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Channel limitations in ultra-fast multihop all-optical soliton networks.

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Abstract

Non-regenerative ultra-fast packet switching networks are severely constrained by the optical channel. Limitations on the maximum achievable bit rate and network physical size are presented when soliton pulses are used in a ShuffleNet network with deflection routing.

1. Introduction

All-optical networks take full advantage of the large bandwidth of the optical fiber since the transmitted signal remains in optical form from source to destination and electronic conversions occur only at the end-points of the connection, so that ultra-high bit rates may be used. However no regeneration of the optical packets is provided nor can error control be performed all-optically at intermediate nodes.

Noise and distortion in the optical fiber channel accumulate as the packet propagates so that the physical distance from source to destination is constrained at a given optical bit rate if the packet error rate is to be bounded below a given threshold.

Deflection routing[1,2] may be employed in regular mesh networks, such as ShuffleNet (SN),[3] to ease the problems arising from buffering at intermediate nodes, which is presently difficult to implement all-optically at very high bit rates, thereby preventing the use of standard store-and-forward (S&F) techniques.

The loss in efficiency of deflection routing with respect to S&F due to the increased average number of hops can be offset by the higher bit rates allowed by the all-optical channel so that a net throughput gain can in principle be obtained.[4] However, under deflection routing, repeatedly deflected packets travel long distances before reaching their destination and are thus more likely to be in error at the receiver.

The packet error rate can be obtained by conditioning on the number of hops n taken by the average packet in the network as

$$P(e) = \sum_{n=1}^{\infty} P(e/n)P(n) . \qquad (1)$$

The average hop distribution $P(n)$ depends only on network topology, routing and load, while the conditional probability of packet error $P(e/n)$ only depends on the characteristics of the optical channel, and is a typical point-to-point communication problem.

When transmitting ultra-high bit rates non-soliton pulses, fiber chromatic dispersion causes strong intersymbol interference and thus becomes the main system impairment. Solitons may be used instead because of their dynamic compensation of chromatic dispersion by high power induced self-phase modulation (SPM).[5]

When dealing with bit rates far beyond the speed of conventional optical receivers, all-optical techniques must be used to demodulate the packets. Recently, optical sampling techniques[6,7] have been proposed to demodulate such ultra-high bit rate data streams. Solitons have been shown to have the highest efficiency of all pulses in such schemes.[8]

We present here the results of a theoretical packet error rate analysis in a 64-node two-connected ShuffleNet (SN64) when ON/OFF soliton packet transmission is used at a fixed optical wavelength.

2. Network architecture

The nodes are connected by dedicated fiber links, and all node operations are slotted. The node structure is shown in Fig. 1. A replica of the incoming packets is used to perform header recognition and make the routing decisions. If the packets are at their destination, the local exchange-bypass

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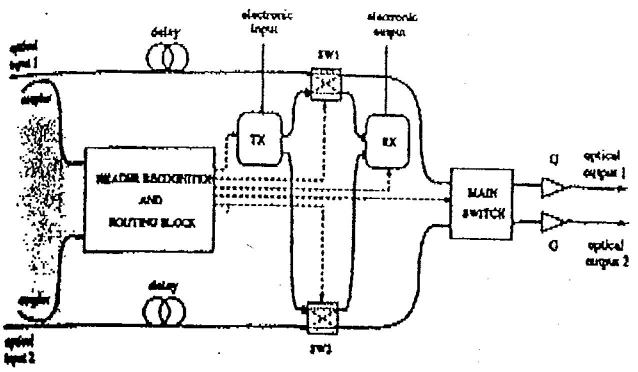

Fig. 1. Block diagram of the optical node.

