Ultra high-speed medium access in packet-switched OTDM networks

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Abstract. High-speed packet-switched OTDM (Optical Time Division Multiplexing) networks could be the best choice when some users in a network occasionally require very high data rate (bandwidth-on-demand principle). In this case, an ultra high-speed medium access can be achieved using an optical rate-conversion scheme. In this paper, some basic schemes of the optical packet compression/expansion are shown and discussed. In addition, a power budget analysis and an estimation of the ASE noise accumulation in the packet compression/expansion units are carried out. The analytical studies show that the ODLL (Optical Delay Line Lattice) scheme permits the use of sufficiently large packets. Moreover, a parallel arrangement of two or more ODLL compression/expansion units can significantly improve the transmission efficiency in time-slotted single-hop networks.

1 Introduction

Currently, most research efforts in photonic networks concentrate on three primary techniques for multiplexing data onto a single fiber: WDM (wavelength-division multiplexing), OTDM (optical time-division multiplexing) and OCDM (optical code-division multiplexing). The major part of that research is devoted to WDM systems. An important reason is that the basic technologies used in WDM networks are to a large extent commercially available (e.g. optical filters, WDM demultiplexers, sources with narrow linewidth, etc.). On the other hand, OCDM has been receiving considerable attention in recent years. However, the implementations of the OCDM technology are yet restricted to LAN applications using star topology. High-speed OTDM systems overcome some of the difficulties associated with WDM transmission, e.g. four wave mixing (FWM) and lacking gain-uniformity of fiber amplifiers with respect to wavelength. Recently, very high bit-rate point-to-point transmission up to 640 Gbit/s of RZ (Return to Zero) optical signal over a 60 km dispersion-managed fiber has been reported [7]. This high link capacity offers great opportunities for the Next-Generation Internet (NGI).

Relying on the technology that is available today, the network nodes operate up to 40 Gbit/s electronics. In the future, the network nodes should be able to accept data beyond 100 Gbit/s. To overcome the electronic processing bottleneck, high-speed all-optical signal processing have to be deployed in the network node, thereby all-optical header recognition and optical packet compression/expansion techniques may play a very important role in the future. On the one hand, all-optical header recognition will allow signals to remain in an optical format until they arrive at their destination, so that the throughput bottleneck caused by the electronic processing can be eliminated. On the other side, by the use of the optical packet compression/expansion technique, ultra high-speed access to the optical medium (beyond 100 Gbit/s) could be possible.

To obtain an ultra high bit-rate above the limitation of electronics, the transmitted/received optical packets can be rate-converted at the node using an optical compression/expansion unit, respectively. Optical Packet Compression-Time Division Multiplexing (OPC-TDM) networks are packet-switched OTDM networks, which allow an ultra high-speed access to the optical medium employing the optical packet compression/expansion technique. The essential part of an OPC-TDM access node is the Optical Packet Compression/Expansion Unit (Fig. 1), responsible for rate-conversion of ultra high-speed optical data streams to lower rate data streams that can be detected, saved and processed electronically.

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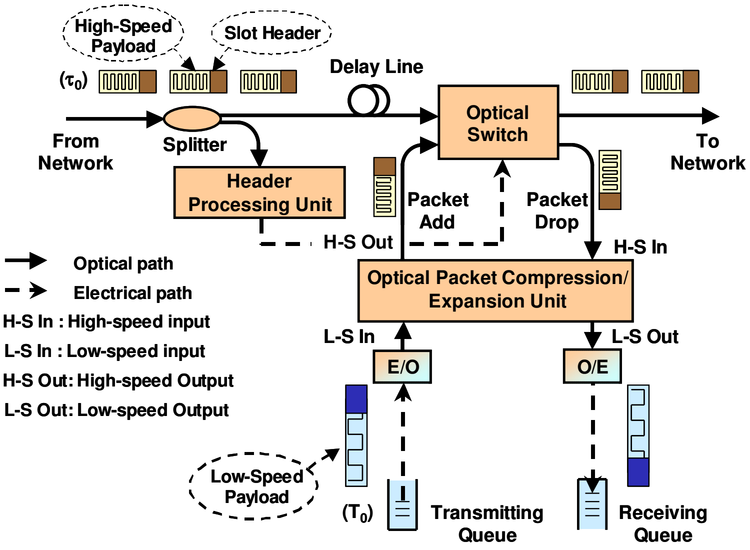

