CHANNEL IMPACT ON ULTRA-FAST ALL-OPTICAL MESH NETWORKS

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ABSTRACT

Simple channel transmission error arguments show how the size of an all-optical multihop network employing deflection routing is limited for a given optical bit rate. These limits are quantified here for non-regenerative all-optical mesh networks such as Manhattan Street network and ShuffleNet employing solitons. It is found that the node-to-node fiber span cannot exceed a few kilometers for network sizes greater than about 64 nodes when the optical bit rate is in the range of 100 Gb/s if the packet error rate is to be bounded below 10^{-6}.

1   INTRODUCTION

All-optical networks and ultra-high bit rates - The ever-growing need for faster communication speed is leading towards all-optical packet-switching fiber networks, as optical components progressively replace their slower electronic counterparts.

As a first step towards higher transmission rates, optical fibers replaced copper wires as network links between nodes. The switching nodes, however, remained electronic, and the optical signal had to be down-converted to electronics for switching, buffering and routing, and then re-modulated onto an optical carrier for retransmission.

As a next step, in all-optical networks even the switching process will be completely optical. This will allow even higher transmission rates, since the switching can be done much faster than allowed by standard electronic switches, and more flexibility, as the switch is completely transparent to the optical packet, which can thus support any bit rate in the payload. Only the header will need to have a fixed rate, since it is the only part of the packet that needs to be read at every intermediate node to correctly route the packet.

Multihop mesh networks [1],[2] are attractive in this perspective, since they break down the computational complexity of the control of the switching process – which increases exponentially with the number of users – by evenly distributing it among all nodes. In two-connected networks, for instance, each node has only two optical inputs and two optical outputs, and the routing and switching problem is thus reduces to a binary decision on the state of the switch. Very simple minimum-distance routing algorithms have been found for networks with regular topology [3],[4].

Research towards a simpler control of the switching process produced the deflection routing algorithm [5],[1]. This proved to be even more attractive in all-optical networks, where one of the technological limitations is the lack of very fast access, flexible, simple optical memories. The limited-time buffering

strategy of deflection routing is perfectly suited to be implemented with simple recirculating fiber delay loops, with no need of optical amplification in the loop.

Both multihop distributed networks (as opposed to single-hop, centralized networks) and deflection routing (as opposed to store-and-forward (S&F) routing) are solutions which trade efficiency for a much simpler hardware implementation. If ultra-high bit rates can be sustained by these distributed structures using deflection routing, then a net gain in throughput can effectively be achieved.

Generation, multiplexing and demultiplexing of optical packets at ultra-high bit rates is made possible by recent technological breakthroughs in nonlinear optics. Mode-locked semiconductor lasers in the 1.55 μm wavelength region are today capable of producing trains of pulses of width in the range of a few picoseconds [6], which can be interleaved to form optical packets. Ultrafast all-optical AND (or sampling) gates have recently been demonstrated [7],[8], which allow demultiplexing of TDM streams of optical pulses at bit rates approaching 100 Gb/s [9].

The packet error rate - Optical fiber networks are well-known to have a much higher noise immunity than electronic networks. Transmission errors have therefore never been a major issue in the design of such networks. However, as the bit rate of the signals transmitted through the network increases, the peak signal power must be boosted accordingly to keep an acceptable signal-to-noise ratio (SNR) at the receiver. This increases non-linear distortion in the fiber, which, together with chromatic dispersion and the optical noise introduced by the optical amplifiers, contribute to increase the probability of error in the received bits. Optical amplifiers are necessary in all-optical networks, mainly to compensate for the strong power losses at the optical nodes. They introduce optical noise proportionally to their gain. In the all-optical approach, no regeneration of the optical signal is provided at intermediate nodes nor is error control performed on a link-by-link basis. Under deflection routing, repeatedly deflected packets cross many nodes and travel long distances before reaching their destination. They are thus more likely to be in error at the receiver as the bit rate is pushed to extremely high values.