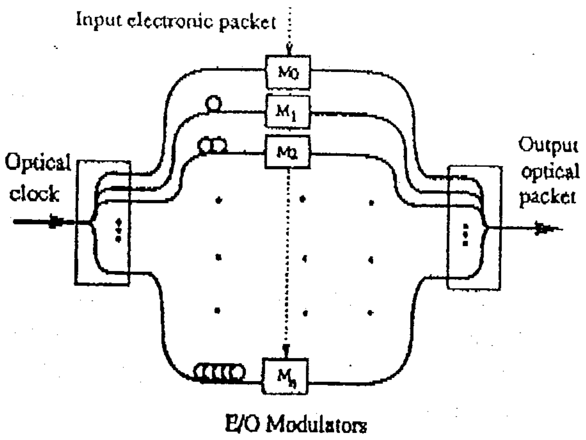

Fig. 3. Optical packet generation block.

switches SW1 and SW2 are set in cross position, and demultiplexing and detection are performed in the RX block. Transiting packets, instead, are routed through the main switch towards their destination nodes. Amplification is provided on the outgoing links to compensate for power losses at the node and in the fiber span leading to the node. The main switch is a simple exchange-bypass switch when no optical buffering is provided and hot-potato routing[1] is adopted. Fig. 2 shows the main switch structure when a single one-packet optical buffer is provided. This simple all-optical solution[9] uses a fiber loop delay where a packet can be stored only for one slot. The control of this switch is relatively simple, while adding more memory elements would only complicate the control and increase the power losses, without yielding an appreciable gain in performance.[10] A mode-locked laser is used as an optical clock to produce a stream of ultra-short pulses. In Fig. 3 one-bit shifted versions of the clock are separately modulated and recombined to form the optical packet. Each information bit controls its corresponding electro-optic modulator in a time as long as the optical packet duration. Fig. 4 shows the optical demultiplexer-receiver. A synchronized version of the optical clock is optically ANDed in a parallel bank of optical sampling gates with the received packet, thereby achieving demultiplexing of the optical bit pulses, which are singularly detected by photodiodes and converted to electronic form. The problem in each branch of the receiver reduces to the detection of suitably powered delta-like spikes in a time as long as the packet duration.

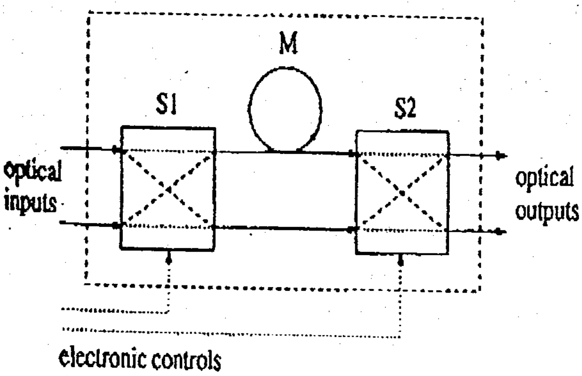

Fig. 2. Main switch with one-packet buffer.

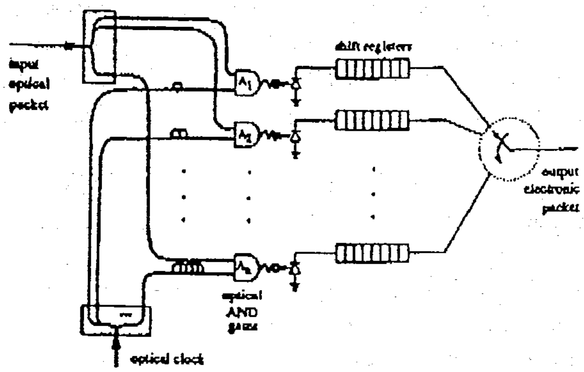

Fig. 4. Scheme of the optical receiver block.

3. Results

In the evaluation of the conditional packet error probability $P(e/n)$, ideal slot synchronization is assumed at all nodes. The optical receiver is assumed to be a bank of optical samplers, and each sampler is modeled as a gating sampling window. If the soliton falls inside the window, no error occurs because of its high energy. Errors are due to jitter of soliton arrival time in excess of the sampling window. This jitter is due to amplified spontaneous emission noise (ASE) added to the packet by the optical amplifiers placed at each node, to soliton self-frequency shift (SSFS) due to Raman scattering, to short-range interaction of neighboring solitons (SRI) and to their interplay.

Average hop distribution distribution curves $P(n)$ for SN64 using both single-buffer deflection routing and hot-potato routing (no buffers) at full load have been used in (1) and are shown in Fig. 5. One can observe the dramatic decrease of the tail probability when the single-buffer memory shown in Fig. 2 is used.