Figure 1: OPC-TDM network node

Fig. 1 shows the generic scheme of an OPC-TDM network node. In principle, processing of the incoming high-speed optical packets by the node can be explained as follows: at first, a small fraction of the incoming optical signal is tapped off for header processing in the Header Processing Unit. An Optical Delay Line is deployed in the optical path to compensate for the header processing latency. If the packet's destination address matches the node's destination address, the packet is dropped by the optical switch located at the node and expanded to a lower data rate for electronical processing. On the transmitter side, the low bit-rate packet acquired from the transmitting queue must be first up-converted to the high medium data rate and after that inserted into the network by replacing a dropped or an empty slot.

2 Optical Packet Compressor/Expander

In this section, some basic schemes of the optical packet compression/expansion are shown and discussed. Most of these schemes are based on a recirculation loop [1,2], whose length is chosen to be (T_0 – τ_0), where T_0 denotes the bit-period of the low-speed packet and τ_0 is the bit-period of the compressed high-speed packet.

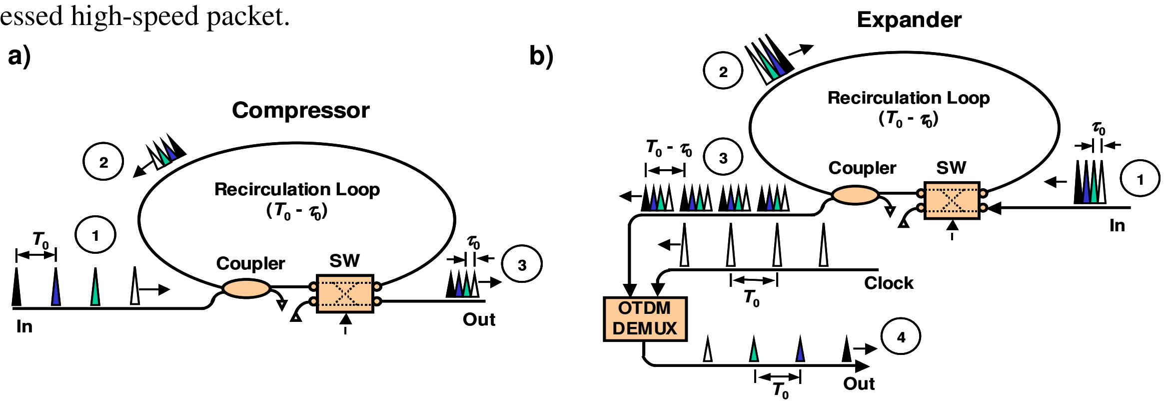

Figure 2: Optical packet a) compressor and b) expander using recirculation loop

An optical packet compressor based on the recirculating loop scheme is shown in Fig. 2-a). Low-speed input packets (1) enter the loop through the coupler. The switch (SW) is set to be in the "bar" state during the compression operation. After the first pulse has finished a round-trip and passed the coupler (t = T_0 seconds), the second pulse enters the loop. It follows the first pulse by the bit-period of the compressed packet τ_0. After NT_0 seconds (N is the packet length in bits), N bits spaced by τ_0 are circulating in the loop (2). The switch is then set into the "cross" state, thereby the whole compressed packet is coupled at the output (3). Note that the pulses, from which the packets are generated, must be sufficiently short to produce high-speed output packets with the bit-period τ_0 without inter-bit interferences, i.e. $\tau_p < \tau_0$. Fig. 2-b) shows an optical packet expander using the recirculating loop scheme.

