, we introduce a new multirate transmission scheme for spectrally phase-encoded OCDMA that does not add any more complexity to encoders and decoders. With these features, system can offer different forwarding equivalency classes (FEC) at physical layer, i.e., optical layer.

Use of passive devices (encoders, decoders, and OHLs) can improve system reliability. Also recent demonstration of WDM compatible OCDMA systems [16], [17] can facilitate implementing OCDMA systems on the existing optical networks.

Number of en/decoders and OHLs and their input–output characteristic is critical for this system. OHL can be implemented by periodic structures consisting of alternating layers of materials possessing different Kerr nonlinearities. Using large number of layers, near-ideal OHLs are introduced in [3]. Optical en/decoders have been implemented in several ways [26]–[28]. Among them, Wada *et al.* reported an integrated on Si-substrate en/decoder using planar light wave circuit (PLC) technique. This solution is interesting for our setup because of the need for many en/decoders in each port since the number of en/decoders and OHLs in each port determine the maximum number of paths that can be handled on each port. But comparing this limit with its counterpart in WDM-based proposals, which is set by the number of wavelength converters, this is a strength of this system because it replaces active wavelength converters with passive optical en/decoders and OHLs.

However, the proposed system is sensitive to reconstructed pulse shape, and therefore, response time and input–output characteristic of OHL are important. Furthermore, since at each switch, data are, in effect, regenerated, optimum performance needs dynamic threshold for OHLs, which is not practical. Due to the characteristics of OHL, pulse width compression and pulse shape change will result at the output of OHL. Optical amplification can alleviate this problem. Achieving ideal hard limiting characteristic is also an issue. Dynamic OXCs play a critical role in this system by routing packets from optical decoders to the desired optical encoders and output ports. The loss through OXC will introduce some performance degradation. Whenever a new path is established, the routing control reconfigures the OXCs to set up physical connection between corresponding ports. This configuration time is a major contributor to path setup delay.

IV. Performance Analysis

In this section, the performance of the proposed scheme utilizing SPE-OCDMA is evaluated. As the underlying OCDMA scheme, we use SPE-OCDMA because of its support of high data rates and large code cardinality. Section IV-A is a brief description of SPE-OCDMA and our proposed multirate SPE-OCDMA scheme. Numerical results for a sample network via simulation are given in Section IV-B, using the results obtained in the Appendix where we have formulated PLR for the proposed multi rate OCDMA system.

A. Multirate SPE-OCDMA

In a SPE-OCDMA system [20], each user is assigned a code of length N_0, where for binary codes, which we consider here, code elements are chosen from the set $\{0, \pi\}$. Transmitter imprints its data bits on this code by dividing an ultrashort pulse's spectrum into N_0 "chips" and multiplying each chip by e^{jc_i}, where c_i is the corresponding element of the code. Then, the encoded stream is sent over a shared media. All receivers receive signals from all transmitters but a matched decoder at the desired receiver ensures that data bits are detected only when they are encoded with the predetermined code. In a sample implementation originally reported in [20], a train of ultrashort light pulses with duration T_c and repetition rate $R_b \propto 1/T_b$ is generated by a coherent mode-locked laser where T_b is bit duration. The pulses pass through a data modulator that modulates them with respect to the data stream using OOK, which is considered as the modulation scheme in the performance evaluation presented in this paper as well. Consequently, modulated light pulses are directed to the optical encoder. The encoder first spatially decomposes the spectral components of the light pulse. By applying a phase mask, the spectral components experience different phase shifts. Phase-shifted components are, then, combined to form an encoded light pulse. The resulting signal has spread in time by a factor of N_0, where N_0 is the number of code's elements.

At the Receiver side, the received signal is again spatially decomposed to its spectral components. If the receiver's code is matched to the transmitter's, each of the signal's spectral components is multiplied by the complex conjugate of its corresponding multiplier factor in the transmitter. The results will then be combined, and the original spectral shape of the ultrashort pulse will be regenerated. When the codes are not matched, the output will be another time-spread signal. The output of this section (optical decoder) is directed to a detecting block that detects "1" when the intensity of the input pulse exceeds a certain threshold at the detection instance or carry more energy than a threshold in a specific time interval.

The signal will be time-spread by a factor of N_0 after being encoded at the transmitter. Therefore, the duration of the encoded signal, T, is equal to $N_0 T_c$. Further, to suppress MAI and to allow receivers to catch up, another factor $K = T_b/T$ may be introduced to the system. This means the transmitter sends only one bit in every KT seconds. Therefore, a straightforward way to implement multirate communication is to allow users to have different value for parameter K. To implement this scheme, the only modification needed is to change modulator's repetition frequency. Analytical performance derivation of this multirate scheme is given in the appendix. A typical implemented value for T_c, as reported in [12], is $T_c \approx 0.4$ ps. With $N_0 \approx 512$ and $K \approx 1$, the rate for each flow is $1/(K N_0 T_c) \approx 4.88$ Gb/s.

