Fundamental Limitation and Optimization on Optical Code Conversion for WDM Packet Switching Networks

Y.G. Wen, L.K. Chen and F. Tong
Lightwave Communication Laboratory, Department of Information Engineering
The Chinese University of Hong Kong, Shatin, N. T., Hong Kong
Tel: (852) 2609 8479 Fax: (852) 2603 5032, Email: ygwen9@ie.cuhk.edu.hk

Abstract: Fundamental performance limitation originated from multi-access interference on a generic code converter for WDM packet switching networks is derived and analyzed. A closed-form optimal threshold value that yields the lowest code conversion error is also given.

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1.Introduction

Future all-optical packet-based WDM networks will exploit all possible domains (time, space, wavelength, polarization, code, etc) to optimize its performances in providing all critical functionality such as data rate/format transparency, dynamic wavelength provisioning, and dynamic network re-configuration [1]. A fundamental problem associated with packet-based network is the contention [2], which could be resolved by a combination of optical buffering (time domain), deflection routing (space), wavelength conversion (wavelength), and code conversion (code). Much attentions were given to various contention resolution schemes with the exception of code-based contention resolution, though OCDM technologies can inherently acclimate themselves to the deployment of multi-protocol label switching (MPLS) [3] technology.

Currently, all reported code conversion could be grouped into three schemes. The first scheme [4] is based on coherent method, but its application is limited by the fiber dispersion and polarization disturbance. The second one [5] relies on look-up table that requires extensive, undesirable OE-EO processing. The third scheme [6] uses an all-optical logic XOR gate to implement code converter. Nevertheless, none of these study deals with the fundamental issue of Multi-Access Interference (MAI). Due to the intrinsic unipolar property of optical orthogonal code (OOC) set, MAI cannot be eliminated and can degrade substantially the performances of packet switching networks. The main contributions of this paper are the derivation of the fundamental MAI limitations of a generic multi-channel code converter, and the means to obtain optimal conversion error rate (CER) through the code regeneration devices.

2. Code Converter Architecture

Fig. 1 shows a generic code-converter architecture designed for contention resolution, showing the four stages in the necessary code conversion process, i.e., decoding, signal regeneration, optical space switching with add/drop, and encoding. Though not explicitly specified in the diagram, the scheme can be greatly expanded by including wavelength as another dimension by inserting filtering and multiplexing elements at the input and output of the code converter.

At the input, the received signal, the sum of all virtual optical code channels (VOCC), is equally split into multiple ports equaling to the total number of VOCCs [6]. Next, each VOCC will be decoded by its corresponding decoder. This process can be carried out in optical domain and no OE/EO conversions are required. Results from the decoded optical correlation process are then fed into the signal regeneration stage. This step is necessary in order to suppress the sub-peaks of the auto-correlation and the MAI from the cross-correlation through threshold devices. The remaining autocorrelation peak pulse is then used as the source of the following encoder. Though it is not the main focus of the paper, wavelength conversion (for example, the use of symmetrical Mach Zehnder interferometer [7]) can also be realized at this stage to provide another dimension of flexibility. The optical space switch in the third stage allows channel adding and dropping in addition to its routing function. The forwarded channel will finally be encoded with new codes to become a new VOCC prior forwarding to the next router.

3. Fundamental Limitation

A fundamental limitation of the generic code converter (Fig. 1) is originated from MAI. This happens when MAI exceeds the threshold of the gate device at the code regeneration stage, resulting in code conversion error from the encoder array. Our formulation assumes that there are (1) M simultaneous VOCCs; (2) all VOCC optical sources are generated from incoherent light sources to avoid beatings in en(de)coder array; (3) all VOCCs have identical average input power at each decoder array element, and (4) identical bit rate and signal format for all VOCCs.

Consider any given channel (take n=1 for convenience), the decoder output Z of the channel at time T is

$$Z = \frac{1}{T_c}\int_0^T r(t)C_1(t)\,dt = d^{(1)}K + I_1 + N \qquad (1)$$

where T and T_c are the respective duration of data bit and code chip, $r(t)$ is the received signal, K is the code weight of the first channel (C_1), and $d^{(1)}$ is the detected data bit of the first channel, which can take on the values of either 0 or 1 with equal probability. In this equation, $d^{(1)}K$ is the desired signal term, $I_1 = \sum_{n=2}^{M} I_n^{(1)}$ describes MAI, and N is the quantum noises with zero mean and variance σ_N^2. Note that I_1 is the sum of (M-1) interference channels $I_n^{(1)}$, of which each $I_n^{(1)}$ is a random variable with mean $\mu_{I_n^{(1)}}$ and variance $\sigma_{I_n^{(1)}}^2$. With the assumption that $I_n^{(1)}$ are independent and identically distributed, the mean μ_Z and the variance σ_Z^2 of the Gaussian random variable Z are $d^{(1)}K + (M-1)\mu$ and $(M-1)\sigma^2 + \sigma_N^2$, where $\mu = \mu_{I_n^{(1)}}$ and $\sigma^2 = \sigma_{I_n^{(1)}}^2$ for $2 \le n \le M$. Thus, the probability density function (PDF) for Z is

