BER Floors due to Heterodyne Coherent Crosstalk in Space Photonic Switches for WDM Networks

D. J. Blumenthal, *Member, IEEE,* P. Granestrand, and L. Thylen, *Member, IEEE*

Abstract—**The occurrence of bit-error-rate floors due to coherent heterodyne crosstalk in photonic space switches is studied. This source of errors occurs when a particular switch is used to route signals of nominally the same wavelength in a WDM network, DFB lasers are run at multigigabit rates, and wavelength referencing is held to a relatively tight tolerance to facilitate wavelength demultiplexing. In this letter we compare the dependence of switch architecture and size on the rate of coherently induced bit errors. Three regions of interest are identified: 1) random uniformly distributed laser phases with binomially distributed bit statistics in interfering channels, 2) random uniformly distributed laser phases with ones in interfering channels, and 3) worst-case laser phases with ones in interfering channels. Critical crosstalk values are identified for four different switch architectures and two different switch sizes in order to avoid coherently induced errors and therefore BER floors due to this mechanism. The minimum crosstalk required to avoid coherent errors can vary from −10 dB to −42 dB depending on the switch architecture, size, and requirement for short-term BER stability.**

I. Introduction

Multiwavelength all-optical networks have received much attention due to their data-rate and format transparency. Crosstalk is an important component parameter that can severely degrade network performance. Coherent crosstalk in particular can lead to data dependent errors, and hence bit error rate (BER) floors. Single source, or homodyne crosstalk, has been studied in great detail and results from interferometric conversion of laser phase noise to intensity noise (PIIN) [1]. Multiple source, or heterodyne crosstalk, can occur when the laser linewidth is less than the bit rate and the center frequency difference between interfering lasers is within the receiver electrical bandwidth making the laser phase noise negligible during the detection process [2]. Heterodyne crosstalk has been studied in wavelength division multiplexed (WDM) add/drop networks with wavelength reuse [3] and for coupled arrays of straight optical waveguides [4].

Manuscript received April 4, 1995; revised September 18, 1995. This work was supported in part by the National Science Foundation under a National Young Investigator (NYI) award and partially carried out under the RACE MWTN (R2028) project. L. Thylen was supported in part by the Swedish Board of Technical Development (NUTEK) and Ericsson AB.

D. J. Blumenthal is with the School of Electrical and Computer Engineering and the Microelectronics Research Center, Georgia Institute of Technology, Atlanta, GA 30332 USA.

P. Granestrand is with the Fiber Optics Research Center, Ericsson Components, AB, S-16481 Stockholm, Sweden.

L. Thylen is with the Laboratory of Photonics and Microwave Engineering, Department of Electronics, Royal Institute of Technology, Electrum 229, S-164 40 Kista-Stockholm, Sweden.

Publisher Item Identifier S 1041-1135(96)00933-0.

In this paper we investigate the occurrence of BER floors due to heterodyne crosstalk in photonic space array switches used in WDM networks. This type of crosstalk will occur in architectures such as MWTN [5] where nominally the same wavelength channels from all node inputs are routed by a common switch fabric. This type of crosstalk has been experimentally determined to be one source of BER floors [6] in the MWTN network demonstrator. In these networks, wavelength positions are maintained to within a tight tolerance to minimize intensity noise and channel crosstalk at an optical filtered receiver. The amount of heterodyne crosstalk will be strongly dependent on switch architecture, size, and implementation, and the occurrence of BER floors will be dependent on laser phase statistics and data pattern statistics. It is shown that critical crosstalk values can be specified for a given switch architecture and size and for certain bit arrival statistics in order to minimize the error rate due to coherent heterodyne crosstalk.

II. Theory

For an $N \times N$ photonic space switch, the total optical field at an arbitrary output is the sum of fields from primary and crosstalk paths from the other $N-1$ inputs. The optical field at the examined switch output can be written to include the statistical phase distribution of the sources and bit statistics at each input as

$$U^{(N)} = \sqrt{S}\left[\cos\omega_0 t + \sum_{n=2}^{N} a_n b_n \cos(\omega_n t + \theta_n)\right] \quad (1)$$

where a_n, the *crosstalk path coefficient*, accounts for the combination of switch element crosstalk, the overall switch structure and the method of setting undefined switch elements. $S/2$ is the power in a *one* bit, ω_0 is the frequency of the desired channel, ω_n is the frequency of the nth of $N-1$ crosstalk channels, and θ_n is the phase of the nth of $N-1$ crosstalk channels. The b_n are random numbers that take on the values of zero or one and represent the bits in the data stream at the nth input.