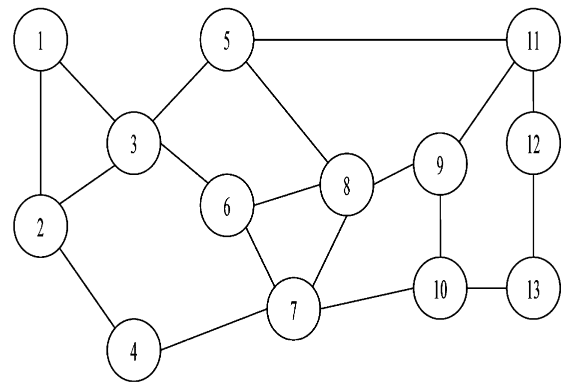

Fig. 4. Network topology; each line indicates a full duplex fiber link.

0	0.2	0	0.4	0.5	0	0.8	0	0	0	1	0.5	0.7
0.2	0	0.2	0.5	0.3	0.3	0.8	0.4	0.1	0.1	1	0.7	1
0	0.2	0	0.5	0.5	0.5	1	0.3	0	0	0.5	1.1	1
0.4	0.5	0.5	0	0.5	0.5	1	0.5	0.5	0.5	1	0.5	0.8
0.5	0.3	0.5	0.5	0	0	1	0	1	0	0.5	1	0.5
0	0.3	0.5	0.5	0	0	0.6	0.5	1	0.6	0.5	0.6	1
0.8	0.8	1	1	1	0.6	0	0	0	0	1	0.6	1
0	0.4	0.3	0.5	0	0.5	0	0	0.5	1	0.8	0.8	1
0	0.1	0	0.5	1	1	0	0.5	0	0	0.5	0.7	1
0	0.1	0	0.5	0	0.6	0	1	0	0	0.7	0.5	1
1	1	0.5	1	0.5	0.5	1	0.8	0.5	0.7	0	1	1
0.5	0.7	1.1	0.5	1	0.6	0.6	0.8	0.7	0.5	1	0	0.5
0.7	1	1	0.8	0.5	1	1	1	1	1	1	0.5	0

fig. 5. Average load between nodes.

B. Numerical Results

The topology of the network used for obtaining numerical results is depicted in Fig. 4. The network supports two rates, high rate and low rate, where the high rate is twice the low rate. However, in general, there is no limit on the number of rates or their ratio. The traffic model used is a Poisson traffic model with parameters given in the load matrix of Fig. 5. For instance, node 1 sends data to node 2 with average of 0.2 messages/T_p, where T_p is packet duration of low-rate users. Each user may produce high-rate or low-rate messages with equal probability. Each message contains a number of packets derived from a Poisson distribution. For the sake of simplicity, the control flows are neglected.

The ports of the routers are connected via optical fiber links. Multiple flows may use a link simultaneously as a shared medium utilizing OCDMA. Each output port is connected to N optical encoders, and each input port is connected to N optical decoders; hence, we can have up to N flows of data on each link. These optical en/decoders are utilized when a path is set up. When node m requests a path to node n, the shortest available path, according to a hop count metric, is found and assigned to the corresponding data flow between m and n. However, when the session ends, the path is not broken, although it has become

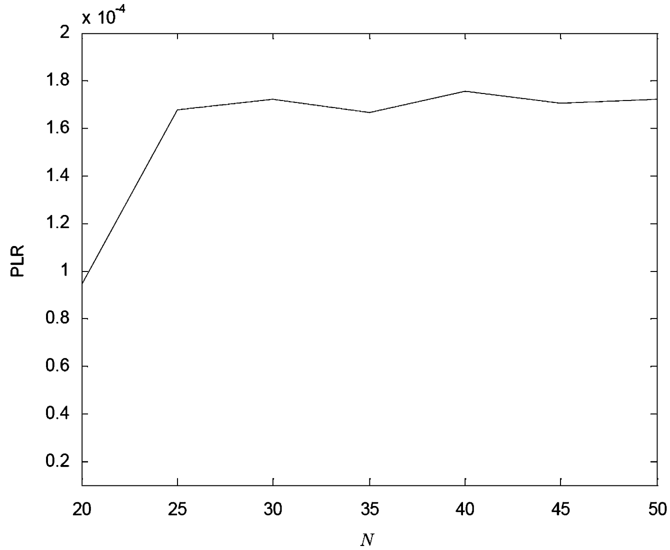

Fig. 6. Average PLR vs. number of optical en/decoders (N).

