Soliton ultrafast all-optical mesh networks

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Abstract: 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 for nonregenerative all-optical mesh networks such as Manhattan Street network and ShuffleNet employing solitons. It is found that the node-to-node fibre span cannot exceed a few kilometres for network sizes up to 400 nodes when the optical bit rate is as high as 100 Gbit/s if the packet error rate is to be bounded below 10^{-6}.

1 Introduction

1.1 All-optical networks and ultrahigh bit rates

The ever-growing need for faster communication speed is leading towards all-optical packet-switching fibre networks, as optical components progressively replace their slower electronic counterparts. As a first step towards higher transmission rates, optical fibres 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 remodulated 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 reduced 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 fibre delay loops, with no need of optical amplification in the loop.

Both multihop distributed networks (as opposed to single-hop, centralised 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 ultrahigh bit rates can be sustained by these distributed structures using deflection routing, a net gain in throughput can effectively be achieved.

Generation, multiplexing and demultiplexing of optical packets at ultrahigh bit rates is made possible by recent technological breakthoughs 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 Gbit/s [9].

1.2 Packet error rate

Optical fibre 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 nonlinear distortion in the fibre, 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

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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.

1.3 Solitons

Since high signal peak power levels are required to keep a high SNR at the receiver, and the pulse spread due to fibre 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 fibre into a positive factor. Solitons have also been shown to have the highest efficiency of all pulses in the all-optical sampling gates [8, 11], owing to their particle-like behaviour in switching.

1.4 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 Gbit/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 eqn. 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 modelled 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 fibre 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 synchronisation jitter is neglected. They must therefore be considered as upper bounds on the achievable performance. Synchronisation at the bit level at these ultragigabit rates remains an open issue, and its practical implementation will determine the range of applicability of these ultrafast all-optical networks.

Possible improvements may be achieved by the use of recently demonstrated optical filtering techniques at the output of each optical amplifier [13–15]. These would effectively reduce the jitter due to ASE. However, the frequency downshift of the soliton spectrum due to SSFS will require broader optical filters, possibly reducing their effectiveness.

2 Network operation

2.1 Logical operation

Throughout this paper, slotted, or synchronised, 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 generalised into the deflection routing algorithm if some buffering is provided [1].

2.2 Optical implementation

A possible scheme for the all-optical implementation of this node is shown in Fig. 1. There are two local switches

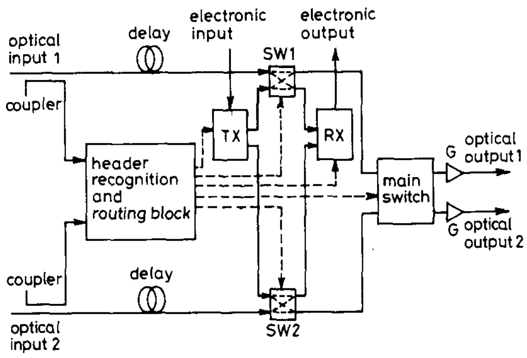

Fig. 1 *Block diagram of optical node*

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) [12, 16], as shown in Fig. 2. A copy of the header of the incoming

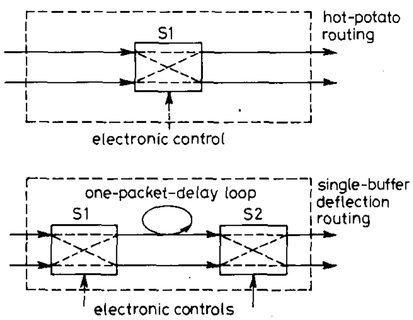

Fig. 2 *Main switch with no-buffer and single-buffer configurations*

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 subblocks and pipelined. No control bottleneck occurs as long as the computation time of the slowest subblock is shorter than the packet duration [17]. 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.

2.3 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

$$\lambda = \frac{2N}{D} uR \text{ bit/s} \tag{2}$$

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 minimised and thus the throughput is maximised. 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 [18]. However, for a given network size, that is number of nodes N and node to node separation l, the bit rate R is limited by the allowed packet error rate. Finding this limit on R for the soliton channel in SN and MS topologies is the object of the following 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 higher powered and need to be amplified after much shorter propagation intervals to not broaden and disperse like low-power pulses.

While the ASE added by optical amplifiers still causes a jitter of the arrival time of these ultrashort high-power solitons [19], 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 [20]. Another jitter source is due to the SRI of neighbouring solitons [21], which appears as an attractive force for inphase solitons. At a fixed bit rate, the pulsewidth reduction necessary to avoid short-range interaction strongly enhances the SSFS effect.

