"Optical Packet Switching System for Optical Nodes in Next-Generation Metropolitan and Access Networks"

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***Resumo* – Um novo sistema para geração, chaveamento e roteamento de pacotes ópticos é descrito visando aplicação em nós de redes ópticas de próxima geração (NGON). Os pacotes ópticos são compostos por um campo de cabeçalho em freqüência e um campo de carga útil digital de alta capacidade (Gb/s). Os nós de chaveamento óptico incluem as funcionalidades de bloqueio, roteamento e retirada de pacotes, e são controlados por circuitos eletrônicos lógicos, que rapidamente processam a informação contida no cabeçalho dos pacotes ópticos, permitindo baixa latência. O chaveamento é realizado pacote-a-pacote, e o tempo de reconhecimento do cabeçalho e chaveamento dos pacotes ópticos é de alguns microsegundos (μs) . Este sistema, aplicável a redes metropolitanas de acesso, apresenta arquitetura simples, operação eficiente, e pode ser visto como uma solução atraente nos aspectos técnicos e econômicos. É totalmente compatível com redes ópticas WDM.**

Palavras-Chave: **Chaveamento de pacotes ópticos, Comunicações Ópticas, Sistemas de Transmissão digital.**

Abstract: **A simple system for generation, switching and routing of optical packets is described, aimed for use in nodes of next-generation optical networks (NGON). The optical packets are composed of an in-band frequency tone header, and a high-capacity transparent digital payload, occupying separate fields. The optical node switching action includes blocking, routing and drop functions, controlled by electronic logic circuits, performed on a packet-by-packet basis, with only the header information being processed. Total header processing and optical packet switching time is few micro seconds (~μs). This system is designed as a techno-economical solution for metro-access transport, having low latency and low packet loss, being fully compatible with WDM optical networks**.

Keywords: **Photonic packet switching, Optical Communications, Digital Transmission Systems.**

I. Introduction

All-optical networks will require photonic switching with opto-electric conversion only at end users[1]. Photonic switching is an attractive solution for connectionless next-generation optical networks (NGON) [2,3,7] based on decentralized switching and routing and high-capacity connections. Packet switching in today's optical networks using Internet protocol (IP) packets and Ethernet protocols, require statistical multiplexing and synchronous framing for transport [2]. Optical packets, on the other hand, do not require any further framing; they are self-routing asynchronous transport units that carry digital payload independent of the transmission rate, modulation format, and framing. An optical packet bypasses all the intermediate nodes along a communication path. Consequently, the digital payload characteristics and transmission properties become transparent to these nodes. Optical packet switching (OPS) is more appropriate in metro-access networks. It complements wavelength routing, which is proving effective in wavelength division multiplexing (WDM) backbone networks [5,7]. However, to be an attractive solution, OPS nodes must be simple, cost effective, and reliable.

In this paper we describe a 2x2 OPS node that has been designed and implemented in our labs. The present solution adopts short-duration packets with radio frequency (RF) headers, and high-capacity payload, in a time frame with separate fields for header and payload. This switching system also provides optical packet contention resolution at nodes through deflection routing, keeping very low packet loss. The optical nodes architecture includes drop (and add) function, and is controlled by electronic logic circuits, with switching and routing performed on a packet-by-packet basis, according to pre-established allocation tables. Allocation tables correlate the header frequency of packets with the network node addresses [4, 6]. The digital payload remains untouched through the network, and is processed only at end user's location, outside the optical packet switching network. We assume that this feature should guarantee simple node architecture, low latency, and fast switching, keeping in mind that the actual packet remains all the time in the network at the optical layer only.

II. Optical Packet Generation And Switching

The optical packets used in the project suggest a packet that has header and payload field separated, called field-header (FH) optical packets. Header and payload thus form a TDD (Time Division Duplexing) structure. The optical packets are characterized by having a frequency tone header in the low RF band (few MHz) and a digital payload. Packets have total duration of few μs, the payload range has been from 1 to 5 Gbps, but can be further extended. In Fig. 1 we can see the optical packet diagram, as implemented.