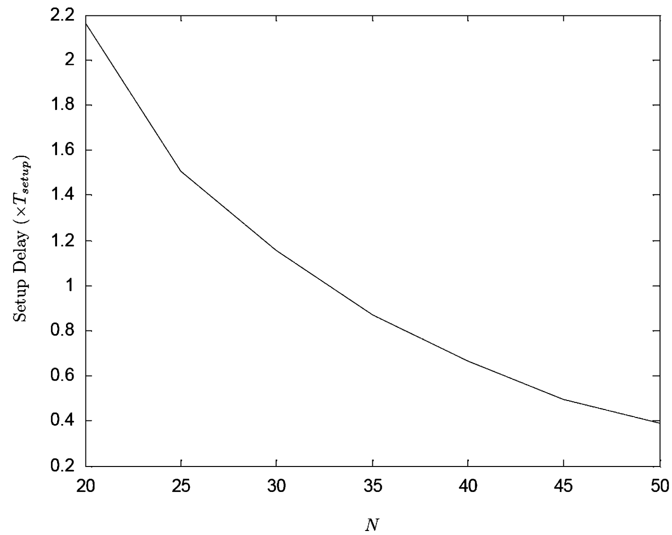

Fig. 7. Average setup delay vs. number of en/decoders (N).

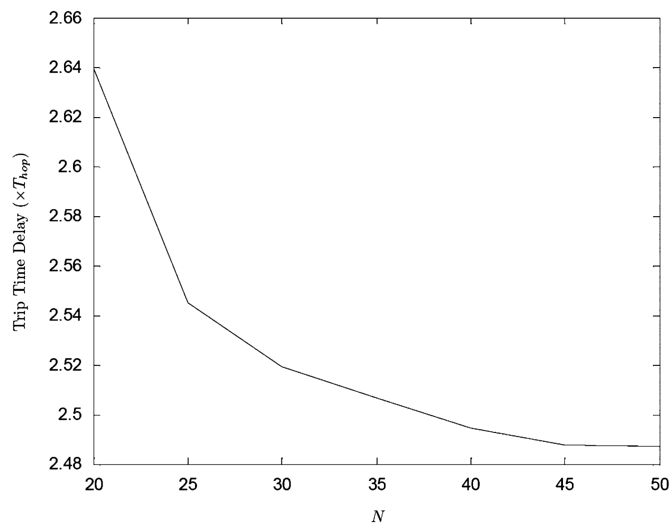

Fig. 8. Average trip time delay vs. number of optical en/decoders (N).

idle, it is kept accessible for future use by a data flow between the same nodes, unless its resources (en/decoders) are needed by another request.

Since MAI is the main contributor to bit error in OCDMA systems, links in the network must not be overutilized. High-rate users generate twice as many light pulses as low-rate users; therefore, they produce two times more MAI. For this reason, link utilization is defined as $2n_h + n_l$, where n_h and n_l are the number of high- and low-rate users on each link, respectively. To avoid high BER, link utilization must be limited. This limit, denoted by E, determines the upper bound on BER and also upper bounds the number of users on each link, therefore, limiting the throughput. Hence, E should be chosen considering this tradeoff.

The path-selection process is as follows: first, when a path is requested, it is examined to see whether there is an idle path between the nodes requesting the path. If such a path exists, the transmission can start instantly. This significantly reduces the delay caused by path setup phase in the network. If not, the system attempts to set up a new path with minimum hop count using the en/decoders that are used neither in active paths nor in idle paths. Still, if finding a path is not possible, it is examined whether a path can be established by breaking some idle paths. If so, the path is set up by breaking idle paths and freeing enough en/decoders. If establishing the required path is not possible even with breaking up idle paths, the call is blocked and the user is backlogged. At any stage, if several paths are possible, the path is chosen according to minimum hop count. Backlogged users will request the path according to an exponential backoff rule, i.e., they will request the path $T_{rt} = 2^n N_m T_p$ seconds later, where N_m is the average message length and n is the number of times that the request has been backlogged.

The simulation is run to evaluate the performance of a network utilizing proposed routers in terms of throughput, PLR, blocking probability, and delay. Throughput is defined as the total number of delivered packets in the network in T_p seconds. MAI is considered as the only source of error on the links. For this case, packet success probability on each link is obtained in the Appendix. PLR is the probability of a packet to be received at the destination with some erroneous bits. For each packet, this probability is calculated at the destination as $1 - P_s$, where P_s is obtained by multiplying success probabilities of the packet on each link it traveled on, and then, averaged over all packets transmitted in the network.

Several components contribute to delay including "path setup delay," "trip time delay," and "delay caused by blocking." For each packet, path setup delay is equal to the time needed to program a router for the requested path, T_{setup}, times the number of routers in the path. Similarly, trip time for each packet is equal to the time needed to travel from one router to the next one, T_{hop}, times the number of links in the path. Note that when a previously set path is reused, setup delay is zero but trip time delay is nonzero. For blocking delay, when a path request is blocked, all its flow packets suffer a delay equal to T_{rt}.