It is therefore of high interest to have a rough idea of what the upper limits on the transmission speed can be in such all-optical networks using deflection routing.

The average packet error rate in a multihop network with equal-length links can be obtained by conditioning on the number of hops n as

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

The hop distribution $P(n)$ depends only on network topology, on the routing algorithm and on network load, while the conditional probability of packet error $P(e/n)$ depends on the noise and distortion introduced by the optical channel, and is a typical point-to-point communication problem, since for given number of hops and link length the source-destination distance is given.

Solitons - Since high signal peak power levels are required to keep a high SNR at the receiver, and the pulse spread due to fiber chromatic dispersion can be counteracted by high power induced self-phase modulation (SPM) [10], solitons appear as a natural choice that turns the nonlinearities of the fiber into a positive factor. Solitons have also been shown to have the highest efficiency of all pulses in the all-optical sampling gates [11], [8], due to their particle-like behavior in switching.

About this work - We present the results of a simplified theoretical packet error rate analysis in two-connected Manhattan Street Network (MS) [1] and ShuffleNet (SN) [2] when ON/OFF *soliton* packet transmission is used at a fixed optical wavelength and at bit rates in the 100 Gb/s range. Average hop distribution curves $P(n)$ for MS and SN using both single-buffer deflection routing and hot-potato routing [12] have been used in (1) . In the evaluation of the conditional error probability $P(e/n)$, the optical

receiver is assumed to be a bank of optical samplers, and each sampler is modeled as a gating sampling window. Errors arise from the jitter of the soliton arrival time in excess of the sampling window. This jitter is due to amplified spontaneous emission noise (ASE), to soliton self-frequency shift (SSFS), to soliton short-range interaction (SRI) and to their interplay. Limits on the maximum achievable optical bit rate, network throughput and node-to-node fiber span will be given for a fixed packet error rate $P(e) = 10^{-6}$.

The results only take into account the impact of the soliton channel on performance, while the synchronization jitter is neglected. They must therefore be considered as upper bounds on the achievable performance. Synchronization at the bit level at these ultra-gigabit rates remains an open issue, and its practical implementation will determine the range of applicability of these ultra-fast all-optical networks.

2 NETWORK OPERATION

Logical operation - Throughout this paper, slotted, or synchronized, fixed length packet transmission in two-connected networks will be considered. A node logically consists of an exchange-bypass switch connecting two input links to two output links, capable of transmitting and receiving on both links and to route packets in transit. When a packet arrives on an input link, its header is read and the best route to its destination, i.e the best output link, is selected according to a routing table. If both input links have a packet, and both packets wish to exit on the same output link, a *contention* occurs. If buffers are not available, one of the two packets, chosen at random, or by low priority, is deflected on the other output link. This routing strategy, called hot-potato [5], can be generalized into the deflection routing algorithm if some buffering is provided [1].