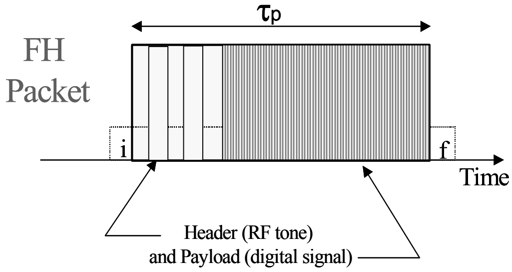
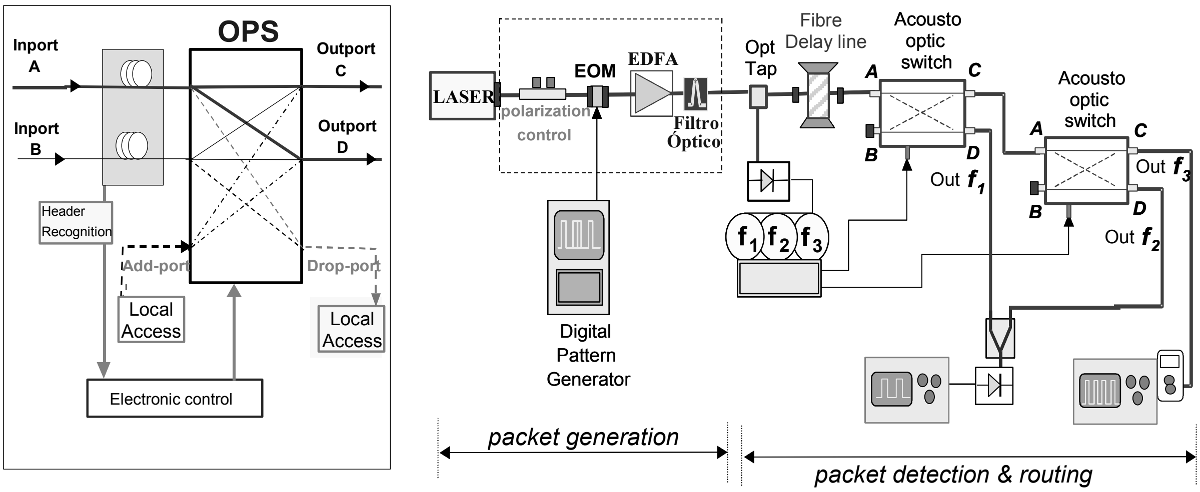


Fig. 1 – Frequency Header Optical Packet Diagram

In Fig. 2 the optical node diagram and the experimental setup for optical packet generation and switching are presented. Fig. 2a shows the node architecture, which includes add-drop functions, controlled by electronic logic circuits. The node control has allocation tables that relate packet frequency header with node output directions (addresses). In Fig. 2b we observe the experimental setup for optical packet generation and switching in a 2x[1x2] configuration. The packets are constructed initially in the pattern generator, as a sequence of different header frequency packets with the same payload field. Such sequence is then loaded on the optical CW (Continuous Wave) laser signal through an electro-optical lithium niobate (E-O $LiNbO_3$) modulator. Each header is composed of long alternate 1 and 0 bit sequences, which reproduce the RF waveform; the payload is made of PRBS ($2^{23} - 1$) words at rates adjustable between 1 and 5 Gb/s – the experimental values were adjusted between 1.8 and 3.3 Gb/s. The header-payload field relative length is also adjustable, from initial 0.5-0.5 to practical 0.1-0.9.

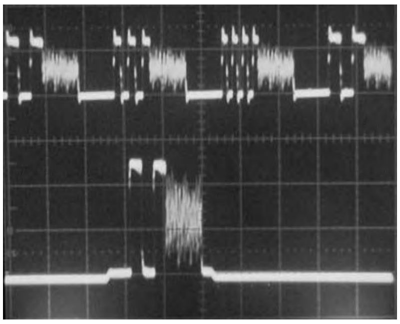
Currently, optical packets have 0.2-0.8 frame relation with total frame length of 2μs (which corresponds to payload of 500 bytes @ 2,55 Gbps); and header frequencies 3, 5 and 7 MHz. Other header frequencies and longer packets have been used with equivalent performance, demonstrating that packets are adjustable to different network transport requirements. An optical amplifier is included to overcome modulation and polarization control losses. An optical filter centered at DFB laser wavelength, with pass-band ± 0.5 nm (18 dB rejection), is included to eliminate the amplified stimulated emission (ASE). This concludes packet generation stage.