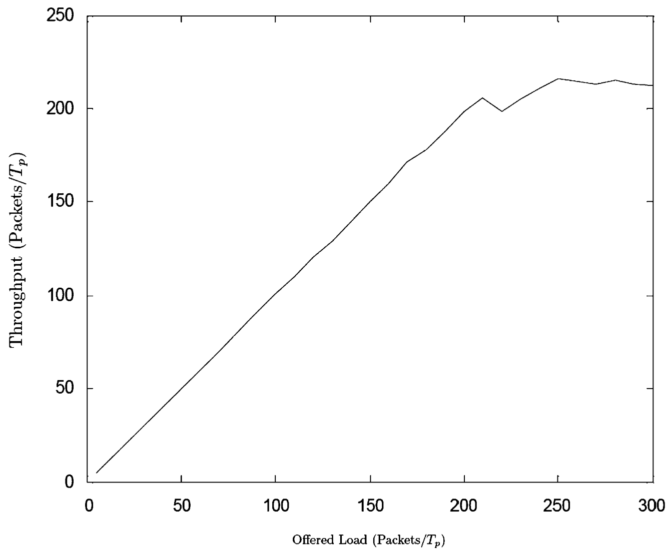

Fig. 9. Total network throughput (packets/T_p) vs. total offered load (L_o).

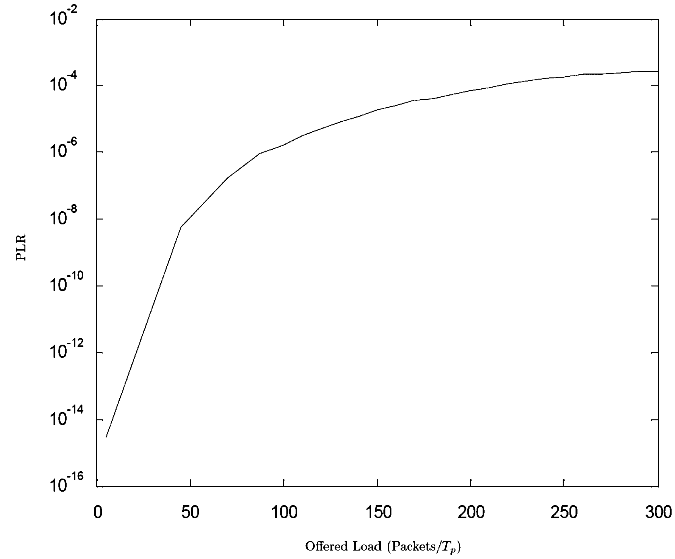

Fig. 10. Average PLR vs. total offered load (L_o).

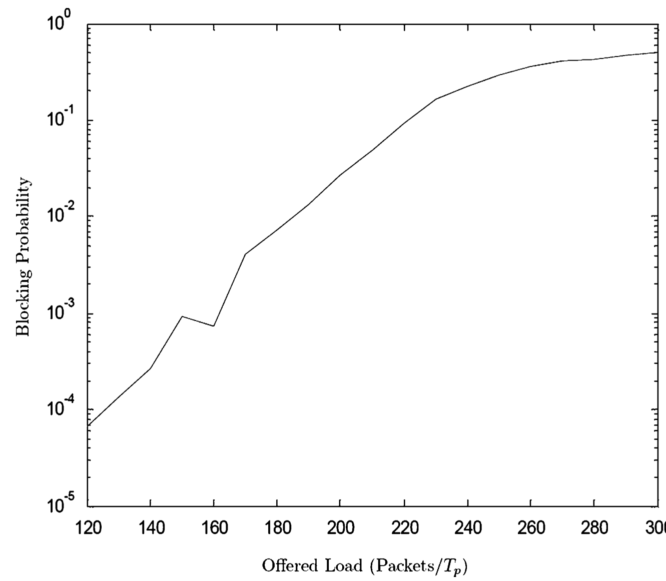

Fig. 11. Blocking probability vs. total offered load (L_o).

The following parameters are assumed: $I_{\rm th} = 0.25$, $N_0 = 512$, $K_0 = 1$ for high-rate users, and $K_1 = 2$ for low-rate users.

In the first part of the simulation, we examined the effect of the number of optical en/decoders on the delay that packets experience in the network. The average load is 200 packets per T_p, i.e., all nodes, combined, on average send two messages per T_p with average message length of 100 packets. Packet length is 1000 bytes. In this part, maximum link utilization E is 30, and N, the number of optical en/decoders per link, is ranged from 20 to 50. The simulation results indicate that for all ranges above 25, throughput is approximately 200 packets per T_p, PLR is about 1.7×10^{-4}, and blocking probability is roughly fixed at 3.5×10^{-3}. Fig. 6 shows that when the value of N reaches E or exceeds it, it does not have a significant effect on PLR due to the limiting effect of E. This is also true for blocking probability. Higher values of N will result in less delay because increasing N allows establishing shorter paths; consequently, it reduces trip time delay. Also, when N is high, fewer paths need to be broken to establish new paths; therefore, paths can remain idle and be used again, which decreases the setup delay. This trend is seen in Fig. 7 and Fig. 8. However, this does not have an effect on blocking delay because when N is greater than E, blocking is mainly limited by E and does not decrease as N increases. When N is greater than E, blocking delay is fixed at $0.73T_p$. From the aforementioned results, we reach the conclusion that for a proper load, selecting N slightly greater than E will result in low delay. We use this result to choose N for the next part of the simulation.