High-speed optical packets (1) enter the recirculating loop through the switch (SW), which is initially set to be in the “cross” state. After the whole high-speed packet has entered the loop, the swich is set to the “bar” state and remains in this state up to the end of the expansion operation. The packet circulates in the loop N-times (2), while in each round-trip a fraction of the high-speed packet is coupled at the output of the loop. Consequently, N copies of the packet are produced (3). Because of the round-trip propagation time in the loop of ($T_0 - \tau_0$), each copy of the packet is delayed with respect to the next copy by ($T_0 - \tau_0$). An OTDM demultiplexer selects bits spaced at the bit-period T_0, thereby expanding the whole high-speed input packet (4).

However, this method leads to some restrictions concerning bit-rate and packet size. To prevent bit overlapping in the loop, the number of bits in a packet (N) must be smaller than the compression rate K, i.e. $N < K - 1$, where $K = T_0/\tau_0$. Moreover, the switch must change its state arbitrarily quickly, namely in the time gap between the last bit and the first bit of the packet in the loop. Since the recirculation loop length is chosen to be ($T_0 - \tau_0$) and the length of the high-speed packet is $N\tau_0$, the switching time can be calculated from: $t_{sw} = (T_0 - \tau_0) - N\tau_0 = \tau_0(K - 1 - N)$. For example, assuming a compression rate $K = 100$, a switching time $t_{sw} = 200$ ps, and $\tau_0 = 10$ ps, the maximal packet length $l_{p,max}$ is limited to 79 bits.

A further technique for optical rate-conversion is the feed-forward delay-line structure consisting of $q = log_2(N)$ stages reported in [3]. The packet compressor/expander using a feed-forward delay line structure, a gate, and an OTDM demultiplexer for decompression operation is shown in Fig. 3. It allows the compression of packets to be transmitted simultaneously with the expansion of the received packets using the same device. The number of stages increases logarithmically with the number of bits to be processed. Because of the fact that the complete compressed packet occurs in the gap between two bits of the low-speed signal, the number of bits in the packet is, similar to the recirculating loop scheme, limited by the compression rate K as follows: $N < K - 1$. If the response time of the gate (t_{gate}) is taken into account, the limitation of the packet size is given by: $l_{p,max} < K - 1 - 2\cdot\lceil t_{gate}/\tau_0 \rceil$. If larger packet sizes are needed, a larger compression rate or a parallel arrangement of optical delay line lattices (ODLL) can be used.

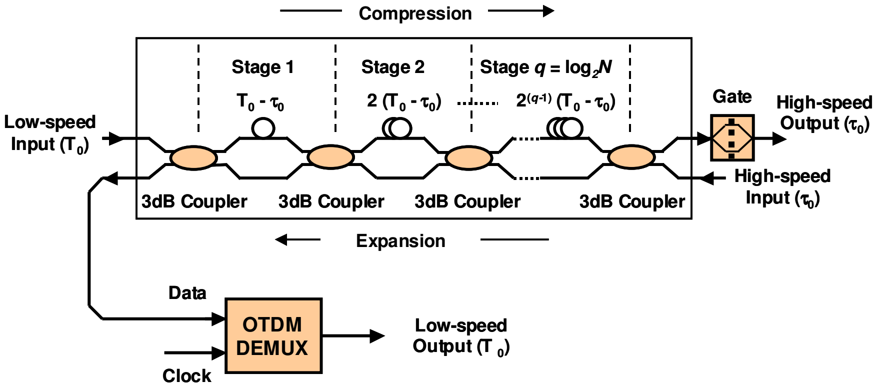

Figure 3: Packet compressor/expander using an optical delay line lattice (ODLL)

In [4] a scalable optical packet compression/expansion scheme using a parallel arrangement of optical delay line structures has been proposed and investigated. This scheme allows high compression rates and large packet sizes thereby reducing the impact of the “time out” phenomenon. The “time out” phenomenon [5] prevents receiving or transmitting of two packets by a node within a time period equal to the packet compression/expansion latency ($KN\tau_0$). For example, for a conversion rate $K = 100$ the receiver can access only each 100th packet in the network. This hard restriction leads to an inefficient bandwidth utilization.