The optical packet is then transmitted to the network node. At node input, optical packet is split and partly directed to an optical receiver followed by an especially designed circuit for header frequency detection and recognition, which will deliver TTL signals to activate the acousto-optical switches (AOS), according to a pre-allocated frequency table, making the packets switching. The optical packet itself follows to the optical switch, and a fibre delay line is included for the optical packets to wait the header detection and processing and switch activation. The header recognition circuit (HRC), acts on the following way: a counter is activated by the first transition of the header waveform and opens a gate equal to the header duration. At the end of the header duration, the counter transfers a gate signal to a memory and timer circuit, which in turn opens a new gate with duration equal the payload field. Both gates are combined to form a new one, with duration larger than packet size. This gate is the one that activates the AOS. The HRC response time is very short (40ns); whereas the header conversion/ reading/processing composite time is 450ns, and the AOS drive time 2.1μs.



a) b)

Fig. 2 – Optical node diagram (a) and Experimental setup (b)



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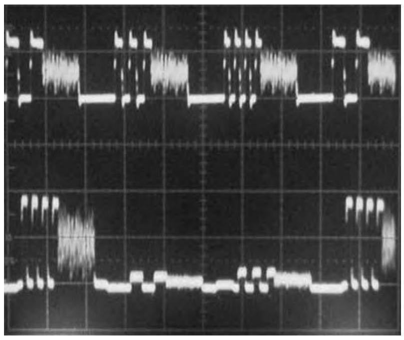

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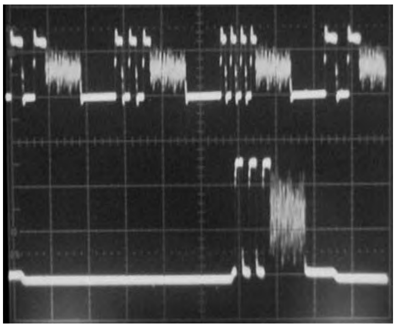

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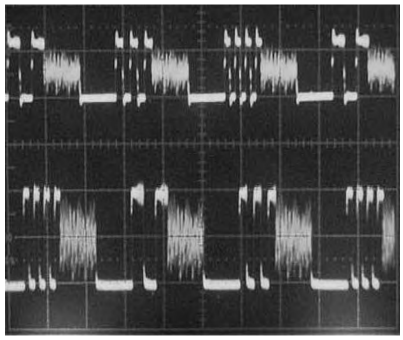


d)

Fig. 3 – FH Packets: a) Output D of Switch 1, ON – Cross State; b) Output D of Switch 2, ON – Cross State; c) Output C of Switch 2, ON – Cross State; d) Output C of switch 2, OFF –Parallel State.

In Fig. 3 we can appreciate the results of the packet switching in the experiment above. The upper trace in all cases is the input optical packet stream at the tap receiver; and the bottom traces are the switch outputs. Fig. 3a shows the output D of switch 1 that assumes cross-state for packets with header f_1 to be dropped; the other packets are directed to output C (switch 1). Fig. 3b shows the output D of switch 2 that assumes cross-state for packets with header f_2 to be dropped, while packet with header f_3 is directed to output C (switch 2), as we see in the Fig. 3c. Finally Fig. 3d shows output C of switch 2, when both AOS are in parallel state.

It is seen that switching is performed on single packet basis, with rejection ratio measured to be excess of 50 dB. The present transmission power balance is +2dBm at laser CW output, and -12 dBm average power, as measured at out-port C of switch 2 (Fig. 2d), when both switches are off. Under this condition we measured transmission BER$<10^{-12}$ @ 2,55 Gb/s using PRBS (2^{23} –1).

