OPTICAL PACKET SWITCHING: GENERATION, TRANSMISSION AND RECOVERY DEMONSTRATION USING A FREQUENCY TONE HEADER

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Abstract - We have successfully implemented in our labs the generation, transmission, detection and routing of optical packets for next generation all-optical networks.. Ultrafast switching function (µs timebase) is demonstrated using a RF frequency tone as header, combined with a high-capacity digital payload, both inserted in the optical packet. The packet may propagate kilometers in the network, without degrading. At node input the optical packet header is detected and a switching control mechanism directs the packet to a prescribed output, without further opto-electric conversion. The optical circuit is noise-free, with BER results better than 10^{-12} .This system is applicable to metropolitan and access WDM optical networks. style.

Keywords: Optical Packets, Photonic Switching, Optical networks, digital communications.

Resumo - Implementamos com sucesso em nossos laboratórios, a geração transmissão detecção e roteamento de pacotes ópticos para Redes Todas-Ópticas de Próxima Geração. Chaveamento ultra-rápido (base de tempo µs) é demonstrado usando um tom RF como cabeçalho, que é inserido no pacote óptico combinado com uma carga útil digital de alta capacidade. O pacote carregado propaga-se pela rede óptica e é detectado na entrada do nó seguinte, distante do local de geração até vários kilometros, sem degradação. Na entrada do nó, um mecanismo de controle de chaveamento direciona o pacote óptico a uma porta de saída, sem conversão eletro-óptica. O circuito óptico é livre de ruído, com medidas de taxa de erro até melhores do que 10^{-12}. Este sistema pode ser aplicado em redes ópticas WDM metropolitanas e acesso.

Palavras-Chave: Pacotes Ópticos, Chaveamento Fotônico, Redes Ópticas, Comunicações Digitais.

1. INTRODUCTION

It is expected that in the near future all-optical networks, where opto-electric conversion takes place at or near end points, will prevail, following the "connectionless" principles of IP packet routing. In this way, a demand for optical packets and optical packet switching naturally comes into scene. Our objective is to demonstrate optical packet transmission and recovery as a solution for optical network transport and switching.

WDM networks have already provided important benefits of increased available bandwidth for point to point optical links, but the processing capabilities of electronic switches and routers are expected to impose serious bottlenecks on future optical networks [1].

The bandwidth offered by the optical fiber combined with the flexibility of WDM and optical switching offers the possibility for implementing optical packet switched networks, which are expected to overcome the above mentioned technological bottlenecks.

Optical packet switching provides greater flexibility and easier management for the network because data remains in the optical domain from source to destination, and therefore avoids delays in opto-electronic conversion and electronic processing at switching nodes. Photonic switching combines higher switching speed with greater bandwidth which are expected to provide node throughputs above Tb/s [2]. Moreover, by keeping signals in the optical domain, without opto-electric [OE] conversion for switching and routing, nodes can be simplified, and applicability to high-capacity access networks becomes a real issue [6]. Some important issues that are still under investigation, include optical packet routing and flow control, contention resolution and synchronization at switch input and output ports [3].

At present, electronic processing of packet headers, without any impact on payload content, remains an attractive alternative to perform switching functions such as addressing and forwarding. One of several coding techniques introduced for optical packet switching is sub-carrier multiplexing (SCM) [3]. SCM involves the transmission of a signaling or control channel, which is the header signal, on a frequency band separate from the payload data, which is usually in the RF band of electromagnetic spectrum, so that the header and payload are encoded as separate frequency bands on the optical carrier. However, it should be pointed out that the payload is necessarily of high capacity, and the frequency tone can be modulated or not, and located inside or outside the baseband of the digital payload. An important consideration in the switching mechanism and technology is the synchronization of the payload and header during the routing process, and the ensuing complexity of the switch node, which increases severely if electronic processing or high frequency active microwave components are chosen [4, 5]. The solution using a single tone RF frequency header mixed with the payload avoids synchronization and signaling problems. In this case, the duration of identification and switching control at the nodes is asynchronous, and only linked with the arrival and duration of the optical packet itself. Also the need for complex microwave techniques is avoided.

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In this work, we investigate addressing and forwarding at optical nodes, using header of RF frequency as pilot tone in optical packets for digital transmission. This maintains payload transparency, which can be of any rate or format, and contributes for demonstration of packet switching in optical networks. In section 2, we describe the experimental setup for photonic packet switching architecture that we have implemented; and in section 3, we present the results that were obtained and the discussion and analysis of our data.