Optical implementation - A possible scheme for the all-optical implementation of this node is shown in Fig. 1. There are two local switches for reception from the two input channels and a main routing switch, which may be a simple cross/bar switch (hot-potato) or may contain a simplified one-packet delay loop buffer (single-buffer deflection routing) [13],[12] as shown in Fig. 2.
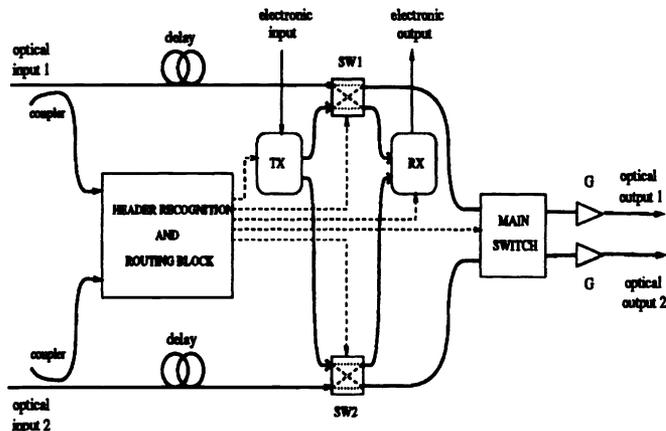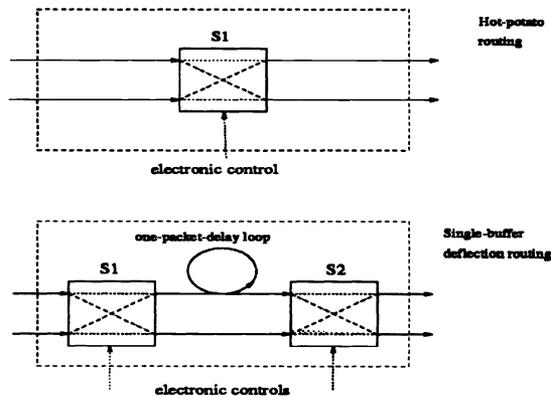

Figure 1: Block diagram of the optical node.

Figure 2: Main switch with no-buffer and single-buffer configuration.

A copy of the header of the incoming packets is read and the controls of the $LiNbO_3$ electro-optic switches are set according to the routing algorithm. The electronic control computations have to be performed within a packet duration, or may be broken down into sub-blocks and pipelined. No control bottleneck occurs as long as the computation time of the slowest sub-block is shorter than the packet duration [14]. A delay equal to the control computation time is inserted on the optical input links so that the state of the switches can be changed shortly before the arrival of the packets.

Steady-state operation - Consider a two-connected multihop network at equilibrium. The throughput λ is defined as the average number of packets inserted/delivered per slot in the network. Let u represent the average link load, that is the average fraction of input links delivering a packet to a node at each clock. Little's theorem gives

$$\lambda = \frac{2N}{D} uR \qquad \text{bit/s} \qquad (2)$$

where $2N$ is the number of input links, D is the average number of hops taken by a packet to reach its destination, and R is the bit rate. For shortest path routing, i.e. S&F with infinite buffers, D is minimized and thus the throughput is maximized. Moreover, D does not depend on the link load u. If deflection routing is used instead, D becomes an increasing function of u, thereby inducing a throughput decrease. Since deflection routing can be implemented all-optically, the loss in efficiency with respect to S&F can be in principle offset by the higher bit rates R allowed by the optical channel [15]. However, for a given number of nodes N and optical bit rate R, the node to node separation l is limited by the allowed packet error rate. Finding this limit on l for the soliton channel in SN and MS topologies will be the object of the next sections.

3 PROBABILITY OF ERROR ANALYSIS

Very short solitons, of width in the ps range, have widely different features from the solitons employed in long-haul communication systems. They are much more powered, and need to be amplified after much shorter propagation intervals in order not to broaden and disperse like low power pulses.

While the ASE added by optical amplifiers still causes a jitter of the arrival time of these ultra-short high-power solitons [16], the main source of jitter is caused by SSFS due to Raman scattering, whose effect is inversely proportional to the fourth power of the pulsewidth [17]. Another jitter source is due to the SRI of neighboring solitons [18], which appears as an attractive force for in-phase solitons. At a fixed bit rate, the pulsewidth reduction necessary to avoid short range interaction strongly enhances the SSFS effect.

Distributed amplification will be assumed in the network to compensate for fiber losses, while node losses will be compensated by placing lumped optical amplifiers at each node output. This way, even ultra-short solitons will propagate without broadening in the span of fiber between nodes, so that they won't get closer due to broadening during propagation and the initial pulse separation necessary to weaken the short range interaction can be decreased. This will allow wider soliton pulses for a given initial separation, i.e. bit time, $T = 1/R$.