In order to demonstrate compatibility with wavelength routed WDM networks, the ITU channel 37, λ=1547.7 nm, was adopted because it goes through the OMEGA Network [5]. It is a sister project, which consists of an optical mesh network having five nodes, with wavelength protection and routing at the optical WDM layer level. The signal containing optical packets was directly connected to optical nodes in the Ω-Network. The nodes are 'separated' by 20 km of fiber. At first, the optical packets got in and out of adjacent nodes (single hop); then connections were altered and extended to three nodes (2 hops, 40 Km), and four nodes (3 hops, 60 Km). In all cases the packet integrity was preserved and packet switching performance remained unaltered.

III. OPTICAL PACKET SWITCHING AND ROUTING

In Fig. 4 we can see the experimental setup for a bufferless optical network node, with 2x2 architecture (actually 3x3 considering add-drop), where each node has two input and output ports, typical Manhattan Street [6] networks. Adopting this topology, contention between optical packets appears [7], and an intelligent circuit must solve it. This circuit is called logical decision circuit (LDC); it will act solving contention when two packets that arrive at the two in-ports of node within packet time require the same output port. One is routed, the other is deflected, without packet loss or degradation. In this setup, both inputs of AOS a relatively short fibre delay line (~600m) is included to hold the optical packet while the HRC and the LDC are processing the packet header information, and the optical switch is being actuated (or not!). When a contention occurs between packets the LDC solve it by spatial deflection routing, then the packet that arrives first is served first, characterizing first-in first-out, FIFO. But no packets are lost because this is a condition imposed for the node operation. It should be noted that the LDC has three states (cross, parallel and stand-by), whereas the optical switch has only two states (cross and parallel); thus the LDC will allow the optical switch to change state only when there are no packets present in the node (stand-by state); otherwise the optical switch is blocked at parallel or crossed state. This condition preserves packet integrity and traffic fairness. An additional fibre delay line is included at one input of AOS aiming packets with same header do not arrive at input node in the same packet time, then the LDC make the routing of optical packets according with pre-established allocation table.

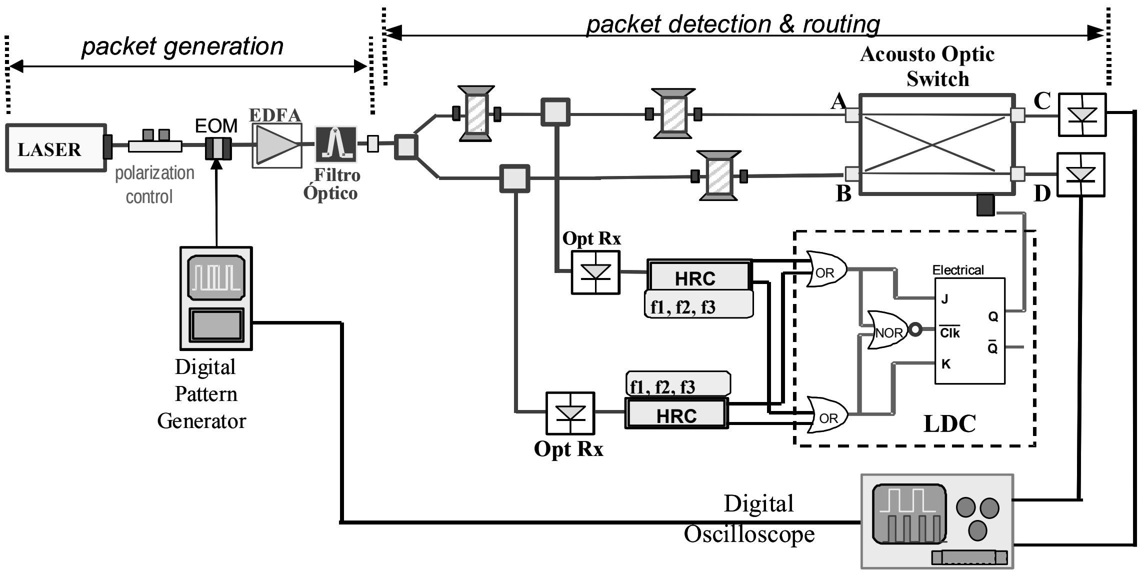
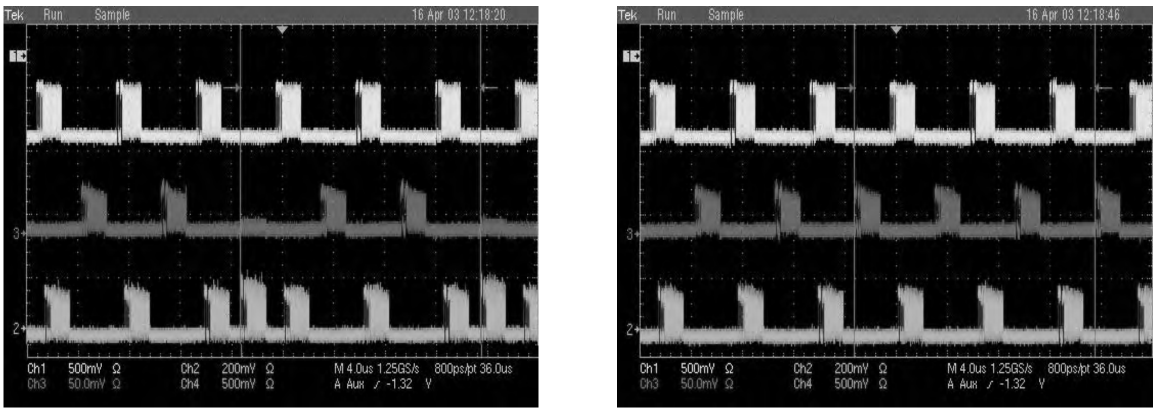


