An optical data rate conversion method for high-speed packed-switched photonic networks

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Abstract: Optical packet compression/expansion allows an ultra-fast media access in packet-switched optical networks. A novel optical packet rate-conversion scheme enabling simultaneous compression/expansion and serial-to-parallel conversion of large optical packets is proposed and investigated. Thereby the rate-conversion time is reduced.

1. Introduction

Very high-speed single channel transmission above the limit of electronics is becoming increasingly important not only for optical time division multiplexing (OTDM) networks, but also for wavelength division multiplexing (WDM) networks. Increasing the bit-rate of WDM channels can be achieved by OTDM technology in a bit-interleaved manner [1,2]. Another promising technique is the optical packet compression/expansion (optical packet rate-conversion) method, which allows high-speed medium access on a packet-by-packet basis. This technique overcomes some of the difficulties associated with bit-interleaved OTDM networks, such as intra- and inter-channel interferometric cross talk and walk-off caused by mismatched wavelengths of the pulse sources at the remote add/drop multiplexer.

Recently, several methods for optical packet rate-conversion have been proposed [3,4,5]. A very promising method is based on an optical delay line structure (ODLS) consisting of $q = log_2(n)$ stages reported in [5]. This technique allows simultaneous compression and expansion of n-bit optical packets using the same device. However, the maximal packet size $L_{p,max}$ is limited by the compression rate $K = T_0/\tau_0$ as follows:

$$L_{p,\max} \le K - 2 \cdot \left\lceil \frac{t_{gate}}{\tau_0} \right\rceil \ , \qquad (1)$$

where T_0 and τ_0 are bit periods of the low- and high-speed packet, respectively, while t_{gate} denotes the response time of the gate located at the output of the device. Consequently, for $K = 100$, $\tau_0 = 10$ ps, and $t_{\text{gate}} = 40$ ps, $L_{p,max}$ is limited to 91 bits. Such short packets are usually impractical in many applications, while the large rate-conversion time ($n \cdot K \cdot \tau_0$) can significantly impair the network performance. Therefore, an optical rate-conversion scheme that allows simultaneous compression and expansion as well as serial-to-parallel conversion of M times larger optical packets compared with the single ODLS is proposed in this paper. Moreover, for a given compression rate K, the time needed for the rate-conversion is reduced by factor M.

2. Principal operation of the compressor/expander

The proposed scalable optical packet compression/expansion unit depicted in Fig. 1 consists of M bidirectional optical gates, M fast optical switches (FOSs), and M parallel active ODLSs, each of them responsible for the rate conversion of a part of the optical packet. An active ODLS is composed of q delay stages and an amplifier stage placed after each i-th delay stage to compensate for the optical losses (inset Fig. 2). The operation of the device can be described as follows: an N-bit high-speed input packet (at H-S In) is divided into M separate n-bit large sequences ($n = N/M$) using a splitter and M bidirectional optical gates. Those sequences are then copied n times in the active ODLSs. Each copy is delayed by (T_0 - τ_0) with respect to the next copy of the packet. A FOS selects bits separated by the bit period T_0 within a very narrow switching window, thereby expanding the high-speed sequence. Thus, the whole high-speed input packet is down-converted and divided into M n-bit low-speed sequences, which are received in a parallel manner by M receivers.

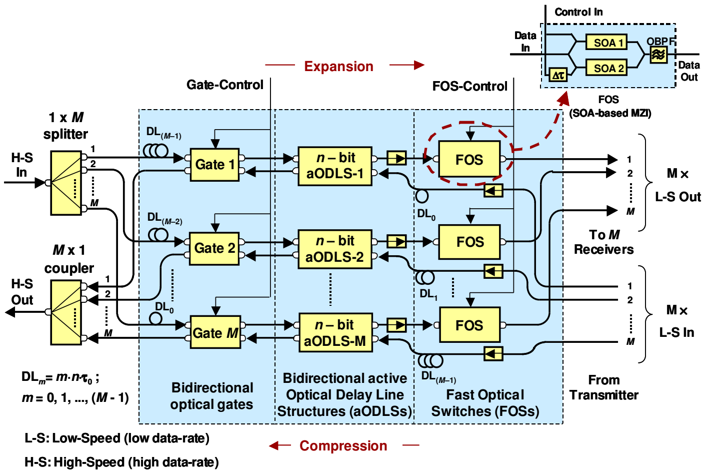

Fig. 1. Optical packet rate-conversion unit.

Low-speed packets (with bit period T_0) can be compressed using the same device in the reverse direction. The parallel data acquired from the transmitting queue can be used to modulate M parallel short pulse trains, thereby generating low-speed optical sequences. In the compression/expansion unit, M low-speed sequences (at L-S In) are first delayed by the delay lines DL_m to meet the timing requirements for combining the compressed sequences at the output, and then compressed in the active ODLSs. The fully compressed sequences are finally selected by the gates and combined by an $M \times 1$ coupler. The resulting signal at H-S Out represents an N-bit compressed packet ($N = n \cdot M$).

3. Simulation results and discussions

Extensive numerical simulations were carried out in order to investigate the feasibility of the proposed scheme. In the simulation set-up, 2.5 ps FWHM optical pulses were generated at 1.55 μm wavelength with a repetition frequency of $f_{L\text{-}S} = 1/T_0$, and split into M ways. The M pulse trains were then modulated in a parallel manner using pseudo random bit sequences (PRBS) to generate M n-bit optical sequences. The low-speed optical sequences were first compressed using the proposed scheme, then transmitted through a transmission line composed of 300 m standard single mode fiber (SSMF), an optical amplifier (EDFA) and an optical band-pass filter (OBPF), and finally expanded using the same compression/expansion scheme in the inverse direction. $LiNbO_3$ modulators were used for implementing the gating functionality, while Mach-Zehnder interferometers with semiconductor optical amplifiers in its arms (SOA-based MZI, Fig. 1) were used as FOSs.