The optical packet receiver is supposed to be a bank of parallel optical sampling AND gates. Each AND gate is modeled as a gating window of width $\tau_w = w\tau$, where τ the soliton pulsewidth and w the relative window width. The factor w accounts for the sampling time tolerance in the optical sampler. A soliton pulse will come out of the sampling AND gate if its center is inside the corresponding window.

Very short soliton pulses have such a high energy that a strong light pulse will come out of the AND gate, and the optical energy falling inside the following optoelectronic receiver bandwidth (photodetector and electronic amplifiers) is thus high enough to neglect the receiver thermal noise. Moreover, the optical SNR is shown to be high enough to justify the assumption that no errors are made when the soliton is inside the sampling window. Therefore errors at the receiver are caused only by jitter of the pulse arrival time in excess of the window width.

Synchronization jitter is neglected here. The results that will be obtained must then be interpreted as upper bounds.

It is assumed that all node operations are synchronous, so that packets are transmitted at the same slot rate $R_s = 1/T_s$. Define the slot spatial length l_s as the distance traveled by an ideal slot frame with speed

v_s in the slot time T_s. To ease slot synchronization, the link length is assumed to be an integer multiple of the slot length. Packets are embedded in this ideal slot frame, in flight from node to node. The speed of each bit in the packet slightly differs from that of the frame v_s, since it varies during propagation because of SSFS, ASE noise and SRI, and this variation induces a jitter of each bit in the packet with respect to its nominal position within the frame. The spatial jitter is detected as a time jitter at the receiver. Focus on a generic bit in the packet and make zero its nominal arrival time. Its time jitter t_a is the sum of three terms accounting for the above-mentioned effects

$$t_a = t_{SSFS} + t_{ASE} + t_{SRI} \quad . \tag{3}$$

Let t_L and t_U be the start and stop times of the sampling window.

No error occurs when a "0" (no pulse) is transmitted, nor when a "1" pulse falls inside the window, while an error certainly occurs when a "1" pulse is outside the window. Therefore, if "0"'s and "1"'s are equally likely, the probability of bit error $P_b(e/n)$ conditioned on the number of hops n is

$$P_b(e/n) = \frac{1}{2} P(\text{pulse out of window}/n) = \frac{1}{2} \left[P\left(t_a < t_L\right) + P\left(t_a > t_U\right) \right] \quad . \tag{4}$$

SSFS - The Raman shift t_{SSFS} is the same for all bits in a packet and is a deterministic function of the propagation distance $z = n\ell$, where n is the number of hops taken by the packet in its travel and ℓ the link length. If the slot frame is chosen to propagate with speed slightly lower than the soliton's initial group velocity and the link length is supposed to be an integer multiple of the slot length, the Raman shift t_{SSFS} is from [19]

$$t_{SSFS} = T_R\, n^2 - T_D n \,, \tag{5}$$

where T_R is the Raman shift with respect to a frame moving with the soliton initial group velocity, known as the soliton retarded frame, in one hop of length ℓ, and the second term on the RHS represents the drift of the slot frame with respect to the soliton retarded frame. *Randomness* in t_{SSFS} arises when deflection routing is used, since the received packets have hopped a random number of times when they arrive at their destination.

ASE - The time shift t_{ASE} introduced by the amplifiers is a zero mean gaussian random variable whose variance σ^2_{ASE} is proportional to [16]

$$\sigma^2_{ASE} \propto \frac{(G-1)D}{\tau}\, f(n)\, \ell^2 \tag{6}$$

where G is the amplifier gain, D the fiber dispersion, τ the soliton width, and

$$f(n) = \sum_{i=0}^{n-1} (n-i)^2 = \frac{n^3}{3} + \frac{n^2}{2} + \frac{n}{6} \quad . \tag{7}$$

The jitter t_{ASE} is independent bit by bit in the packet.