$$P_Z(Z) = \frac{1}{\sqrt{2\pi\sigma_Z^2}}\exp\left(-\frac{(Z-\mu_Z)^2}{2\sigma_Z^2}\right) \qquad (2)$$

We can then define the conversion error rate (CER) by

$$\begin{aligned} PE_{CER}(Th) &= \Pr(d^{(1)}=0)\Pr(Z = I_1 + N \ge Th) + \Pr(d^{(1)}=1)\Pr(Z = K + I_1 + N \le Th) \\ &= \frac{1}{2}\left[\int_{Th}^{\infty} P_Z\left(Z \mid d^{(1)}=0\right)dZ + \int_{-\infty}^{Th} P_Z\left(Z \mid d^{(1)}=1\right)dZ\right] \end{aligned} \qquad (3)$$

where Th is the threshold.

To eliminate the lengthy calculation of all the cross-correlation functions of a certain OOC set, the CER bounds under two extreme conditions are analyzed: the chip synchronous case corresponding to an upper bound, and the ideal chip asynchronous case corresponding to a lower bound [8]. For the chip synchronous case, the mean and variance of the individual interference signals $I_n^{(1)}$ are $\mu = K^2/2F$ and $\sigma^2 = \left(K^2/2F\right)\left(1-K^2/2F\right)$. For the ideal chip asynchronous case, the mean and variance are $\mu = K^2/2F$ and $\sigma^2 = \left(K^2/F\right)\left(1/3 - K^2/4F\right)$, where F is the code length. In Fig. 2, the upper and lower bound of CER is plotted against the threshold value. In comparison of 2(a) and 2(b), the two traces show similar characteristics. First, there is an optimum threshold value to achieve the minimum CER. This can be derived from Eqn. (3) and is given by $Th_{\text{opt}} = K/2 + (M-1)K^2/2F$. The dash line in fig. 2 shows the trace of Th_{opt} value versus the number of channel. Second, the performance of CER degrades with the increased number of simultaneous VOCCs, because more simultaneous VOCCs will contribute more MAI. Thus, the optimum threshold increases with the increased number of VOCCs. Third, there is a CER floor for the proposed code/wavelength converter. It originates from the interaction of the MAI and the quantum noise.

4. Conclusion

Code conversion can be a powerful means to resolve the contention in the packet switching network. But performances of such scheme are bounded by a fundamental limitation originated from MAI. To enhance the routing capability of future data-centric photonic packet switching networks, a generic all-optical multi-channel code conversion architecture is proposed for contention resolution. The fundamental performance limitation, Conversion Error Rate, is derived, and a close-form optimal threshold value is given to achieve the lowest CER. Furthermore, the scheme can facilitate the deployment of MPLS in the packet-based switching networks.

Acknowledgements

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5. Reference

[1] Daniel J. Blumenthal, Paul R. Prucnal and Jon R. Sauer, "Photonic Packet Switches: Architectures and Experimental Implementations," Proceedings of the IEEE, Vol. 82, No. 11, November 1994, pp.1650-1667

[2] Shun Yao, Biswanath Mukherjee and Sudhir Dixit, "Advances in Photonic Packet Switching: An Overview," IEEE Communications Magazine, February 2000, pp. 84-94

[3] Arun Viswanathan, Nancy Feldman, Zheng Wang and Ross Callon, "Evolution of Multiprotocol Label Switching," IEEE Communications Magazine, May 1998, pp. 165-173

[4] K. Kitayama, " Code Division Multiplexing Lightwave Networks Based upon Optical Code Converter", IEEE Journal of Selected Areas in Communications, Vol. 16, No. 7, pp. 1309-1319,September 1998

[5] Chih-Hong Eyoh, Liren Zhang, and Chee-Hock Ng, " Architecture of ATM Transit Switching Using Optical CDMA Technique", International Conference on Information, Communications and Signal Processing, ICICS'97, pp.873-877, Singapore, 9-12 September 1997.