An optical packet compression/expansion scheme consisting of M parallel ODLLs (Fig. 4) can significantly reduce these hard restrictions [4]. Each of the M parallel delay line lattices is responsible for rate-conversion of a part of the incoming optical packets. The input packets are first divided into M separate n-bit sequences. Each sequence can be separately processed (compressed or expanded) by a dedicated optical delay line structure and then combined together with the other sequences by an M x 1 optical coupler. Moreover, it is possible to build an optical packet compression/expansion unit that allows simultaneous compression and expansion of optical packets not limited in size and conversion rate thereby reducing the impact of the time out phenomenon.

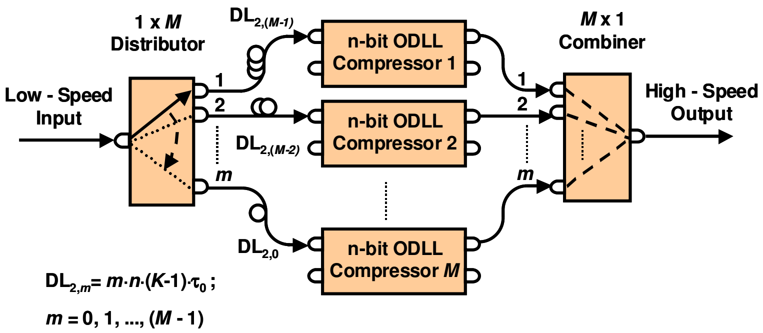

Figure 4: Optical packet compression using a parallel arrangement of M compressors.

3 Power Budget Analysis

This section is devoted to the analysis of the optical power required to compress and expand an n-bit optical packet. Limitations on the packet size caused by the losses in the compressor/expander will be shown for the realizations described above. Moreover, ASE (Amplified Spontaneous Emission) noise accumulation and the impact of insufficient loss compensation in the compression/expansion units on the allowed packet size are investigated and discussed.

3.1 Passive Compression/Expansion

First, we consider a compressor/expander without loss compensation. In other words, there is no amplifier in the system. Moreover, losses in the OTDM demultiplexer, which is used for the expansion operation, are not taken into consideration. Consequently, we obtain complete mirror symmetry of the compressor and the expander making the analytical study easier. Fig. 5. shows the system under consideration, which consists of a transmitting node with an optical packet compressor and a receiving node containing an optical packet expander.

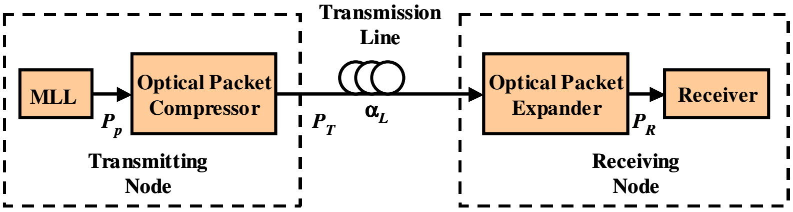

Figure 5: System under consideration

Short pulses with the period T_0 are generated at the transmitting node using a mode-locked laser (MLL). Let P_p be the pulsed power of the MLL. The pulses are first compressed by a compressor, then transmitted through the transmission line characterized by the attenuation α_L, and finally decompressed by an expander located in the receiving node. P_T and P_R denote the pulsed optical power after compressor in the transmitting node and after the expander located in the receiving node, respectively. Next, we consider the compressor/expander consisting of only one ODLL as shown in Fig. 3. Regarding the power budget, the scheme depicted in Fig. 4 can be seen as an expansion of the ODLL shown in Fig. 3, taking into account the additional losses in the 1 x M splitters and smaller number of stages in each ODLL due to the parallelism ($q_M = log_2(N/M)$). A smaller number of stages imply less splitting losses in the ODLLs, but due to the additional losses in the 1 x M splitters the total power loss in the compressor/expander remains almost the same. Let α_c, β_0, and γ_G denote the coupling coefficient of the passive coupler, the optical loss in the delay line for ($T_0 - \tau_0$), and the insertion loss of the gate respectively. Thus, the power level of the j-th pulse after the N-bit compressor $P_{T,j}$ is:

$$P_{T,j} = P_p \gamma_G \beta_0^{(N-j)} \alpha_c^{(q+1)} \qquad (1)$$

For $\alpha_L = 0$ (no losses in the transmission line), the pulsed power after the expander located at the receiving node can be expressed as:

$$P_{R,ODLL} = P_{T,j} \gamma_G \beta_0^{(j-1)} \alpha_c^{(q+1)} = P_p \gamma_G^2 \beta_0^{(N-1)} \alpha_c^{2(q+1)} \qquad (2)$$

Assuming a receiver operating at the quantum limit of 10 photons ($\overline{N}_p = 10$ for BER = 10^{-9}), i.e.

$$\frac{\tau_p P_{R,ODLL}}{hf_c} = 10 \tag{3}$$

where h represents the Planck's constant, f_c is the optical carrier frequency, and τ_p is the pulse width, the average power required from the mode locked laser can be calculated from:

$$\overline{P}_{ql,ODLL} = \frac{P_p \tau_p}{T_0} \frac{10hf_c}{T_0 \gamma_G^2 \beta_0^{(N-1)} \alpha_c^{2(q+1)}} \tag{4}$$

For a parallel arrangement of M ODLLs the average required power from the MLL is:

$$\overline{P}_{ql,ODLL} = \frac{10hf_c M^2}{T_0 \gamma_G^2 \beta_0^{(\frac{N}{M}-1)} \alpha_c^{2(q_M+1)}} \tag{5}$$

Using $q_M = log_2\,(N/M)$ and assuming $\alpha_c = 0.5$ (3dB coupler), (5) can be expressed as:

$$\overline{P}_{ql,ODLL} = \frac{40hf_c N^2}{T_0 \beta_0^{(\frac{N}{M}-1)} \gamma_G^2} \tag{6}$$

In the case of the optical packet compression/expansion via recirculating loop (Fig. 2), the received pulsed power $P_{R,Loop}$ can be expressed as [5]:

$$P_{R,Loop} = P_p \alpha^N \beta_C^2 (1-\beta_C)^N \tag{7}$$

where β_C represents the coupling coefficient of the passive coupler, α denotes the optical loss in a round-trip in the loop including the fiber loss and the insertion losses of the coupler and the switch, and N represents the packet length. Differentiating Expression (7) with respect to β_C, it can be obtained: $\beta_{C,opt.} = 2/(N+2)$. Using expression for $\beta_{C,opt}$ and assuming a receiver operating at the quantum limit of 10 photons similar to (3), the average power required from the mode locked laser can be calculated as follows:

$$\overline{P}_{ql,Loop} = \frac{P_p \tau_p}{T_0} = \frac{10hf_c (N+2)^{(N+2)}}{4T_0 \alpha^N N^N} \tag{8}$$

In real systems is always $\alpha_L > 0$ dB. Therefore, we calculate the allowable loss margin for both compression/expansion schemes (recirculating loop and ODLL) from:

$$L_M = \overline{P}_{laser} - \overline{P}_{ql} \tag{9}$$

Fig. 6 shows the calculated allowable loss margin versus N for select values of the optical loop loss (α) and the insertion loss of the gate (γ_G), whereby the average power of the MLL is selected to be $P_{laser} = 10$ mW with the repetition rate of 1 GHz ($T_0 = 1$ ns) and the wavelength of 1.55 µm.