2. EXPERIMENTAL SETUP

To implement optical packet switching, the experimental setup in Fig.1 was constructed. It consists of a section where the packet is generated, and a section where it is detected. These two sections can be several kilometers apart, simulating a transmission node and a routing node. At the present configuration the routing node is just 1x2, and an arriving packet must decide output port 1 or 2. The time frame, or envelope, for the optical packet is provided by pulse generator which directly modulates a single longitudinal mode DFB laser (ITU-grid) with a square pulse of fixed duration. The pulse width can be adjusted in the range 2-4 µs, with a typical repetition frequency of 100 kHz. The RF frequency tone f_1 is mixed with the digital load signal through an RF combiner and inserted in the packet, using an EOM (electro-optic modulator) ensemble, consisting of driver and modulator, and also input polarization control. An optical arm for signal reference is also provided, linked directly to the reception end receiver.

The packet is amplified by an EDFA to overcome modulator and polarization control losses, which add to ~10 dB; at the EDFA output an optical tunable filter is inserted to mitigate ASE (amplified spontaneous emission) noise generated by the optical amplifier. The optical packet is thus assembled and can now travel for any distance from few hundred meters to several kilometers before reaching the next node. At present, we have limited this distance to 3 km from node to node, but longer distances can be considered if demanded. Upon arrival at a node input the optical signal is split. One part follows to a delay line, and another part goes to optical detection, header recognition and switching control. To actuate the optical gate (or switch) the header signal is converted and sent to switching control circuit, which detects presence of prescribed frequency tone f_i (i=1). If f_1 is there, a gate (or switch) control signal is instantly generated and opens the optical gate (or switch). If f_1 is not detected, gate remains closed (or switch remains in the same state [7]). Once the gate is open it remains open for packet duration, and then closes. The switch control circuit has an adjustable delay that provides a guard time before and after the optical packet, so that no packet or part of it is lost at the optical gate (or switch). This system is also now being used to direct packets in a 2x2 optical switch [7]. Finally, optical packets are received in a fast optical receiver (BW>2 GHz) connected to an analog oscilloscope for visualization and timing, or to a digital oscilloscope and error detector for BER measurements.