Distributed amplification is assumed in the network to compensate for fibre losses, while node losses will be compensated by placing lumped optical amplifiers at each node output. This way, even ultrashort solitons will propagate without broadening in the span of fibre between nodes, so that they won't get closer owing 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 modelled 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 centre 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.

Synchronisation jitter is neglected here. The results that will be obtained must then be interpreted as upper bounds on the achievable network throughput.

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 travelled by an ideal slot frame with speed v_s in the slot time T_s. To ease slot synchronisation, 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

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

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 zeros and ones are equally likely, the probability of bit error $P_b(e/n)$ conditioned on the number of hops n is

$$\begin{aligned} P_b(e/n) &= \tfrac{1}{2} P(\text{pulse out of window}/n) \\ &= \tfrac{1}{2}[P(t_a < t_L) + P(t_a > t_U)] \end{aligned} \tag{4}$$

3.1 SSFS

The Raman shift t_{SSFS} is the same for all bits in a packet and is a deterministic function of the propagation distance $z = nl$, 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 [22]

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

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.

3.2 ASE

The time shift t_{ASE} introduced by the amplifiers is a zero mean gaussian random variable whose variance σ_{ASE}^2 is proportional to [19]

$$\sigma_{ASE}^2 \propto \frac{(G-1)D}{\tau} f(n) l^2 \tag{6}$$

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

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

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

3.3 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 neighbouring 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-neighbouring 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 111 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 neighbouring pulses are interacting. In this case the absolute value of t_{SRI} can be found from [10]

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

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 normalised initial pulse separation T/τ.

A simple worst-case approximation is obtained by assuming all bits are independently affected in the packet, and by modelling 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 neighbouring 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 per packet.

3.4 ASE–SRI interaction

The ASE jitter t_{ASE} may cause two neighbouring pulses to get closer together thereby accelerating the short-range interaction. This interference has already been studied in Reference 23. For the case of two in phase, equal amplitude solitons in a 110 or 011 pattern, where the centre bit is the bit under test, it is shown there that, for propagation distance

$$z = nl \leqslant 0.36 Z_0 \exp\frac{T/\tau}{1.134} \tag{10}$$

the mutual interaction between ASE and SRI is small so that, on 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 Reference 23, 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 neighbouring pulses within short distances z. A conservative criterion to select T/τ has been used so that the approximation of eqn. 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

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

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

3.5 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 eqns. 5 and 9, the shift t_a in eqn. 3 becomes a gaussian RV with mean

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

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

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

where $Q(\cdot)$ 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 eqn. 1

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

One can optimise the slot frame velocity mismatch with respect to the soliton retarded frame, as well as the window initial time t_L to minimise $P(e)$. This corresponds physically to optimising 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 Reference 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 meaningful 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 rate curves obtained from eqn. 15, plotted against the optical bit rate R. All the results have been ly higher throughput than SN, because of its better error figure. However, when single-buffer deflection routing is employed, the tails of the hop distribution get drastically