Fig. 6 plots equation (1) versus the optical bit rate in the soliton packet for SN64 at full load and for 2 km node-to-node fiber span, with fiber dispersion $D = 1$ ps/nm/km and amplifier gain $G = 10$dB for hot-potato and $G = 15$dB for single-buffer deflection routing. Since errors are mostly due to frequently deflected packets, which have propagated for many hops, the error probability is higher for hot-potato because of the tail behavior of $P(n)$. If $P(e)$ must be kept below 10^{-6}, without optical buffers (hot-potato) the bit rate should not exceed 60 Gb/s, while it can be increased to 90 Gb/s if single-buffer deflection routing is used. The simple one-buffer optical memory achieves substantially higher bit rates at a low added cost.

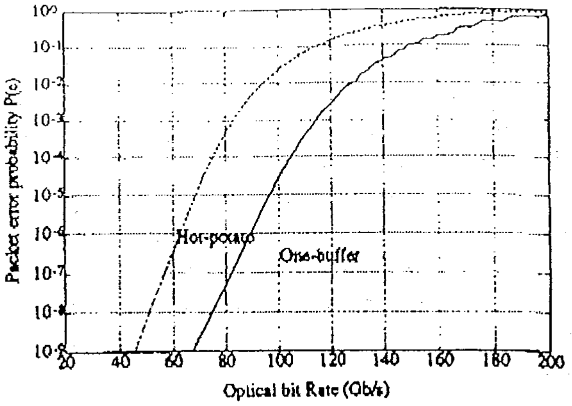

Fig. 6. Packet error probability for 2 km link length in SN64.

The effect of increasing the link length is shown in Fig. 7. To keep the packet error probability below 10^{-6} the optical bit rate must be reduced as the link length increases, and is bound below 40 Gb/s at 5 km link length with no memory, or below 50 Gb/s with the single optical buffer.

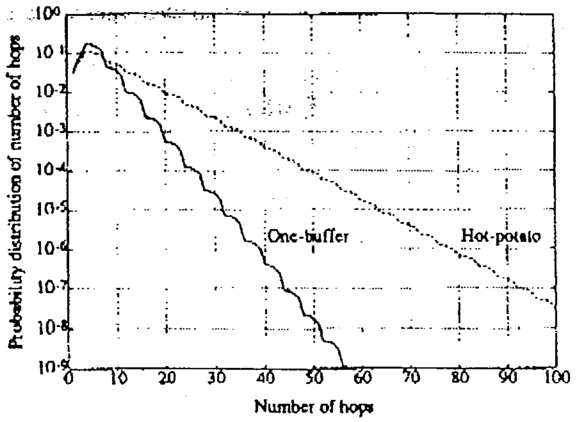

Fig. 5. Average hop distribution curves $P(n)$ for SN64.

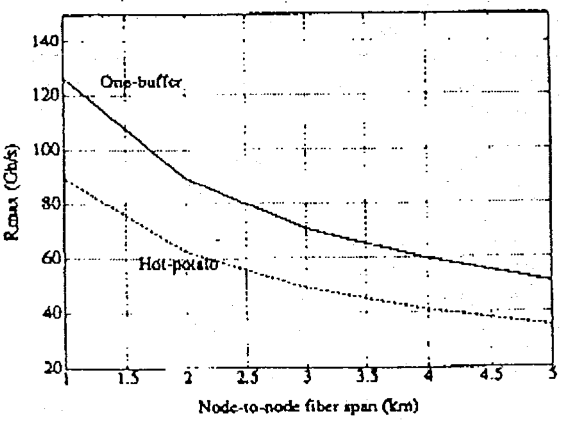

Fig. 7. Maximum bit rate at $P(e) = 10^{-6}$ vs link length.

These results, quantified for the soliton ultra-st channel, show that non-regenerative all-optical ultihop networks at ultra-high bit rates could be nplemented only for small size local or metropolin area networks, with link length close to 1 km if optical bit rate around 100 Gb/s is desired.

If wider networks are to be implemented, regen-ation of the optical packet must be provided at e nodes.

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