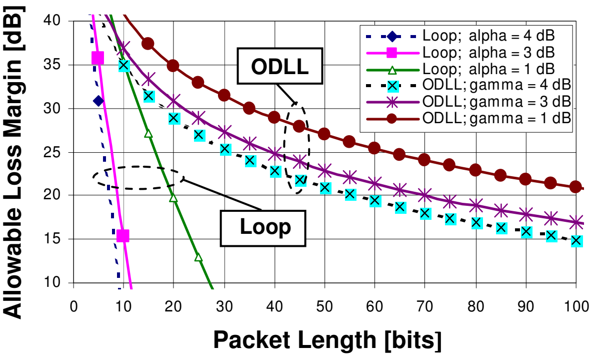

Figure 6: Allowable Loss Margin

In the case of an optical packet compressor/expander using recirculating loop and for a loop loss of 1 dB, 20-bit large packets will enjoy a link margin of 20 dB relative to the quantum limit, while for the loop loss parameter α = 4 dB, only 7-bit large packets are achievable if the same link margin is required. Unlike the scheme using recirculating loop, the compressor/expander using ODLLs allows compression/expansion of packets consisting of more than 100 bits for chosen values of γ_G = 1 dB and L_M = 20 dB. Even for γ_G = 4 dB, the scheme still allows the packet lengths up to 55 bits for L_M = 20 dB.

3.2 Compressor/Expander with Loss Compensation

As we seen in the previous subsection, optical losses in the compressor/expander prevent the formation of longer packets. To compensate these losses, optical signal amplification during compression/expansion operation can be applied. However, added amplifiers induce additional noise caused by ASE. The impact of the OSNR (Optical Signal to Noise Ratio) degradation caused by the ASE noise accumulation and by the imperfect loss compensation on the maximal achievable packet length is investigated in this subsection.

The gain of the amplifiers has to be selected such that the optical losses in the compressor/expander are completely compensated. Moreover, the overall gain of the recirculating loop (product of the amplifier gain and losses in the loop) has to be slightly less than unity to prevent oscillation. We assume the presence of an OBPF (Optical Band Pass Filter) for limiting the noise bandwidth. The spectral density of ASE noise produced at the output of the amplifier is:

$$P_n = n_{sp} h f_c (G-1) B_0 \tag{10}$$

where n_{sp} is the population-inversion factor, G is the amplifier gain and B_0 is the optical bandwidth. At first, we consider an optical packet compressor/expander consisting of an ODLL with loss compensation. The losses can be compensated by adding of additional amplifiers, for example after each 4th ODLL stage. Therefore, the overall gain in a segment consisting of 4 ODLL stages and an amplifier is given by: $\delta = \alpha_c^5 G$ (neglecting the losses in the delay lines because of $\beta_0 << \alpha_c$). The number of these segments in a compressor-expander constellation as shown in Fig. 5 is $2\cdot\lceil q/4 \rceil$. The received signal power at the receiver is then:

$$P_{R,ODLL} = P_p \beta_0^{(N-1)} \alpha_L \gamma_G^2 \delta^{2\left\lceil \frac{q}{4} \right\rceil} \tag{11}$$

The noise produced at the output of an amplifier is than sum of any noise appearing at its input amplified by the gain G, plus the spontaneously generated noise in the amplifier. Therefore, the noise level after $2\cdot\lceil q/4 \rceil$ stages is:

$$P_N = P_n \sum_{i=0}^{2\left\lceil \frac{q}{4} \right\rceil - 1} \delta^i = P_n \frac{1-\delta^{2\left\lceil \frac{q}{4} \right\rceil}}{1-\delta} \tag{12}$$

Also, the noise power at the output of the expander located by the receiving node is given by:

$$P_{N,O} = \beta^{(N-1)} \gamma_G^2 \alpha_L P_n \frac{1-\delta^{2\left\lceil \frac{q}{4} \right\rceil}}{1-\delta} \tag{13}$$