In the next step, E and N are set to be 30 and 40, respectively. We examine the system performance as the network load L_o (packets/T_p) varies. Fig. 9 shows the average throughput. As can be observed in this figure, for $L_o < 200$ (packets/T_p), throughput increases almost linearly with offered load, but above this value, it is approximately constant, and the network is saturated. Comparing this with Fig. 10 reveals that the maximum allowed level of PLR is also reached at $L_o = 200$ (packets/T_p). Blocking probability is shown in Fig. 11. For $L_o < 200$ (packets/T_p), blocking probability is roughly below 10^{-2} but increases to 0.48 for $L_o = 300$ (packets/T_p). The normalized average trip time delay is depicted in Fig. 12. As load increases, the network has to utilize available longer paths to avoid call blocking. Blocking delay in Fig. 13 is also affected by increasing load. For $L_o = 200$ (packets/T_p), it is 3.1, but as L_o increases further, blocking delay increases rapidly. As can be observed in Fig. 14, setup delay increases linearly for L_o above 100; for L_o below 50, setup delay is negligible. The earlier discussion suggests that if we utilize the system with a load less than the saturation level [$L_o = 200$ (packets/T_p) in this case], it will result in good performance in terms of throughput, PLR, and delay. The system maintains its PLR, and works with its maximum throughput if the load is increased beyond this level, but delay and blocking probability will increase.

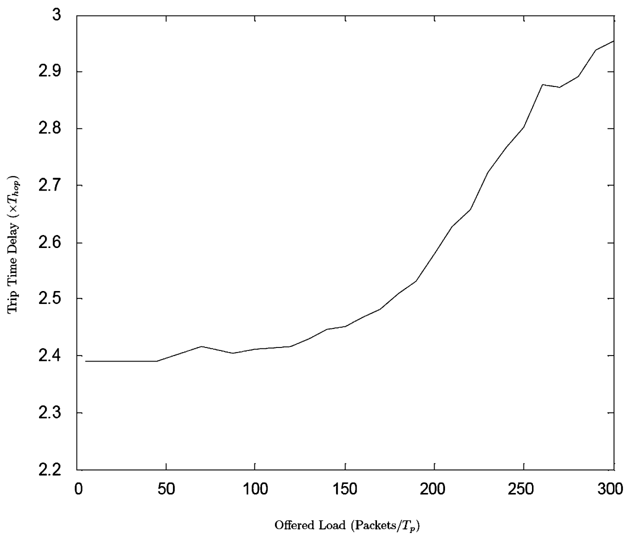

Fig. 12. Average trip time delay vs. total offered load (L_o).

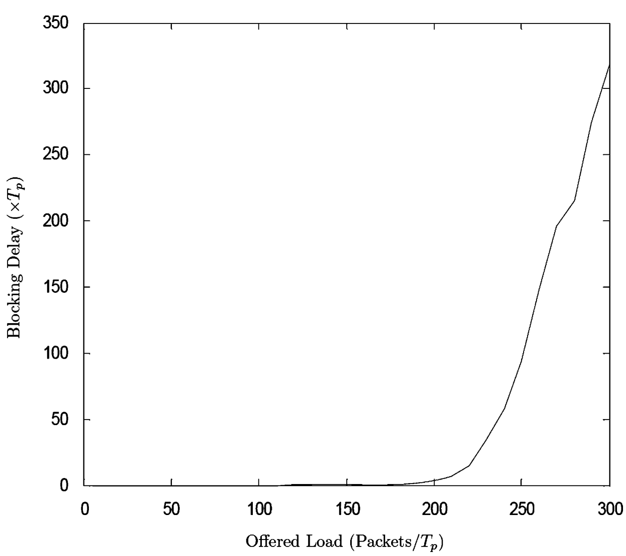

Fig. 13. Average blocking delay vs. total offered load (L_o).

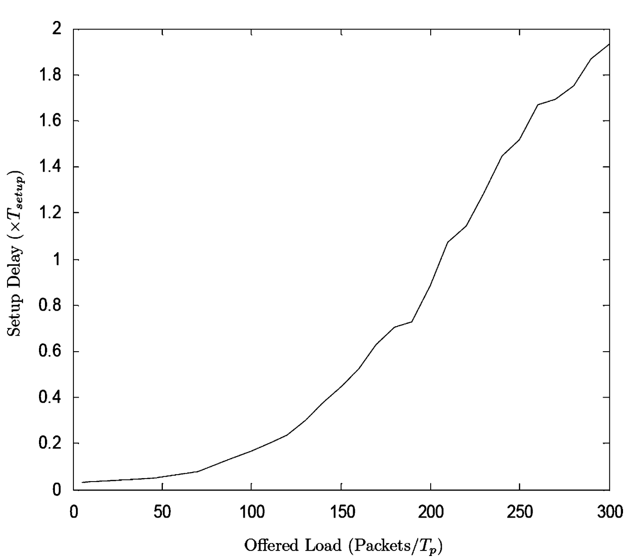

Fig. 14. Averagesetup delay total vs. offered load (L_o).