Fig. 4 – Experimental setup for optical packet switching, using 2x2 topology.



a) b)

Fig. 5 – Actuation of LDC routing packets with header f_2 only; a) LDC on; b) LDC off.

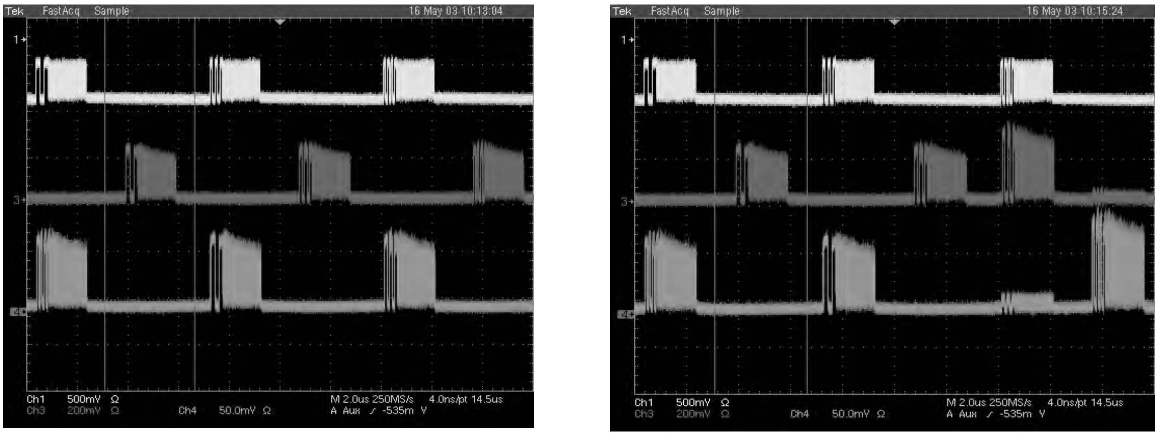
In Fig. 5 we can see the LDC routing packets only with header f_2 , as in [9]. In this situation frequencies f_1, f_2 and f_3 are assigned in the pre-established allocation table as f_1, f_3 → indifferent output; f2 → output D. Then all packets with header f_2 are directed to output D, without degradation or packet loss. The top traces are the electrical pattern input. The middle trace and bottom traces are the optical outputs C and D of the AOS, respectively. When the LDC is actuating, only packets with header f_1 and f_3 will exit in output C, while all packets with header f_2 are directed to output D together with the packets with header f_1 and f_3; as we see in Fig. 5a. In Fig. 5b we can see the packets traffic when the LDC is off, then the packets that arrive in the AOS input are transmitted to the outputs without any alteration; the switch keep parallel state and transfers the packets. Thus, the LDC acts according with pre-established allocation table. At this stage, it can be noticed that packets with same header occur in both outputs because in this case the LDC is routing only packets with header f_2 [9]. Later we will see that further implementations permit more frequencies to be routed.

