Exact Analysis of Homodyne Crosstalk Induced Penalty in WDM Networks

Keang-Po Ho, Chun-Kit Chan, Frank Tong, and Lian K. Chen

***Abstract*— We present an exact analytical probability density function and a closed-form bit-error-rate (BER) formula for wavelength-division multiplexing (WDM) networks with homodyne crosstalk from a single dominant channel. The derived crosstalk penalties are in excellent agreement with that obtained from experiments.**

***Index Terms*— Crosstalk interference, homodyne crosstalk, wavelength-division multiplexing (WDM) networks.**

I. Introduction

THE BASIS of future information infrastructure will be built upon an all-optical multiwavelength networks in which wavelength-division-multiplexing (WDM) signals are transmitted in the fiber link, channel routing and add-drop functions are performed by wavelength routers. One fundamental difficulty of the router is the homodyne crosstalk originated from inputs from neighboring fibers carrying channels of the same or identical wavelength to that of the signal, causing severe degradation in system performance. Because of the similar or identical wavelength, this crosstalk is difficult to be eliminated by filtering, and the crosstalk will beat with the signal and generate a new kind of noise at the receiver [1]–[6]. Previous analyzes on homodyne crosstalk in wavelength routers were largely based on Gaussian approximation [1], [3], [4], [6], though there were reports and evidences that this assumption is inadequate [3], [5]. From central-limit theorem, Gaussian assumption is only valid for a large number (approximately larger than five) independent interference sources with more or less the same variance. For the case in which the number of dominant interference source is limited to one or two, a more accurate model is required. This scenario could arise from the near–far effect [7], where one particular crosstalk channel is located closer to the router than the rest of the crosstalk channels and, thus, has a higher input power.

Here, to the best of our knowledge, we are the first to present an exact closed-form power penalty analysis for a single-homodyne crosstalk source. A closed-form bit-error-rate (BER) formula is also provided. The results are in excellent agreement with that obtained through experiments [6].

Manuscript received October 14, 1997; revised November 10, 1997.

K.-P. Ho, F. Tong, and L. K. Chen are with the Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong.

C.-K. Chan is with the Department of Electronic Engineering, City University of Hong Kong, Kowloon Tong, Kowloon, Hong Kong.

Publisher Item Identifier S 1041-1135(98)01835-7.

II. Exact Analysis

We assume the crosstalk channel has the same wavelength with that of the desired signal, i.e., $E_0(t) = E_0 e^{j\omega t}$ for the signal, and $E_1(t) = re^{j\omega t + j\varphi(t)}$ for the crosstalk with a random phase of $\varphi(t)$ distributed uniformly in $[0, 2\pi)$. Without loss of generality, for a unit detector responsivity, the photocurrent generated is $i(t) = |E_o + re^{j\varphi(r)}|^2$. Ignoring the term in the order of r^2, the overall receiver noise in the photodetector is [1]–[6]

$$n(t) = A\cos(\varphi(t)) + n_0(t)$$

where $A = 2E_0 r$ is the crosstalk amplitude, and $n_0(t)$ is the usual Gaussian noise in the receiver. To calculate the BER, we must evaluate the probability density function (p.d.f.) of $n(t)$.

The p.d.f. of $A\cos(\varphi(t))$ is given by $p(x) = (1/\pi)(A^2 - x^2)^{-1/2}$ for $-A < x < +A$ [3], [5], which yields the characteristic function:

$$\Psi_I(\omega) = \frac{1}{2\pi}\int_0^{2\pi} \exp(j\omega A\cos(\varphi))\, d\varphi = J_0(A\omega)$$

where $J_0(\cdot)$ is the Bessel function. The characteristic function of $n(t)$ then becomes

$$\Psi_n(\omega) = J_0(A\omega)\exp(-\sigma^2\omega^2/2)$$

where σ^2 and $\exp(-\sigma^2\omega^2/2)$ are the variance and the characteristic function of the receiver Gaussian noise, respectively. The p.d.f. of $n(t)$ is [8], [9, Sec. 9.3]

$$p_n(r) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{k=0}^{\infty}\frac{(-r^2/2\sigma^2)^k}{k!}\,{}_1F_1\left(k+\frac{1}{2}; 1; -\frac{A^2}{2\sigma^2}\right)$$

where ${}_1F_1(a; b; x)$ is the confluent hypergeometric function [9, Sec. A.1.2]. Assuming a detection level of d, the error probability is then

$$p_b = \frac{1}{2} - \frac{1}{\sqrt{2\pi}}\sum_{k=0}^{\infty}\frac{(-1)^k(d/\sigma)^{2k+1}}{2^k(2k+1)k!}\,{}_1F_1\left(k+\frac{1}{2}; 1; -\frac{A^2}{2\sigma^2}\right).$$

The BER of the system can be evaluated according to the error probability p_b.