SRI - If one assumes that the soliton pulses in the packet have equal amplitude and phase, the shift t_{SRI} due to short-range interaction of neighboring solitons is a deterministic attractive force, function of the hop number n and of the pattern of pulses around the bit under test. It is assumed that interaction forces between non-neighboring pulses are negligible. Therefore it is only necessary to consider the bits to the right and to the left of the bit under test to determine the drag. The variable X will indicate whether no forces are present on the test pulse ($X = 0$ for the 010 pattern), if it is dragged to the left ($X = -1$ for 110), or to the right ($X = 1$ for 011). In the unspecified case 1 1 1 two more side bits must be considered

to determine the drag. By assuming that all bit configurations are equally likely, it is easily found that X assumes values -1,0,1 with equal probability. Within the same set of configurations for which $X = 1$ (or $X = -1$) the attraction forces do not have the same intensity. However a worst-case situation can be considered in which the attraction has maximum strength, as it is the case when only two neighboring pulses are interacting . In this case the absolute value of t_{SRI} can be found from [10]

$$|t_{SRI_{max}}| = 0.283\tau \left\{ \ln 2 - \ln \left[1 + \cos \left(2\pi \frac{nl}{Z_0} e^{-\frac{T/\tau}{1.134}} \right) \right] \right\} \tag{8}$$

where Z_0 is the soliton characteristic length (or soliton period [10]) and T the bit time. It is thus a deterministic function of the hop number n, and it strongly depends on the normalized initial pulse separation T/τ.

A simple worst-case approximation is obtained by assuming all bits are independently affected in the packet, and by modeling the random variable t_{SRI} as

$$t_{SRI} = X|t_{SRI_{max}}| . \tag{9}$$

This approximation is based on the observation that, although correlations between neighboring bits obviously exist, these are already taken into account by the average variable X, and edge effects can be neglected in long packets, as in the ATM standard of about 500 bits/packet.

ASE-SRI interaction - The ASE jitter t_{ASE} may cause two neighboring pulses to get closer together thereby accelerating the short-range interaction. This interference has already been studied in [20]. For the case of two in phase, equal amplitude solitons in a 110 or 011 pattern, where the center bit is the bit under test, it is shown there that, for propagation distance

$$z = nl \leq 0.36 Z_0 e^{\frac{T/\tau}{1.134}} \tag{10}$$

the mutual interaction between ASE and SRI is small so that, upon conditioning on X, the random variable $(t_{ASE} + t_{SRI})$ may be considered gaussian with mean $X|t_{SRI_{max}}|$ ($X = 1$ for the pattern 011, $X = -1$ for 110) and variance $\hat{\sigma} = F(z)\sigma_{ASE}$, where the function $F(z)$ — given in [20], Fig. 4 — increases almost exponentially with propagation distance z. Including also the 010 pattern where no interactions are present, the variance of $(t_{ASE} + t_{SRI})$ is

$$\sigma = (1 - X^2)\sigma_{ASE} + X^2 \hat{\sigma}. \tag{11}$$

For a fixed bit time T, $|t_{SRI_{max}}|$ is negligible at any distance of interest z if the pulses are initially well separated, i.e. T/τ is very large, but the Raman shift is greatly enhanced since τ becomes very small. On the other hand, if T/τ is small, SRI would cause the collapse of neighboring pulses within short distances z. A *conservative* criterion to select T/τ has been used so that approximation (11) is satisfied down to a target packet error probability of 10^{-12}. To achieve this, a maximum number of hops of interest in the network n_{max} is found so that

$$\sum_{n=n_{max}+1}^{\infty} P(n) \leq 10^{-12} \tag{12}$$

The value of T/τ is selected so that, at a distance $z_{max} = n_{max}l$, relation (10) holds with equality, which from (8) corresponds to a maximum SRI shift $|t_{SRI_{max}}| \cong \frac{\tau}{2}$.