In this paper, we consider three conditions related to laser phase and bit arrival statistics: Condition (I) phases are random and independent between primary and crosstalk paths and in time, zeros and ones are binomially distributed in time for all crosstalk paths; Condition (II) phases are random as in case I, but ones are always present at all crosstalk paths; Condition (III) phases of all crosstalk paths are π out of phase with the primary path and all ones are present. Signal-crosstalk beating

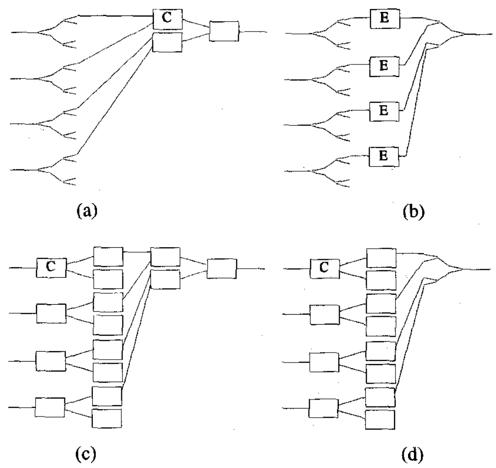

Fig. 1. Four switch architectures investigated are: (a) asac, (b) aspc, (c) psac, and (d) gaa. Power crosstalk for directional coupler switches are indicated by C and the gate array element extinction ratio is indicated by E. Passive splitters and combiners are shown as Y branched waveguides.

can result in a coherent error (i.e., a zero being detected given that a one was routed). We focus on coherent errors due to detection of a *zero* given that a *one* was sent and minimization of this interference to eliminate the resulting BER floors. We assume the polarization states of primary and crosstalk fields are aligned. Although taking into account the polarization states will improve the BER average over a long sequence of bits, data dependent error bursts can occur over relatively short bit sequences leading to periodic occurrence of a BER floor and potential channel drop-out. Assuming that incoming bits at all switch inputs are time aligned, that the laser linewidth is less than the bit rate, and that $\omega_0 - \omega_n$ lies within the low pass filter function of the receiver (denoted LP[..]), the time averaged intensity at the considered output is given by

$$\begin{aligned} Q^{(N)} &= \mathrm{LP}\left[|U^{(N)}|^2\right] \\ &= \frac{S}{2} + S\sum_{n=2}^{N} a_n b_n \cos\theta_n \\ &\quad + S\sum_{n=2}^{N}\sum_{m=2}^{N} a_n a_m b_n b_m \frac{1}{2}\cos(\theta_n - \theta_m) \qquad (2) \end{aligned}$$

A heterodyne coherent error occurs if $Q^{(N)} < S/4$, assuming a threshold value of $S/4$. The expectation value of $Q^{(N)}$ is $S/2$ and the optimum threshold is $S/4$ when the double summation term in (2) is assumed small. Our simulations show that variation in crosstalk values due to the double summation term is less than 1 dB. We consider only beating between the signal and crosstalk fields (the single summation term), and the error condition is $\sum_{n=2}^{N} a_n \cos\theta_n \leq -\frac{1}{4}$.

Four switch architectures are investigated: active-split/active-combine (asac), active-split/passive-combine (aspc), passive-split/active-combine (psac), and gated-amplifier-array (gaa). Examples of four inputs and one output are shown for each type in Fig. 1. The field amplitude equations for each are given below in Eqs. 3 to 6. Note that each equation contains a primary signal (first term) and $N-1$ crosstalk terms (summations). The following assumptions are made in calculating the field amplitudes and crosstalk path terms: (asac) the switch is configured in a full permutation setup with worst case crosstalk, all nonused switches are set to the 3 dB state; (aspc) all permutation states are equivalent, nonused switches are set to the 3 dB state; (psac) all permutation states are equivalent, nonused switches are set in an arbitrary state; (gaa) all permutation states are equivalent, only one gate is transparent for each input/output pair. In each switch element, the value C is the power crosstalk, and is assumed to be the same for all elements. For the gaa case, E, the extinction ratio, is equivalent to C when used as a relative power leakage in a gate. In all cases, crosstalk in waveguide crossovers is ignored (otherwise implementation specific issues must be taken into account). The optical field at a primary output port was numerically simulated for each of the four switch types using (3) to (6). Optical phases were assumed constant over a bit interval, independent in time and across inputs, and uniformly distributed over $[0,2\pi]$.