First, the scalability of an active ODLS was investigated. Each delay stage consists of a 3dB coupler and an appropriate fiber delay line. The fiber delay lines were modeled employing the split-step Fourier method using the parameters of commercially available SSMF. The scalability of an active ODLS is mainly limited by the chromatic dispersion in fiber delay lines, and additionally by the optical signal-to-noise ration (OSNR) degradation caused by the amplified spontaneous emission (ASE) noise accumulation [6], which can be calculated from:

$$OSNR = \frac{P_p}{2n_{sp}hf_c(G-1)B_0\lceil \log_2(n)/i \rceil}, \quad (2)$$

where n_{sp} is the population-inversion factor, h represents the Planck's constant, f_c is the optical carrier frequency, P_p is the peak power of the optical pulses, G represents the amplifier gain, and B_0 is the optical bandwidth limited by the OBPF. Small-signal gain and noise figure of the amplifiers were assumed to be 20 dB and 5 dB, respectively. As it can be seen from Fig. 2, nine stages (corresponding to 512-bit packets) induce a power penalty of about 1 dB. That is, M·512-bit packets can be provided using the proposed scheme without any dispersion compensation. Because the number of employed amplifiers is q/i, the OSNR degradation has less influence on the scalability than the chromatic dispersion.

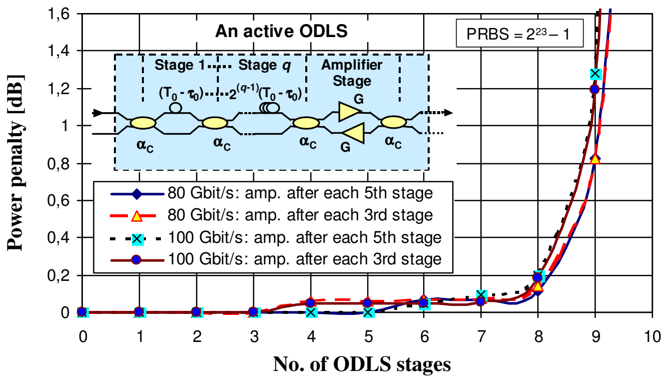

Fig. 2. Scalability of an ODLS.

Second, the gate-control signal has to be synchronized with the incoming/outgoing high-speed optical packets. The impact of the gate-control signal detuning and broadening was investigated recently [7]. The obtained power penalties have shown that a gate-control signal detuning from –7.5 ps to +1.9 ps (an interval of 9.4 ps) as well as a pulse broadening from –1.65 ps to +2.8 ps (in total 4.45 ps) results in a power penalty lower than 3 dB. These results show that the proposed scheme is sensitive to the gate-control signal synchronization; hence very fast and well-synchronized gates should be used or the separation gap between the sequences has to be enlarged.

Furthermore, the impact of the FOS-control pulse power and switching window on the achievable extinction ratio at the output of the device was also studied. The FOS was modeled as a SOA-based MZI using an improved SOA model based on the transmission-line laser modeling (TLLM) method [8], which allows an efficient simulation of full dynamics in the SOA including spatial hole burning. It is observable from Fig. 3 that an extinction ratio better than –14 dB can be obtained for an 80 Gbit/s signal using a FOS with a switching window less than 15 ps and a FOS-control peak power larger than 15 mW. Extinction ratios better than –8 dB were obtained by down-converting from 100 Gbit/s for a wide range of the FOS-control powers and switching windows.

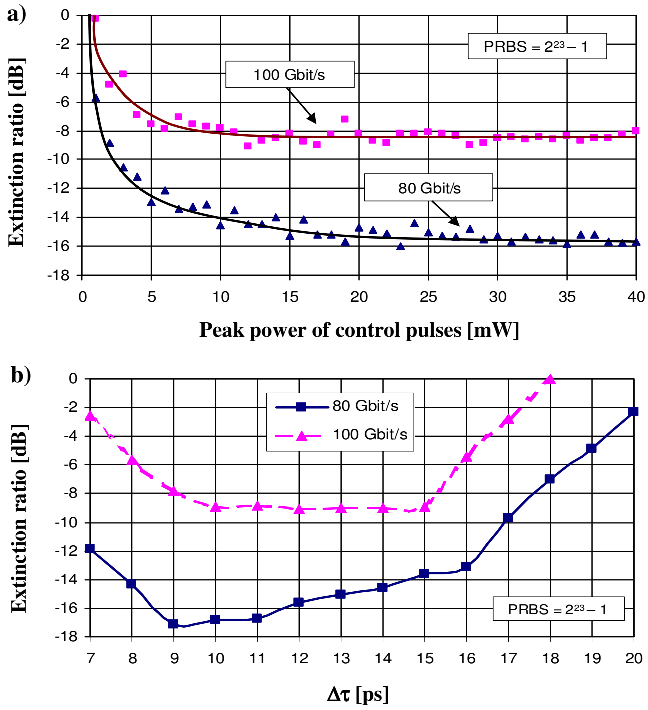

Fig. 3. FOS performance: a) control pulse power b) switching window.

4. Conclusions

In conclusion, a novel optical packet rate-conversion scheme was proposed and investigated. The feasibility of the proposed method was proven by simulations. Particularly, the impact of imperfect gate-control signal synchronization and FOS performance on the down-converted signal as well as scalability of an active ODLS were studied. The results show that the proposed scheme provides rate-conversion of large optical packets (M·512 bits) suitable for the future optical Internet.

5. Acknowledgements

This work is funded by the Austrian Science Fund (FWF) under contract P13144-INF.

6. References

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