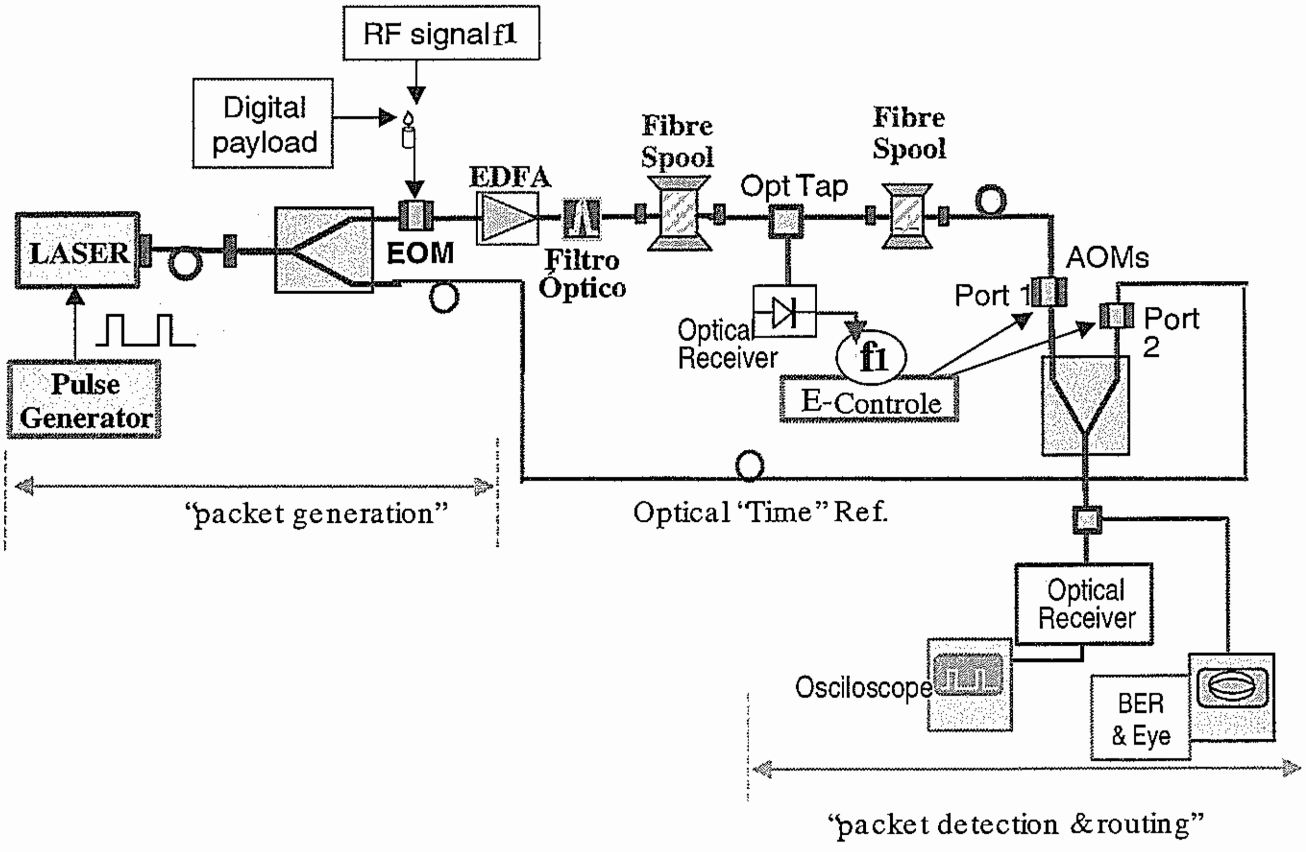

Figure 1. Experimental setup showing optical packet generation, detection and switching parts.

3. RESULTS AND DISCUSSION

The oscilloscope traces showing optical packet and reference signals is shown in Fig.2 . Trace *a* is the original (inverted) electrical pulse envelope, with duration 2.4 µs, and fixed spacing of ~14 µs. Trace *b* shows both the direct reference optical signal (not a packet), aligned in time with the input electrical signal, and the optical packet, shifted in time by exactly 4.1µs, which is the travel time through the complete optical circuit. Inside the packet are contained the digital load signal and the analog RF tone signal. In Trace *b* the tone signal is *on*, and gate 1 will open and close exactly for the packet duration, because the gate control TTL signal will keep it open only when and while the signal tone f_t is present. Gate 2 is maintained closed by a simultaneous <u>TTL</u> (complementary negative) signal. In Trace *c*, the tone signal is *off*, and gate 1 remains closed, so the packet cannot go through. This we demonstrates the optical packet detection and routing.

It must be noted that several adjustments and conditions must be met. First the RF tone must be above 100 mV for the gate to open and close precisely; also the pattern generator signal must not exceed 600 mV amplitude, otherwise some of the digital signal component frequencies will mask the tone in the decision circuit. The proper input to decision circuit from the optical tap receiver must be between 30 and 60 mV, otherwise it will simply not trigger the gate or will be saturated, respectively. The latter condition leads to the undesirable situation where the decision circuit input filter is overruled, with an overall degradation of output signal.

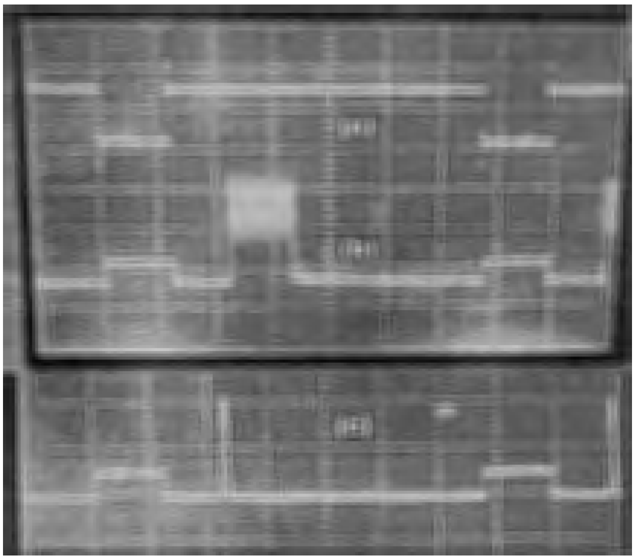

Figure 2. Analog oscilloscope traces showing optical packet and reference signals. (See text for *a*, *b* and *c*)

To ensure that the digital transmission has low error rate, the BER measurements were realized under controlled conditions. Due to the high sensitivity of the electro-optic modulator to input state of polarization, care was taken to stabilize polarization control, both at the modulator input and the electric DC bias input, as well as the relative amplitudes of RF tone and digital signal. The resulting eye diagrams were wide open, as can be seen in Fig.3, which implies very low error rate,. The best BER results were better than 1 x 10^{-12}, and under typical conditions, results were ~2 x 10^{-11} for received optical power in the range –15 to -16 dBm. A precision optical attenuator was introduced at gate output to verify performance with lower received power. When optical power value falls below –22 dBm, the error rate increases markedly.