After the correct routing of packets with header f_2, we proceeded to investigate the functionality of LDC when two frequencies are simultaneously inspected. In this new stage the system works with optical packets that have headers with frequencies f_2 and f_3. Thus a new allocation table was pre-defined as f_1 →

indifferent outputs; $f_2 \rightarrow$ only output C; $f_3 \rightarrow$ only output D.

In Fig. 6, the results of the LDC actuation can be appreciated, when it works analysing two header frequencies. The upper trace (Tr.1) is again the electrical pattern input; the middle trace (Tr.2) and bottom trace (Tr.3) are the optical outputs C and D of the AOS, respectively. It can be noticed that the LDC routes the optical packets according to the pre-established allocation table. Fig. 6a shows the optical packet traffic when the LDC is off. The AOS keeps parallel state and packets that arrive at node inputs are directly transferred to outputs without information treatment. In Fig. 6b we appreciate the actuation of LDC in combination with the HRC's, making the correct routing of packets with header f_2 and f_3. At output C, we have only packets with header f_1 and f_2, while packets with header f_1 and f_3 are in the output D. Packets with header f_1 are present in both outputs because it is the indifferent frequency (does not contend).

The assembly of more HRC's is underway, in other implement a combination of Fig. 2b and Fig.4, that will allow all the demonstrated functionalities to be working together in one complete single experiment.



a) b)

Fig. 6 – Actuation of LDC routing optical packets with header f_2 and f_3; a) LDC off; b) LDC on.

An important detail can be noticed in the Fig. 6b: the cross-talk of the optical switch (or the rejection ratio of the routed packet) is an unsatisfactory -10 db for C→D, and an excellent -35 dB for D→C; this, unfortunately is intrinsic to both AO switches [10] that we have available in the lab. We interpret that since the AOS's operate based on zero and first-order diffraction in an acousto-optic crystal, the rejection ratio from order 0 to first order is not the same as the converse. Another aspect to notice is that packets that are actually switched present a slightly higher power compared with the undeflected (pass thru) ones; we can only attribute this to an effect related to different optical paths inside the optical switch. To solve these matters, we anticipate that a change in switch technology, from AOS to SOA (semiconductor optical amplifiers) based switches will help solve these matters. Furthermore, the present concept of OPS can be extended from packet-by-packet to burst switching (OBS), where several packets are switched together within a gate duration, using the same frequency header configuration, as well as the same experimental set-up and node architecture.

IV. CONCLUSION

We have successfully demonstrated a simple system for optical packet generation, switching and routing for next-generation optical networks (NGON's), based on asynchronous packet transport. Total switching times in the nodes of ~2 μs - from packet arrival at node to its exit route - were obtained. This means orders of magnitude faster as compared to values of hundreds of milliseconds that IP routers take to process and forward packets. The optical packets presented here are characterized by having independent separate fields for the RF header and the high-capacity digital payload can have duration adjustable in the range 2-6 μs, with maintaining a 0.1-0.9 relation. Headers consist of a low-RF frequency tone, which uniquely identifies destination nodes in the network; further work will include double headers to include priority, hierarchy and size information. The digital payload is transparent to data rates and formats and is not processed at any point in the network.

Experiments on transmission and switching were performed with packets having header frequencies between 2 and 12 MHz, and variable rate payloads from 1.8 to 3.3 Gb/s. Bit-error rate measurements were carried out at 2.5 Gb/s, with excellent results of BER figures below 10^{-12}. Packet-by-packet switching was demonstrated and packet contention was solved by deflection routing, controlled by an electronic logical circuit.

In all cases, the fast optical switching and routing preserved packet integrity and guaranteed low latency for the node, and consequently for the optical network. Support from network simulation studies under various packet traffic situations [8, 11] complemented this experimental work, and has indicated very low packet loss for moderate traffic load (<40% network capacity, 16-node MS network), in favor of our deflection routing assumptions. Experiments of packet transmission extending beyond 60 km, through optical nodes in a multiwavelength network with dynamic wavelength routing (OMEGA network [5]), successfully demonstrated full compatibility and applicability to DWDM networks.

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