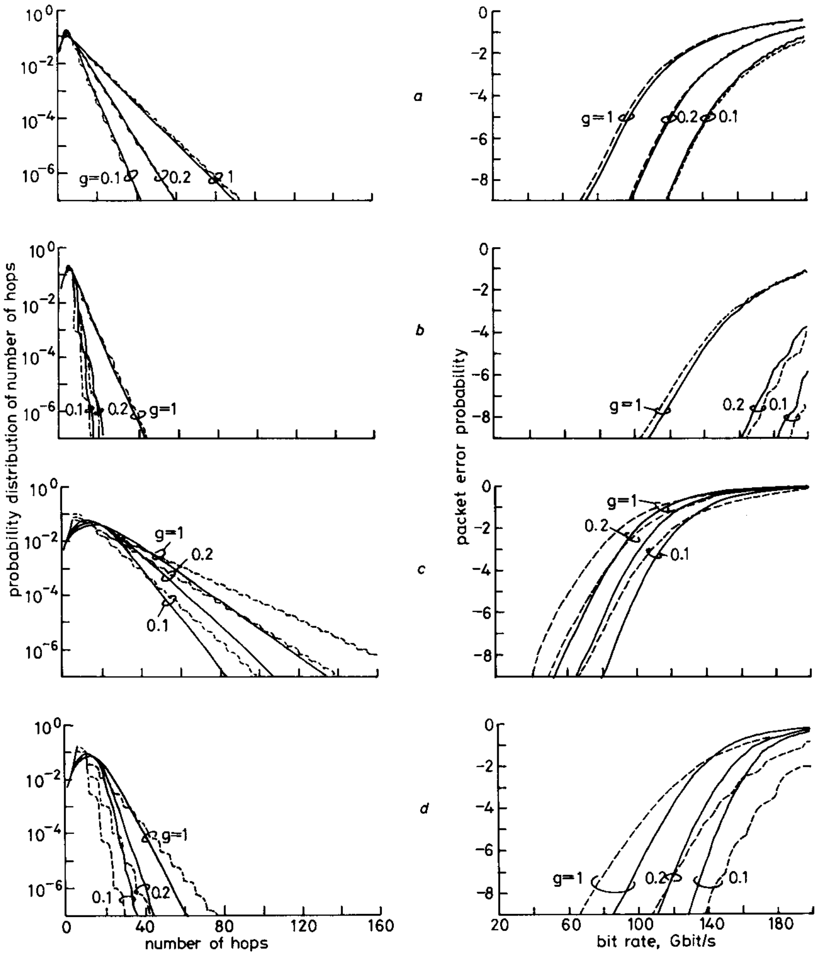

Fig. 3 *Hop distribution P(n) and packet-error probability P(e) with hot-potato and single-buffer deflection routing for link length l = 1 km and relative sampling window width w = 4*

Parameter g is packet generation probability per slot per node
a ——— MS64 hot potato
- - - - SN64 hot potato
b ——— MS64 single buffer
- - - - SN64 single buffer
c ——— MS400 hot potato
- - - - SN384 hot potato
d ——— MS400 single buffer
- - - - SN384 single buffer

obtained for fibre dispersion parameter $D = 1$ ps/nm/km and node amplifier gain per channel $G = 10$ dB for hot-potato and $G = 15$ dB for single-buffer deflection routing, as an extra switch must be added. The power losses in the fibres are supposed to be perfectly compensated by the distributed amplification.

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.

The values of R that give $P(e) = 10^{-6}$ have been substituted in eqn. 2 to obtain the throughput per node curves of Fig. 4. Under hot-potato routing MS has slightly lowered, and even though the MS error figure remains better than that of SN, the greater compactness* 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.

Fig. 5 shows the maximum node-to-node fibre span l to achieve an error rate $P(e) = 10^{-6}$ as the optical bit rate is increased from 20 to 140 Gbit/s. These curves clearly show a threshold effect due to an increase in the transmission speed. To keep a constant packet error rate

* By compactness we mean that SN has a much lower minimum distance than MS [12].

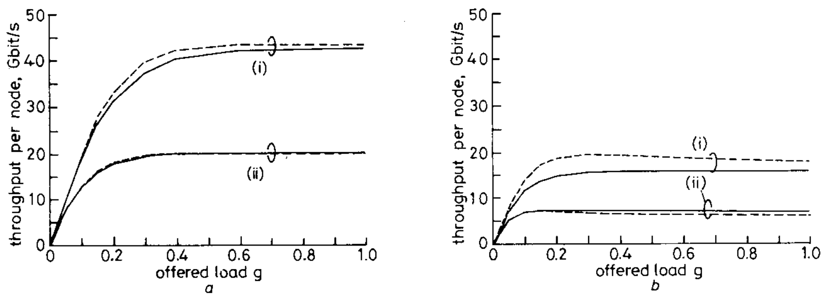

Fig. 4 *Throughput per node against offered load g at $P(e) = 10^{-6}$ with 1 km link length*

a —— MS64, ---- SN64 } (i) single buffer; *b* —— MS400, ---- SN384 } (ii) hot potato

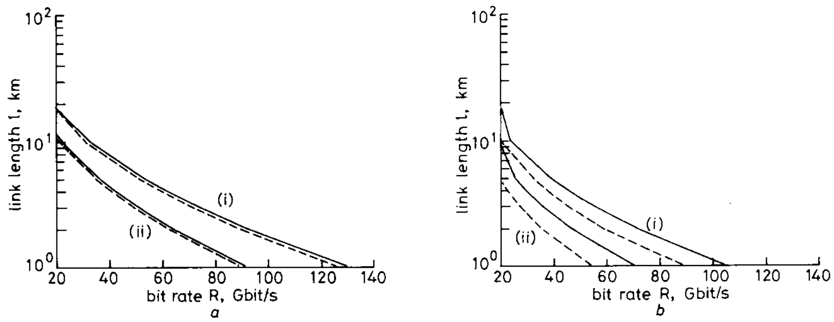

Fig. 5 *Maximum node-to-node fibre span against optical bit rate R at $P(e) = 10^{-6}$*

a —— MS64, ---- SN64 } (i) single buffer; *b* —— MS400, ---- SN384 } (ii) hot potato

$P(e) = 10^{-6}$, the node-to-node fibre span has to be reduced down to a few kilometres as the bit rate R approaches 100 Gbit/s.

This means that ultrafast all-optical networks without regeneration at bit rates around 100 Gbit/s could only be conceived for local or metropolitan area networks, that is for a physical diameter of the network of several tens of kilometres for network sizes up to about 400 nodes.