Packet error rate - The conditional bit error probability $P_b(e/n)$ can now be obtained by putting the previous results together. By conditioning on the RV X and using relations (5) and (9), the shift t_a in (3) becomes a gaussian RV with mean

$$E t_a(X, n) = T_R n^2 - T_D n + X|t_{SRI_{max}}| \tag{13}$$

and variance $\sigma(X, n)$ given in (11). Hence, by conditioning on X, relation (4) becomes

$$P_b(e/n) = \frac{1}{6} \sum_{X=-1}^{1} \left[Q\left(\frac{\text{E}t_a(X,n) - t_L}{\sigma(X,n)}\right) + Q\left(\frac{t_U - \text{E}t_a(X,n)}{\sigma(X,n)}\right) \right] \tag{14}$$

where $Q(.)$ is the standard gaussian Q function.

Each bit will be assumed independently affected in the packet so that the packet error rate is finally from (1)

$$P(e) = \sum_n [1 - [1 - P_b(e/n)]^M]P(n). \tag{15}$$

One can optimize the slot frame velocity mismatch with respect to the soliton retarded frame, as well as the window initial time t_L to minimize $P(e)$. This physically corresponds to optimizing the optical link length and the phase of the sampling clock.

4 RESULTS AND CONCLUSIONS

Hop distribution curves for MS and SN using both single-buffer deflection routing and hot-potato routing have been obtained for uniform traffic and uncorrelation between packets as described in [12] for 64 node network size (MS64 and SN64) and 400 node network size (MS400 and SN384), and are presented in the left column of Fig. 3 for three values of the offered traffic $g = 0.1, 0.2, 1$. g is defined as the probability that a packet is ready for transmission at each node at each clock.

The right column of Fig. 3 shows the corresponding packet error probability curves, obtained from equation (15), plotted versus the optical bit rate R. All the results have been obtained for fiber dispersion parameter $D = 1ps/nm/Km$ and node amplifier gain per channel $G = 10dB$ for hot-potato and $G = 15dB$ for single-buffer deflection routing, as an extra switch must be added. The power losses in the fibers are supposed to be perfectly compensated by the distributed amplification.

The packet error probability roughly corresponds to the integral of the hop distribution tails. Since the tails of the hop probability distribution are much higher in SN than in MS, the error probability curves for SN are worse than those relative to MS. The difference is more evident in the 400-node size. This is why MS allows higher bit rates than SN for low error probability.

The values of R that give $P(e) = 10^{-6}$ have been substituted in eq.(2) to obtain the throughput per node curves of Fig. 4. Under hot-potato routing MS has slightly higher throughput than SN, because of the higher allowed bit rates. However, when single-buffer deflection routing is employed, the tails of the hop distribution get drastically lowered, and even though the allowed bit rate remains higher in MS than in SN, the greater compactness [1] of SN emerges, allowing a higher throughput in SN. This is more evident in the 400 node size, where the presence of a maximum throughput at $g = 0.3$ can also be observed.

The effect of varying the link length has also been addressed. Fig. 5 shows the maximum node-to-node fiber span l to achieve an error rate $P(e) = 10^{-6}$ as the optical bit rate is increased from 20 to 140 Gb/s. These curves clearly show a "threshold" effect due to an increase in the transmission speed. To keep a constant packet error rate $P(e) = 10^{-6}$, the node-to node fiber span has to be reduced down to a few kilometers as the bit rate R approaches 100 Gb/s. This means that ultra-fast all-optical networks without regeneration at bit rates around 100 Gb/s could only be conceived for local or metropolitan area networks, that is for a physical diameter of the network up to several tens of kilometers, for network sizes up to about 400 nodes.