V. Conclusion

In this paper, we propose a PPLSR for an OCDMA-based network. Characteristics and advantages of the proposed PPLSR are discussed. Some issues concerning current systems that can be mitigated by the proposed system in this paper are addressed. PPLSR can gain various inherent advantages of CDMA technique when implemented for multimedia and data networks. Obtained results show that the proposed system can conceptually have excellent performance. Also, the system can coexist with current WDM-based systems on the same infrastructure, which can prove to be important for gradual deployment. Enhanced security of the system due to the use of OCDMA technique can make it appropriate and desirable. An experiment can justify the assumption made here and prove the addressed characteristics and features.

Appendix

Performance Of Packet-Based Multirate System Based On SPE-OCDMA

In this appendix, the performance of a packet-based multirate spectrally phase-encoded OCDMA system is formulated in terms of packet success probability. The main source of error in OCDMA systems is MAI [20], [25]; hence, these systems suffer from high correlation between errors at different bits of a packet. The correlation is the result of the fact that if a user interferes in one bit of the desired packet, it will also interfere in the rest of this packet as long as the interfering and desired packets overlap. To suppress this effect, in this system, we assume that the encoded pulses hop among the K possible pulse slots in each bit. This functionality needs to be implemented in the OCDMA transmitter and is not part of the switch fabric. One possible implementation is to pass the output of the laser trough a fiber delay line bank with H branches, where H is the length of hopping sequence, and each branch implements one element of hopping sequence. The combined train of light pulses is, then, treated as the output of a laser that hops in time. In a single-rate system, this approach would entirely eliminate the correlation; however, because we utilize a multirate scheme, as explained later, there is still correlation among consecutive bits.

Assume there are $r+1$ rates with n_i users in the ith rate class. The duration of the encoded pulse is denoted by T. For the sake of simplicity, we consider the bit duration of the jth user to be $K_j T = 2^j K_0 T$, where $K_0 T$ is the bit duration of the highest rate class. In this paper, following the common approach in OCDMA systems analysis, we consider the system to be bit-level synchronous, i.e., bits of different users start at the same time (see Fig. 15). This assumption is known to result in a lower bound for system performance [19], [20]. If we consider a user in the jth class, called u_j, no more than $K_r T / K_i T = 2^{r-j}$ bits are dependent. Here, a sequence of 2^{r-j} bits is called a segment of u_j. Hence, to calculate the error probability of u_j, we need to calculate the joint probability distribution function (pdf) of interference in a segment. This joint pdf is shown by $P_j(a_{(1)}, \ldots, a_{(2^{r-j})})$, where $a_{(l)}$ is the number of interfering users with the lth bit of the segment. To calculate P_j, first we

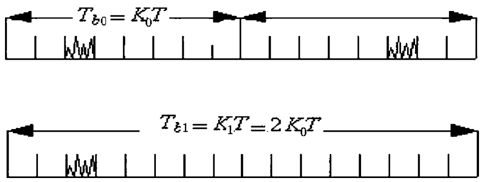

Fig. 15. Schematic timing diagram for two groups in the network.

consider interferences produced by users of different classes separately; P_{ji} denotes the pdf of interference of a user in class j caused by the users of class i. Consider a pulse sent by u_j. This pulse has a duration of T. A user from class $i < j$ sends a pulse every $2^i K_0 T$ seconds. Therefore, these two pulses interfere with probability $p = 1/(2 \times 2^i K_0)$. (The factor $1/2$ is included because we assume u_i sends "1" and "0" with equal probability and only "1" causes interference.) Since we have n_i users in class i, $a_{(k,i)}$ users from class i interfere with the kth bit in the segment with probability

$$P_{ji}^{k}\left(a_{(k,i)}\right) = B\left(a_{(k,i)}; n_i, \frac{1}{2^{i+1}K_0}\right), \qquad \text{for } i < j \quad (1)$$

where

$$B(i; n, p) \stackrel{\triangle}{=} \binom{n}{i} p^i (1-p)^{n-i}. \quad (2)$$

Noting that u_j does not interfere with itself, we have the following:

$$P_{jj}^{k}\left(a_{(k,j)}\right) = B\left(a_{(k,j)}; n_j - 1, \frac{1}{2^{j+1}K_0}\right). \quad (3)$$

Since class i has a higher bit rate than that of class j, and transmitted pulses hop among the available pulse slots in each bit, numbers of interfering users from class i in each bit in the segment are independent; hence,

$$P_{ji}\left(a_{(1,i)}, \ldots, a_{(2^{r-j},i)}\right) = \prod_{k=1}^{2^{r-j}} P_{ji}^{k}, \qquad \text{for } i \le j. \quad (4)$$