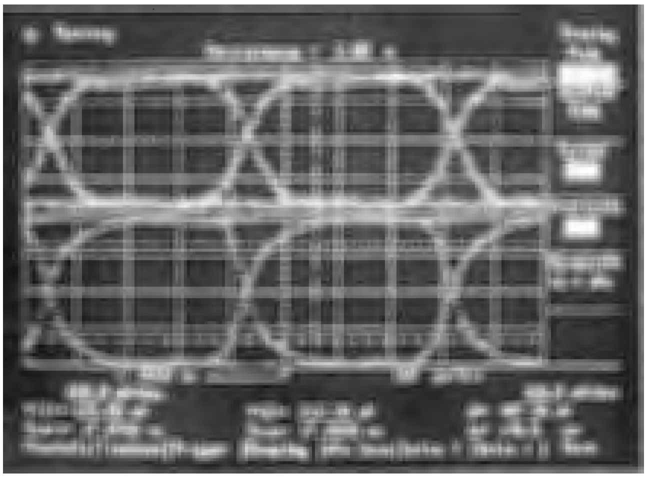

Figure 3. Digital Oscilloscope traces showing eye-diagrams: upper, input reference; lower, optical signal at port 1.

We have also investigated the impact of the presence of an RF analog tone signal on the integrity of the digital signal reception. Actually a compromise situation occurs. If the RF tone amplitude is relatively high, then the header detection is improved, but payload integrity is affected and errors may occur; on the other hand, a low power tone will not disturb the digital payload, but will hinder the detection of the optical packet header. In order to check what exact amplitudes of the RF tone are detrimental to the error rate, measurements where performed with several relative amplitudes. Results can be appreciated in Table 1 and in Fig.4. We observed that tone signal had a strong influence on the error rate beyond 20% relative amplitude, and very small influence for values below 15%, therefore a transition region occurs between these values. It must be emphasized that results in Table 1 and better part of Fig.4 are unattainable with other technologies than optical, except for distances of few meters, which would be rather impractical.

4. CONCLUSION

In this work we have experimentally demonstrated the generation, detection and routing of optical packets with µs duration and spacing. Switching was accomplished on a packet-by-packet basis, due to very fast detection, decision and signaling. Detailed measurements included packet switching performance with the RF tone on and off, with different values for digital signal and RF tone relative amplitudes, and system sensitivity to various tone frequencies. BER measurements using combined signals yielded results better than 10^{-12}, under appropriate conditions, with wide open eye diagrams. This successful demonstration encourages further work towards 2x2 optical node switching operation, already under way.

Digital Signal Amplitude	RF Tone Amplitude	Resulting BER
750 mV	140 mV ⇒ **18 %**	$< 2 \times 10^{-11}$
700 mV	140 mV ⇒ **20 %**	$< 2 \times 10^{-10}$
650 mV	140 mV ⇒ **21 %**	$< 2 \times 10^{-9}$
600 mV	140 mV ⇒ **23 %**	$> 5 \times 10^{-9}$

Table 1. Detailed values for relative amplitudes and BER, at transition region. Results obtained under stable conditions, over several runs, without error bursts.

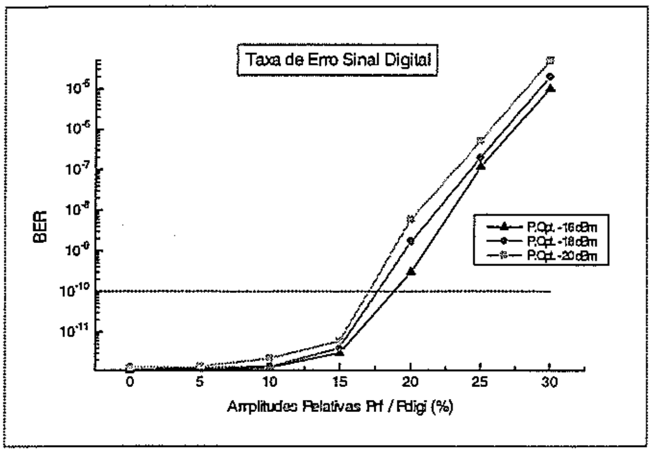

Figure 4. BER measurements for various relative amplitudes of RF tone and digital signal.

In summary, by using an in-band low-frequency tone as header for transmission and recovery of optical packets in transparent WDM networks, we anticipate a cost effective solution for wide access and metropolitan area next-generation optical networks.

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