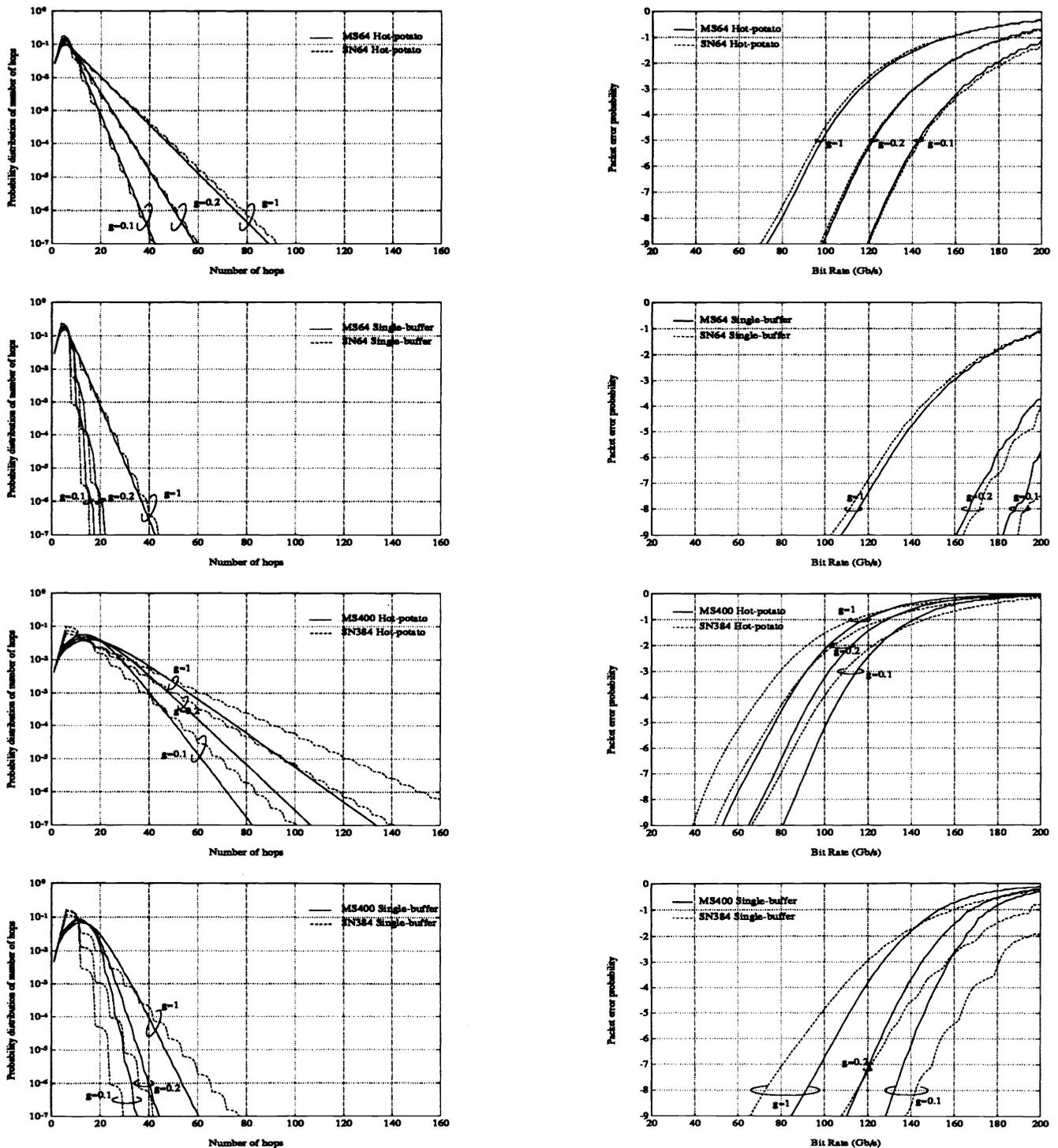[1]by *greater compactness* we mean that SN has a much lower minimum-distance than MS [12]