If $i < j$, different bits are dependent. However, interference caused by users from class i is only dependent over *intervals* containing 2^{i-j} bits. Bits sent by u_i may interfere only with one of the 2^{i-j} bits sent by u_j. Because any user from class i interferes with a certain bit among 2^{i-j} bits of an interval with probability $p = 1/(2 \times 2^i K_0)$, the interference distribution in an interval of 2^{i-j} bits is

$$I_{ji}\left(a_{(1,i)}, \ldots, a_{(2^{i-j},i)}\right) = \binom{n_i}{a_{(1,i)}, \ldots, a_{(2^{i-j},i)}} \left(\frac{1}{2^{i+1}K_0}\right)^{\sum_{k=1}^{2^{i-j}} a_{(k,i)}} \left(1 - \frac{1}{2^{j+1}K_0}\right)^{n_i - \sum_{k=1}^{2^{i-j}} a_{(k,i)}}. \quad (5)$$

Since bits of different intervals of 2^{i-j} are independent, for $i > j$

$$P_{ji}\left(a_{(1,i)}, \ldots, a_{(2^{r-j},i)}\right) = \prod_{m=0}^{2^{r-i}-1} I_{ji}\left(a_{(2^{i-j}m+1,i)}, \ldots, a_{(2^{i-j}m+2^{i-j},i)}\right). \quad (6)$$

And the overall interference in a segment is

$$P_j\left(a_{(1)}, \ldots, a_{(2^{r-j})}\right) = \sum_{\left(\sum_{i=0}^{r} a_{(k,i)} = a_{(k)}\right)} \prod_{i=0}^{r} P_{ji}\left(a_{(1,i)}, \ldots, a_{(2^{r-j},i)}\right). \quad (7)$$

Given that a users are interfering with a bit of the desired user, BER is derived in [20] as

$$\mathrm{BER}(a) = \frac{1 - \gamma(a) + \rho(a)}{2} \quad (8)$$

where

$$\gamma(a) = 1 - e^{-(I_{\mathrm{th}} N_0 / a I_0)} \quad (9)$$

$$\rho(a) = 1 - Q\left(\frac{\sqrt{2N_0}}{a}, \sqrt{\frac{2N_0 I_{\mathrm{th}}}{a I_0}}\right) \quad (10)$$

in which N_0 is the number of code elements, I_0 is the signal power, and I_{th} is the detector's threshold level. Packet success probability of a user in class j can be written as

$$P_s(j) = \left(\sum_{\substack{a_{(l)} \\ 1 \le l \le 2^{r-j}}} P_j\left(a_{(1)}, \ldots, a_{(2^{r-j})}\right) \prod_{k=1}^{2^{r-j}} \left(1 - BER(a_{(k)})\right)\right)^{L/2^{r-j}} \quad (11)$$

where L is the packet size.

REFERENCES

[1] K. I. Kitayama and M. Murata, "Photonic access node using optical code-based label processing and its applications to optical data networking," *J. Lightw. Technol.*, vol. 19, no. 10, pp. 1401–1415, Oct. 2001.
[2] L. Brzozowski and E. H. Sargent, "Optical signal processing using nonlinear distributed feedback structures," *IEEE J. Quantum Electron.*, vol. 36, no. 5, pp. 550–555, May 2000.
[3] L. Brzozowski and E. H. Sargent, "All-optical analog-to-digital converters,hardlimiters,and logic gates," *J. Lightw. Technol.*, vol. 19, no. 1, pp. 114–119, Jan. 2001.
[4] Z. Jiang, D. S. Seo, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, "Reconfigurable all-optical code translation in spectrally phase-coded O-CDMA," *J. Lightw. Technol.*, vol. 23, no. 6, pp. 1979–1990, Jan. 2005.
[5] I. Keslassy, S. T. Chuang, K. Yu, D. Miller, M. Horowitz, O. Solgaard, and N. McKeown, "Scaling internet routers using optics," *Proc. 2003 Conf. Appl., Technol., Archit., Protocols Comput. Commun.*, pp. 189–200.
[6] W. Bux, W. E. Denzel, T. Engbersen, A. Herkersdorf, and R. P. Luijten, "Technologies and building blocks for fast packet forwarding," *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 70–77, Jan. 2001.
[7] N. McKeown, "Optics inside routers," presented at the Eur. Conf. Exhib. Opt. Commun, Rimini, Italy, 2003.
[8] A. Watanabe, K. Noguchi, K. Shimano, T. Kawai, E. Yoshida, A. Sahara, T. Takahashi, S. Okamoto, T. Goh, and Y. Takigawa *et al.*, "Photonic MPLS router to create bandwidth-abundant IP networks," *J. Lightw. Technol.*, vol. 21, no. 11, pp. 2851–2862, Nov. 2003.
[9] Y. Takushima and K. Kikuchi, "Photonic switching using spread spectrum technique," *Electron. Lett.*, vol. 30, no. 5, pp. 436–438, 1994.
[10] K. I. Kitayama and M. Murata, "Versatile optical code-based MPLS for circuit, burst, and packet switchings," *J. Lightw. Technol.*, vol. 21, no. 11, pp. 2753–2764, Nov. 2003.