Note that the closed-form formula for error probability assumes a single dominant homodyne crosstalk. Closed-form formula for multiple crosstalk sources is difficult to derive. The above derivation also assumes there is no distortion of noise waveform $A\cos(\varphi(t))$ by the electrical filter at the receiver. This assumption is valid when the data modulation bandwidth is much larger than the noise bandwidth of $A\cos(\varphi(t))$. The

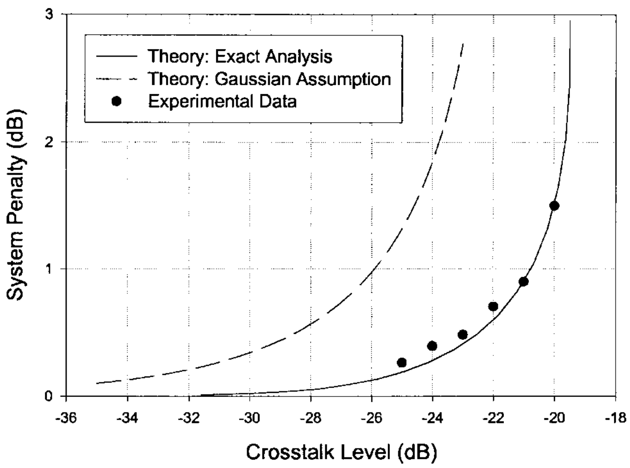

Fig. 1. System penalty as a function of crosstalk ratio.

noise bandwidth is the same as the laser linewidth [4], [10] that is on the order of tens of megahertz and is well within the bandwidth of the receiver filter.

III. Numerical Results and Experimental Verification

Homodyne-crosstalk induced receiver noise is only significant when both the signal and crosstalk channels are in the ONE level. Here, for simplicity, we assume the worst-case scenario in which there is an equal contribution of crosstalk from the ONE and the ZERO levels, i.e., $p_{e1} = p_{e0}$, and the detection level is located at the middle of the "eye." The BER then simply equals to p_b. Without crosstalk, the Q-factor of the system [1], [3], [10] from Gaussian noise can be expressed as $q_g = d/\sigma (q_g = 6$ for a BER $= 10^{-9})$. The system crosstalk penalty then equals to $10\log_{10}(q/q_g)$, where q is the required Q-factor with homodyne crosstalk. Fig. 1 shows crosstalk penalty as a function of crosstalk ratio for system with neglegible input power depending noise. The power penalty derived from Gaussian approximation [1], [10] is also shown as comparison.

Our theoretical results are verified by experiments using setup shown in Fig. 2. A DFB laser is modulated by a 622-Mb/s [($2^{15}-1$ pseudorandom bit sequence (PBRS)] nonreturn-to-zero (NRZ) data with an extinction ratio of 15 dB. To simulate the homodyne crosstalk, the generated signal is split into two paths, with one path 7 km longer than the other

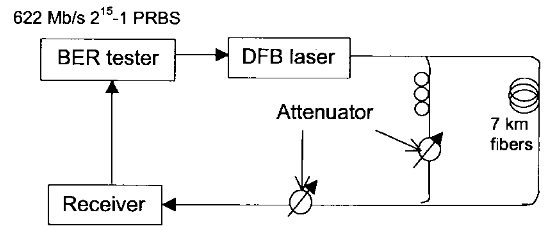

Fig. 2. Experimental setup to measure homodyne crosstalk system penalty.

to avoid coherent effects. The polarization of the crosstalk channel is carefully controlled to yield maximum beat noise at the receiver. The measured crosstalk-induced system penalties are in excellent agreement with that obtained from the analysis.

IV. Conclusion

We have derived closed-form analysis from a single homodyne crosstalk channel in WDM networks. The derived crosstalk penalties are in excellent agreement with that obtained from experiments.

References

[1] E. L. Goldstein, L. Eskildsen, and A. F. Elrefaie, "Performance implications of component crosstalk in transparent lightwave networks," *IEEE Photon. Technol. Lett.,* vol. 6, pp. 657–660, 1994.

[2] P. J. Legg, D. K. Hunter, I. Andonovic, and P. E. Barnsley, "Inter-channel crosstalk phenomena in optical time division multiplexed switching networks," *IEEE Photon. Technol. Lett.,* vol. 6, pp. 661–663, 1994.

[3] H. Takahashi, K. Oda, and H. Toba, "Impact of crosstalk in an arrayed-waveguide multiplexer on $N \times N$ optical interconnection," *J. Lightwave Technol.,* vol. 14, pp. 1097–1105, 1996.

[4] C.-S. Li and F. Tong, "Cosstalk and interference penalty in all-optical networks using static wavelength routers," *J. Lightwave Technol.,* vol. 14, pp. 1120–1126, 1996.

[5] M. Tur and E. L. Goldstein, "Probability distribution of phase-induced intensity noise generated by distributed-feedback lasers," *Opt. Lett.,* vol. 15, pp. 1–3, 1990.

[6] J. Song, C.-K. Chan, F. Tong, and L. K. Chen, "Extinction ratio induced crosstalk system penalty in WDM networks," *Electron. Lett.,* vol. 32, pp. 2112–2114, 1996.

[7] C.-S. Li, F. Tong, M. S. Chen, and C. Georgio, "Gain equalization in metropolitan and wide area optical networks using optical amplifiers," presented at INFOCOM '94, Toronto, ON, Canada, June 1994.

[8] S. O. Rice, "Statistical properties of a sine wave plus random noise," *Bell Syst. Tech. J.,* vol. 27, pp. 109–157, 1948.

[9] D. Middleton, *Introduction to Statistical Communication Theory.* New York: McGraw-Hill, 1960.

[10] J. Gimlett and N. K. Cheung, "Effects of phase-to-intensity noise conversion by multiple reflections on gigabit-per-second DFB laser transmission systems," *J. Lightwave Technol.,* vol. 7, pp. 888–895, 1989.