$$U_{\mathrm{asac}}^{(N)} = \sqrt{S}\cos\omega_0 t + \sqrt{SC}\sum_{i=1}^{\log_2 N}\sum_{j=1}^{2^{i-1}}\left(\frac{1}{2}\right)^{i-1}\cos\phi_{ij} \qquad (3)$$

$$U_{\mathrm{aspc}}^{(N)} = \sqrt{S}\cos\omega_0 t + \sqrt{SC}\sum_{i=1}^{\log_2 N}\sum_{j=2^{i-1}+1}^{2^i} 2^{\frac{-i+1}{2}}\cos\phi_{ij} \qquad (4)$$

$$U_{\mathrm{psac}}^{(N)} = \sqrt{S}\cos\omega_0 t + \sqrt{S}\sum_{i=1}^{\log_2 N}\sum_{j=1}^{\binom{\log_2 N}{i}} C^{\frac{i}{2}}\cos\phi_{ij} \qquad (5)$$

$$U_{\mathrm{gaa}}^{(N)} = \sqrt{S}\cos\omega_0 t + \sqrt{SE}\sum_{i=2}^{N}\cos\phi_i \qquad (6)$$

III. Results

The coherent induced bit error rate as a function of switch crosstalk is shown for each switch structure in Fig. 2 for $N = 32$ and in Fig. 3 for $N = 8$. These curves were calculated numerically by dividing the number of errors (ones mistaken as zeros) detected in $M = 100\,000$ time slots by the total number of slots. The "– · –" curves are calculated assuming random laser phase and binomial bit arrival statistics in the interfering inputs. The solid curves are calculated assuming random laser phase and all ones in the interfering inputs. The dashed line indicates the worst case condition of all crosstalk fields π out of phase with the primary signal and all ones in the interfering inputs.

The curves in Figs. 2 and 3 indicate that the rate of coherently induced bit errors is high until the crosstalk decreases below a critical value given approximately by the asymptotic value of each curve. To the left of this value, it is expected that BER floors due specifically to coherent heterodyne beating will be eliminated and other contributions to errors or floors will dominate (e.g., receiver noise). Comparing the three conditions for a particular switch architecture, we see that the inclusion of random bit patterns at interfering inputs (dashed curves) relaxes the minimum power crosstalk by several dB over that given by random phases and all ones at the interfering inputs (dot-dashed curves). Comparing the worst case condition (solid

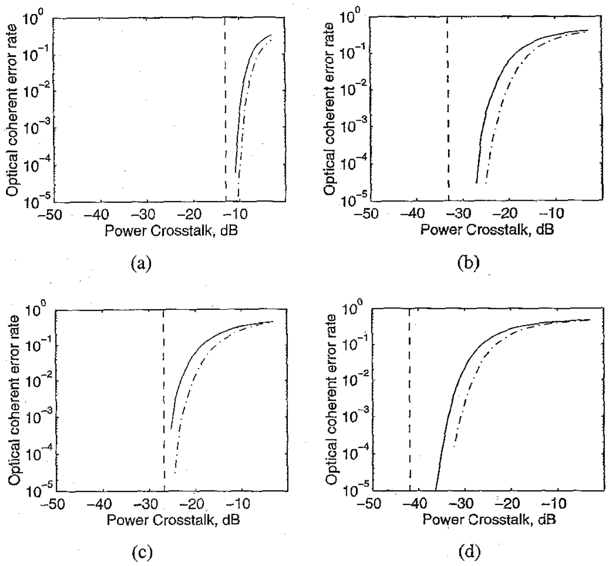

Fig. 2. Influence of crosstalk on coherently induced bit error rate for four switch architectures with $N = 32$: (a) asac, (b) aspc, (c) psac, and (d) gaa. For the "– · –" curves, random laser phase and binomially distributed zeros and ones at the interfering inputs is assumed. For the solid curves, random laser phase and all ones at the interfering inputs is assumed. The "– –" line indicates the worst case with all ones at interfering inputs and all crosstalk terms π out of phase with the primary input.