5 References

1 MAXEMCHUK, N.F.: 'Regular mesh topologies in local and metropolitan area networks', *AT&T Tech. J.*, Sept. 1985, **64**, pp. 1659–1685

2 ACAMPORA, A.S., KAROL, M.J., and HLUCHYJ, M.G.: 'Terabit lightwave networks: the multihop approach', *AT&T Tech. J.*, Nov./Dec. 1987, **66**, pp. 21–34

3 KAROL, M.J., and SHAIKH, S.: 'A simple adaptive routing scheme for ShuffleNet multihop lightwave networks'. Proceedings of IEEE INFOCOM 88, paper, 50.1, pp. 1640–1647

4 MAXEMCHUCK, N.F.: 'Routing in the Manhattan Street network', *IEEE Trans.*, 1987, **COM-35**, pp. 503–512

5 BARAN, P.: 'On distributed communications networks', *IEEE Trans.*, 1964, **CS-12**, pp. 1–9

6 IANNONE, P.P., RAYBON, G., KOREN, U., and PRUCNAL, P.R.: 'Robust electrically tunable 1.5 μm mode-locked fiber-external-cavity laser', *Appl. Phys. Lett.*, 1992, **61**, pp. 1496–1498

7 BLOW, K.J., DORAN, N.J., NAYAR, B.K., and NELSON, B.P.: 'Two-wavelength operation of the nonlinear fiber loop mirror', *Opt. Lett.*, 1990, **15**, pp. 248–250

8 ISLAM, M.N.: 'Ultrafast all-optical logic gates based on soliton trapping in fibers', *Opt. Lett.*, 1989, **14**, pp. 1257–1259

9 ANDREKSON, P.A., OLSSON, N.A., SIMPSON, J.R., DIGIOVANNI, D.J., MORTON, P.A., TANBUN-EK, T., LOGAN, R.A., and WECHT, K.W.: '64 Gb/s all-optical demultiplexing with the nonlinear optical-loop mirror', *IEEE Photon. Technol. Lett.*, 1992, **4**, pp. 644–647

10 AGRAWAL, G.P.: 'Nonlinear fiber optics' (Academic Press, 1989)

11 DORAN, N.J., and WOOD, D.: 'Nonlinear-optical loop mirror', *Opt. Lett.*, 1988, **13**, pp. 56–58

12 FORGHIERI, F., BONONI, A., and PRUCNAL, P.R.: 'Analysis and comparison of hot-potato and single buffer deflection routing in very high bit rate optical mesh networks', *IEEE Trans. Commun.* (to be published)

13 KODAMA, Y., and HASEGAWA, A.: 'Generation of asymptotically stable optical solitons and suppression of the Gordon-Haus effect', *Opt. Lett.*, 1992, **17**, pp. 31–33

14 MECOZZI, A., MOORES, J.D., HAUS, H.A., and LAI, Y.: 'Modulation and filtering control of soliton transmission', *J. Opt. Soc. Am. B*, 1992, **9**, pp. 1350–1357

15 MOLLENAUER, L.F., GORDON, J.P., and EVANGELIDES, S.G.: 'The sliding-frequency guiding filter: an improved form of soliton jitter control', *Opt. Lett.*, 1992, **17**, pp. 1575–1577

16 CHLAMTAC, I., and FUMAGALLI, A.: 'An all-optical switch architecture for manhattan networks', *IEEE J. Sel. Areas Common.* (to be published)

17 PRUCNAL, P.R., and PERRIER, P.A.: 'Optically-processed routing for fast packet switching', *IEEE LCS Mag.*, May 1990, **1**, pp. 54–67

18 ACAMPORA, A.S., and SHAH, A.: 'Multihop lightwave networks: a comparison of store-and-forward and hot-potato routing', *IEEE Trans.*, June 1992, **COM-40**, pp. 1082–1090

19 GORDON, J.P., and HAUS, H.A.: 'Random walk of coherently amplified solitons in optical fiber transmission', *Opt. Lett.*, 1986, **11**, pp. 665–667

20 GORDON, J.P.: 'Theory of the soliton self-frequency shift', *Opt. Lett.*, 1986, **11**, pp. 662–664

21 GORDON, J.P.: 'Interaction forces among solitons in optical fibers', *Opt. Lett.*, 1983, **8**, pp. 596–598

22 WOOD, D.: 'Constraints on the bit rates in direct detection optical communication systems using linear or soliton pulses', *J. Lightwave Technol.*, 1990, **8**, pp. 1097–1106

23 GEORGES, T.: 'Amplifier noise jitter of two interacting solitons', *Opt. Commun. Mag.* (North-Holland), 1991, pp. 195–201