The OSNR can be calculated from:

$$OSNR_{ODLL} = \frac{P_{R,ODLL}}{P_{N,O}} = \frac{P_p}{P_n} \frac{(1-\delta)\delta^{2\left\lceil \frac{q}{4} \right\rceil}}{1-\delta^{2\left\lceil \frac{q}{4} \right\rceil}} \tag{14}$$

Assuming ideal loss compensation, i.e. $\delta = 1$, consequently $P_N = 2\, P_n \cdot \lceil q/4 \rceil$, the OSNR is given by:

$$OSNR_{ODLL}^{\delta=1} = \frac{P_p}{P_n} \frac{1}{2\lceil q/4 \rceil} \tag{15}$$

We consider now a compressor-expander pair using the recirculation loop scheme with an amplifier inserted in the loop for loss compensation. The overall gain in traversing either loop is $\delta = \alpha(1-\beta_{C,opt.})G$. Thus, the received signal after expander can be calculated from:

$$P_{R,Loop} = P_p \beta_C^2 \alpha_L \delta^N \tag{16}$$

The accumulated noise power after traversing the loop N-times (compression of a N-bit large optical packet) is:

$$P_N = P_n \sum_{i=1}^{N-1} \delta^i = P_n \frac{1-\delta^N}{1-\delta} \tag{17}$$

Because of the fact that the last bit in the packet experiences maximal noise corruption (in both compressor and expander), we calculate the noise power at the output of the expander for only this bit:

$$P_{N,O} = P_N \beta_C \alpha_L \delta^N + P_N \beta_C \tag{18}$$

Using (16) and (18), combining $\beta_{C,opt.} = 2/(N+2)$, and assuming $\alpha_L = 1$, we obtain:

$$OSNR_{Loop} = \frac{P_{R,Loop}}{P_{N,O}} = \frac{2P_p}{P_n} \frac{(1-\delta)\delta^N}{(1-\delta^{2N})(N+2)} \tag{19}$$

For ideal loss compensation, i.e. $\delta = 1$, consequently $P_N = P_n \cdot N$, the OSNR is given by:

$$OSNR_{Loop}^{\delta=1} = \frac{P_p}{P_n N(N+2)} \tag{20}$$

Fig. 7 plots the calculated OSNR versus number of bits in a packet (N) for both compression/expansion schemes, where $n_{sp} = 4$, $B_0 = 125$ GHz, $G = \delta/\alpha_c^5$ for the ODLL scheme and $G = \delta/\alpha(1-\beta_{C,opt.})$ for the recirculating loop scheme, and $\alpha_c = \alpha = 3$ dB.

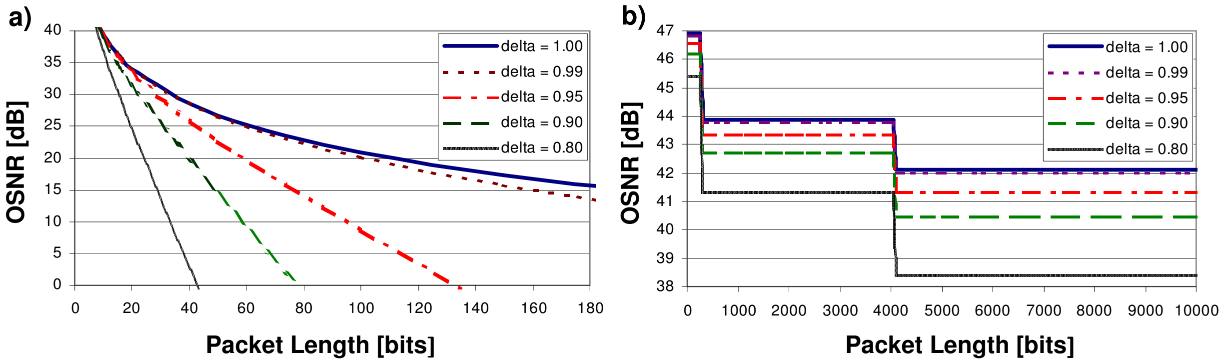

Figure 7. OSNR vs. N for a) the recirculating loop scheme and b) the ODLL scheme

From the curves it can be seen that if the recirculating loop scheme is used, the noise in the loop rises rapidly because of the signal amplification in each roundtrip (N-times for an N-bit packet). The OSNR degradation limits severely the reachable packet length here. Unlike the recirculating loop scheme, the ODLL scheme permits much larger packets by employing signal amplification only after each fourth stage, i.e. $1/4 \cdot log_2(N)$-times for an N-bit packet.