[11] S. J. B. Yoo, F. Xue, Y. Bansal, J. Taylor, Z. Pan, J. Cao, M. Jeon, T. Nady, G. Goncher, and K. Boyer *et al.*, "High-performance optical-label switching packet routers and smart edge routers for the next-generation Internet," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 7, pp. 1041–1051, Sep. 2003.

[12] Z. Jiang, D. Seo, S. Yang, D. E. Leaird, R. V. Roussev, C. Langrock, M. M. Fejer, and A. M. Weiner, "Four-user 10-Gb/s spectrally phase-coded O-CDMA system operating at 30 fJ/bit," *IEEE Photon. Technol. Lett.*, vol. 17, no. 3, pp. 705–707, Mar. 2005.

[13] H. Sotobayashi, W. Chujo, and K. I. Kitayama, "Highly spectral-efficient optical code-division multiplexing transmission system," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 2, pp. 250–258, Mar/Apr. 2004.

[14] R. P. Scott, W. Cong, K. Li, V. J. Hernandez, B. H. Kolner, J. P. Heritage, and S. J. B. Yoo, "Demonstration of an error-free 4/spl times/10 Gb/s multiuser SPECTS O-CDMA network testbed," *IEEE Photon. Technol. Lett.*, vol. 16, no. 9, pp. 2186–2188, Sep. 2004.

[15] N. Wada and K. I. Kitayama, "Photonic IP routing using optical codes: 10 Gbit/s optical packettransfer experiment," presented at the Opt. Fiber Commun. Conf., vol. 2, Baltimore, MD, 2000.

[16] S. Galli, R. Menendez, P. Toliver, T. Banwell, J. Jackel, J. Young, and S. Etemad, "DWDM-compatible spectrally phase encoded optical CDMA," *Proc. IEEE Global Telecommun. Conf. (GLOBECOM 2004)*, vol. 3, pp. 1888–1894.

[17] S. Shen and A. M. Weiner, "Suppression of WDM interference for error-free detection of ultrashort-pulse CDMA signals in spectrally overlaid hybrid WDM-CDMA operation," *IEEE Photon. Technol. Lett.*, vol. 13, no. 1, pp. 82–84, Jan 2001.

[18] T. H. Shake, "Security performance of optical CDMA against eaves dropping," *J. Lightw. Technol.*, vol. 23, no. 2, pp. 655–670, Feb. 2005.

[19] J. A. Salehi and C. A. Brackett, "Code division multiple-access techniques in optical fiber networks. II. Systems performance analysis," *IEEE Trans. Commun.*, vol. 37, no. 8, pp. 834–842, Aug. 1989.

[20] J. A. Salehi, A. M. Weiner, and J. P. Heritage, "Coherent ultrashort light pulse code-division multiple access communication systems," *J. Lightw. Technol.*, vol. 8, no. 3, pp. 478–491, Mar. 1990.

[21] T. Wolf and J. S. Turner, "Design issues for high-performance active routers," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 3, pp. 404–409, Mar. 2001.

[22] E. Inaty, H. M. H. Shalaby, P. Fortier, and L. A. Rusch, "Multirate optical fast frequency hopping CDMA system using power control," *J. Lightw. Technol.*, vol. 20, no. 2, pp. 166–177, Feb. 2002.

[23] J. A. Salehi, "Code division multiple-access techniques in optical fiber networks. I. Fundamental principles," *IEEE Trans. Commun.*, vol. 37, no. 8, pp. 824–833, Aug. 1989.

[24] K. Kitayama, H. Sotobayashi, and N. Wada, "Optical code division multiplexing (OCDM) and its applications to photonic networks," *IEICE Trans. Fundam. Electron., Commun., Comput. Sci.*, vol. 82, no. 12, pp. 2616–2626, 1999.

[25] S. Zahedi and J. A. Salehi, "Analytical comparison of various fiber-optic CDMA receiver structures," *J. Lightw. Technol.*, vol. 18, no. 12, pp. 1718–1727, Dec. 2000.

[26] A. M. Weiner, "Femtosecond pulse shaping using spatial light modulators," *Rev. Sci. Instrum.*, vol. 71, no. 5, p. 1929, 2000.

[27] G. Cincotti, "Design of optical full encoders/decoders for code-based photonic routers," *J. Lightw. Technol.*, vol. 22, no. 7, pp. 1642–1650, Jul 2004.

[28] N. Wada and K. Kitayama, "A 10 Gb/s optical code division multiplexing using 8-chip opticalbipolar code and coherent detection," *J. Lightw. Technol.*, vol. 17, no. 10, pp. 1758–1765, Oct. 1999.

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