Figure 3: Hop distribution (left) and packet-error probability $P(e)$ vs. optical bit rate R (right) for MS64, SN64, MS400, SN384 under hot-potato and single-buffer deflection routing for link length $l = 1\,km$ and relative sampling window width $w = 4$. Parameter g is the packet generation probability per slot per node.
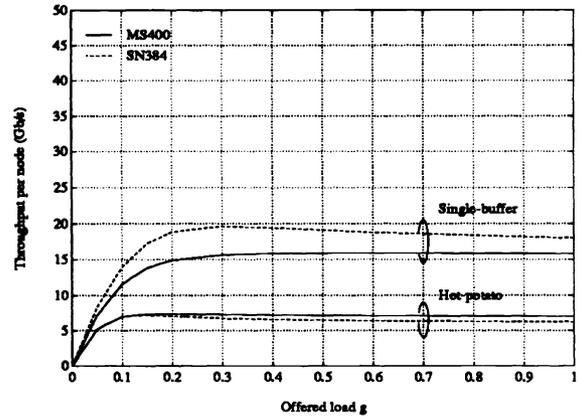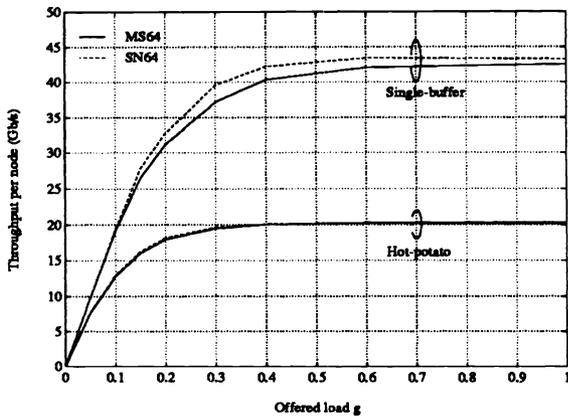
Figure 4: Throughput per node vs. offered load g at $P(e) = 10^{-6}$ in MS and SN with 1 km link length.
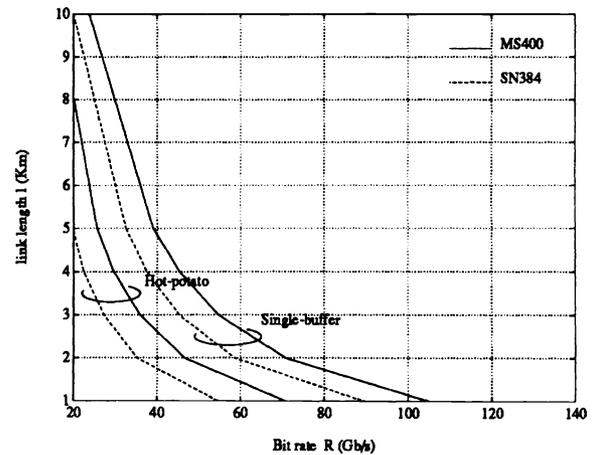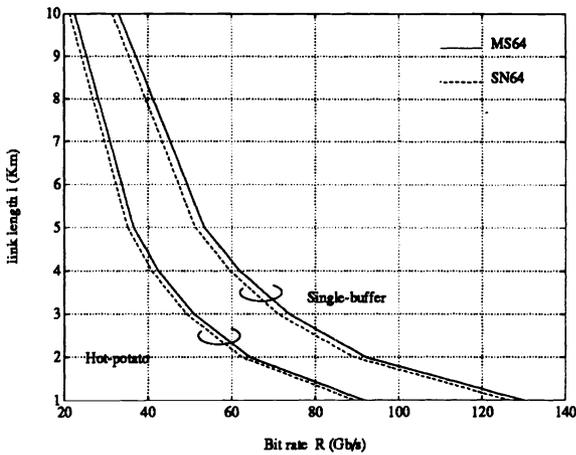

Figure 5: Maximum node-to-node fiber span vs. optical bit rate R at $P(e) = 10^{-6}$

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