Moreover, it can be seen that insufficient loss compensation causes additional OSNR degradation, especially for the recirculation loop scheme. For example, the recirculating loop scheme permits use of packets containing 100 bits for $\delta = 0.99$ and OSNR = 20 dB, while for $\delta = 0.9$ only 40 bits are permitted for the same OSNR level. With very good amplifier stabilization, the overall gain δ can be as high as 0.99. On the other side, the ODLL scheme allows compression/expansion of much larger packets with an excellent OSNR. We estimated an OSNR of more than 30 dB for very large packets (> 100 kbits) if the ODLL scheme is used, even for insufficient loss compensation ($\delta = 0.8$). Such large packet lengths are applicable in many practical cases, thereby making the ODLL scheme suitable for real telecom applications.

4 Transmission Efficiency

In this subsection, we address the impact of the rate conversion latency on the transmission efficiency in time-slotted single-hop OPC-TDM network architectures assuming a compression/expansion unit consisting of M parallel ODLLs. A simple TDMA scheme with the frame length of K/M slots is assumed, where the slot length equals the packet length. Moreover, we assume an overloaded network with uniform traffic and calculate the rate of successful deliveries. Since the TDMA frame length is chosen to be K/M, the transmission inefficiency is caused only by the rate conversion latency of the receiving node. The transmission efficiency for a single-hop single-channel network consisting of N_S nodes is given by: $\eta = N_S/(N_S+\alpha)$ [5]. In Fig. 8, we plot the transmission efficiency as a function of N_S for a compression rate $K = 100$ and different number of parallel ODLLs (M). It can be seen that for a network consisting of 100 nodes the transmission efficiency can be improved by adding of additional ODLLs, e.g. from 50 % for $M = 1$ to 80 % for $M = 4$. Transmission efficiency of more than 90 % can be achieved for a network with more than 100 users if a compression/decompression unit consisting of 8 parallel ODLLs is used.

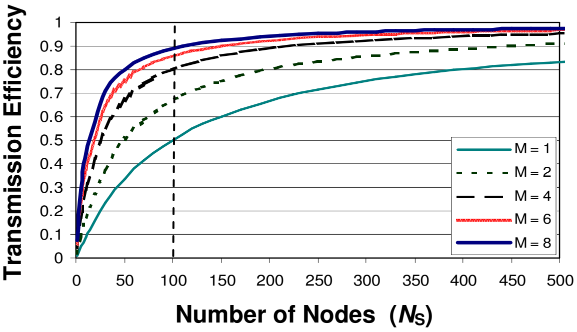

Figure 8: Transmission Efficiency for $K = 100$

5 Summary and Conclusions

OPC-TDM networks that provide a very high-speed access to the optical medium employing the optical packet compression/expansion technique are addressed in this paper. Particularly, basic schemes for optical packet compression/expansion are shown and discussed. The scheme based on a parallel arrangement of ODLLs shows the best characteristics. It allows simultaneous compression and expansion of optical packets not limited in size and conversion rate thereby reducing the impact of the "time out" phenomenon. Power budget analysis and estimation of the ASE noise accumulation performed in this paper show that the ODLL scheme permits use of very large packets applicable in many practical cases. Moreover, the transmission efficiency in single-hop single-channel OPC-TDM networks can be significantly improved if a parallel arrangement of ODLLs is used.

Acknowledgments

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