[6] Yong-gang Wen, Lian-Kuan Chen, Keangy-po Ho and Frank Tong, "An All-optical Code Converter Scheme for OCDM Routing Networks," the 26th European Conference on Optical Communication, September 2000

[7] K. Tajima, et al, ' Hybrid integrated symmetric Mach-Zehnder all-optical switch with ultrafast, high extinction switching', Electrical Letters, Vol. 35, No. 23, November 1999, pp.2030-2031

[8] J. A. Salehi, "Code Division Multiple-Access Techniques in Optical Fiber Networks—Part I: Fundamental Principles", IEEE transactions on communications, Vol.37, No. 8, pp.824-833, August 1989.

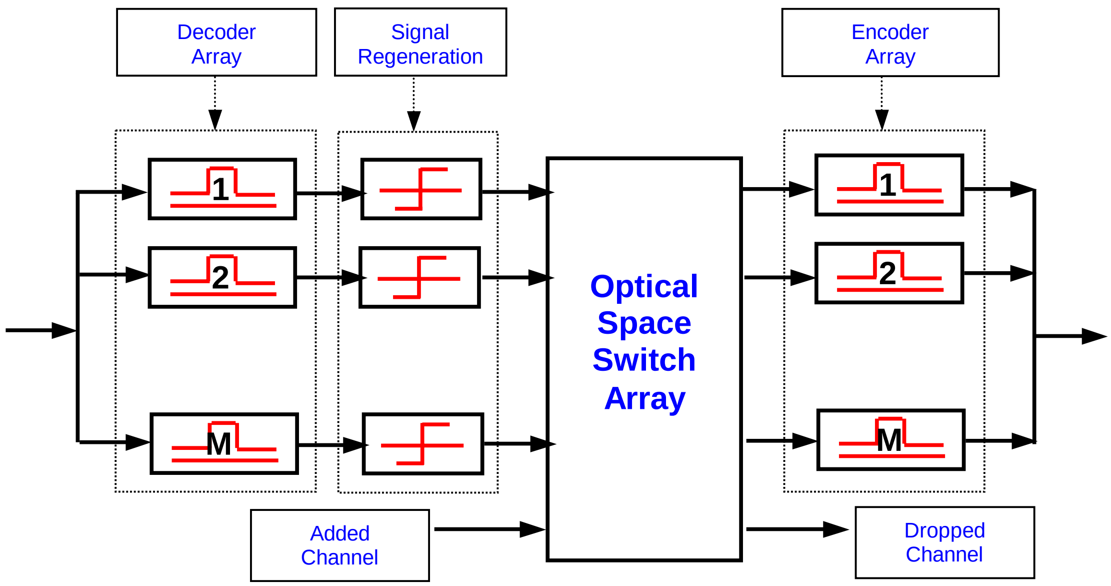
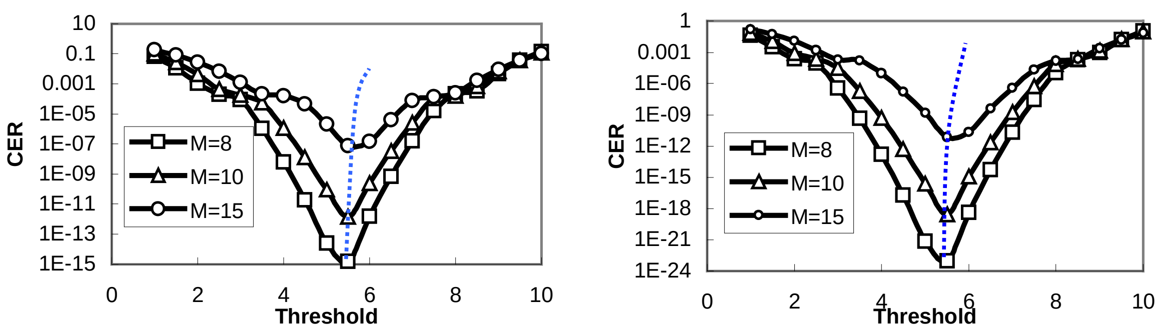


Fig. 1. Architecture of a generic multi-channel code converter.



(a) upper bound

(b) lower bound

Fig. 2. The upper bound (a) and the lower bound (b) of the conversion error rate is plotted against the threshold value. In the figures, K = 10, F = 1000, $\sigma_n = 0.01$, and M = 8, 10 and 15 as shown.