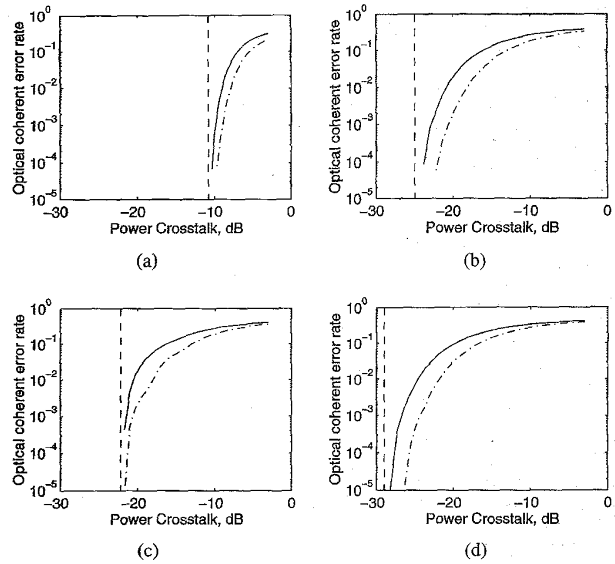

Fig. 3. Influence of crosstalk on coherently induced bit error rate for four switch architectures with $N = 8$: (a) asac, (b) aspc, (c) psac, and (d) gaa. For the "– · –" curves, random laser phase and binomially distributed zeros and ones at the interfering inputs is assumed. For the solid curves, random laser phase and all ones at the interfering inputs is assumed. The "– –" line indicates the worst case with all ones at interfering inputs and all crosstalk terms π out of phase with the primary input.

curves) with the random conditions, it is seen that the worst case is representative of the required crosstalk value for the 8×8 switch whereas the random cases must be considered for the larger 32×32 switch. This is due to an increased probability of the worst case occurring for a smaller number of switch inputs. Overall, the asac architecture places a restriction on the power crosstalk of on the order of -10 to -12 dB whereas the gated-amplifier array places the strongest requirement on switch crosstalk in the neighborhood of -30 to -40 dB. Increasing the number of gates in the gaa structure will significantly improve its performance.

IV. Summary

In this paper we have compared the effect of switch element power crosstalk on coherently induced bit errors in space photonic switches used in WDM networks. When the power crosstalk exceeds a critical value, the error rate due to this mechanism can dominate all other error mechanisms and lead to a BER floor. This type of crosstalk is important in WDM photonic switch networks where channels with nominally the same wavelength are routed in the same photonic switch fabric. The effect of random bit patterns and randomly varying laser phases were included in the simulation as well as worst case conditions where interfering channels are π out of phase with the primary channel. In general, as the switch size increases, lower switch element crosstalk is required. The active-splitting/active-combining switch shows least sensitivity to increase in switch size and requires power crosstalk values on the order of -10 dB. The gated-array switch structure shows a high sensitivity to increase in switch size. However, while the GAA structure places stricter requirements on crosstalk, high extinction values ($E = -40$ dB) are obtainable over wide wavelength ranges with these types of switch gates. In general, our simulations show that for small switch size (8×8), there is a higher probability that the worst case phase condition will occur, and the random-bit/random-phase assumption is close to the worst case. For larger switches ($N \geq 32$), the statistically generated curves serve as a more accurate guide to specifying allowable crosstalk.

References

[1] J. L. Gimlett and N. K. Cheung, "Effects of phase-to-intensity noise conversion by multiple reflections on gigabit-per-second DFB laser transmission systems," *IEEE J. Lightwave Technol.*, vol. 7, no. 6, pp. 888–895, 1989.

[2] G. Jacobsen, "Multichannel system design using optical preamplifiers and accounting for the effects of phase noise, amplifier, and receiver noise," *IEEE J. Lightwave Technol.*, vol. 10, no. 3, pp. 367–377, 1992.

[3] E. L. Goldstein and L. Eskildsen, "Scaling limitations in transparent optical networks due to low-level crosstalk," *IEEE Photon. Technol. Lett.*, vol. 7, no. 1, pp. 93–94, 1995.

[4] T. T. Ha and R. M. Loesch, "Crosstalk analysis of asynchronous optical chip interconnects with direct detection," *IEEE J. Lightwave Technol.*, vol. 12, no. 11, pp. 1932–1936, 1994.

[5] G. R. Hill, P. J. Chidgey, F. Kaufhold, T. Lynch, O. Sahlen, M. Gustavsson, M. Janson, B. Lagerstrom, G. Grasse, F. Meli, S. Johansson, J. Ingers, L. Fernandez, S. Rotolo, A. Antonielli, S. Tebaldini, E. Vezzoni, R. Caddedu, N. Caponio, F. Testa, A. Scavennec, M. J. O'Mahony, J. Zhou, A. Yu, W. Sohler, U. Rust, and H. Herrmann, "A transport network layer based on optical network elements," *IEEE J. Lightwave Technol.*, vol. 11, nos. 5/6, pp. 667–679, 1993.

[6] P. J. Chidgey, J. Laws, D. J. Malyon, G. P. Reeve, and P. Swan, "Crosstalk in multi-wavelength optical networks," in *IEEE/LEOS Summer Top. Mtg. Optical Networks and Their Enabling Technol.*, July 11–13, 1994, paper PD6.