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On the Distribution and Performance Implications of Filtered Interferometric Crosstalk in Optical WDM Networks

Idelfonso Tafur Monroy, Eduward Tangdionga, and Huig de Waardt

Abstract—The distribution and performance implications of filtered interferometric crosstalk in optical networks is theoretically and experimentally studied. The probability density function is estimated by using a maximum entropy approach based on analytically derived statistical moments. The theoretical results are confirmed by relevant experimental data obtained from an amplitude shift keying direct detection (ASK/DD) system using directly, and externally modulated light sources. Power penalties are measured for both types of source modulation. The experimental results are in good agreement with theory.

Index Terms—Error analysis, optical crosstalk, optical communication, wavelength division multiplexing (WDM) networks.

I. INTRODUCTION

INTERFEROMETRIC crosstalk has been reported to degrade the performance, introducing large power penalties and bit error rate floors, of a variety of optical networks, e.g., all-optical trunk networks and wavelength division multiplexing (WDM) systems; see, e.g., [1]–[5]. For a reliable performance analysis of a communication system an accurate statistical description of the noise is required. Although the impact of interferometric noise on the performance of optical networks has been widely studied, the performance evaluation is commonly based on weakly crosstalk statistical assumptions. For instance, crosstalk has been assumed to be either arc-sine or Gaussian distributed, e.g., [2]–[7]. Performance analyzes assuming a two pronged arc-sine distribution for interferometric crosstalk have shown good agreement with experiment when the system uses a directly modulated light source, e.g., [4]–[7], while the Gaussian approximation gives pessimistic results. For systems employing externally modulated sources analyzes using the arc-sine distribution assumption appear to be too optimistic, while analyzes assuming Gaussian statistics have shown good agreement with experiment, e.g., [2]–[4], [8]. Furthermore, it has been observed that systems employing a directly modulated light source incurred smaller power penalties due to interferometric crosstalk than systems using external light source modulation [4], [8].

It is of relevant interest to accurately describe the statistics of filtered interferometric crosstalk for both types of source modulation in order to efficiently predict its impact on the performance of optical networks. In this paper, we present a statistical analysis of filtered interferometric crosstalk which is valid for arbitrary values of the laser 3-dB linewidth, interferometric delay, and electrical filter bandwidth. Of special interest is the dependence of the filtered interferometric crosstalk statistics on the value of the 3-dB laser bandwidth due to the fact that its value can differ significantly depending on the light source modulation type.

A maximum entropy approach is used to estimate the probability density function (pdf) of interferometric noise based on derived moments. The study shows that the statistics of filtered interferometric crosstalk (and the system performance) is strongly dependent on the product of the laser 3-dB linewidth and the electrical filter bandwidth. Namely, for filters with a large bandwidth the statistics of crosstalk shows a two pronged character, while for a narrower filter bandwidth the statistics reverts to a Gaussian-like type. Measured probability density functions and computer simulations confirm the theoretical pdf's. It is also observed that the interferometric crosstalk is substantially reduced (filtered out), resulting in a better system performance, when the 3-dB laser linewidth exceeds the filter bandwidth. This fact indicates that one can reduce interferometric crosstalk in optical networks by broadening (phase dithering) the laser spectrum as already pointed out in [9]–[11].

Power penalties due to interferometric crosstalk are measured for an amplitude shift keying direct detection (ASK/DD) system using directly, and externally modulated light sources. The experimental results are in good agreement with theoretical predictions. Based on the knowledge of the variance of filtered crosstalk a simple Gaussian approximation is proposed for computing power penalties.

The rest of the paper is structured as follows. Section II presents the system model under investigation. In Section III the derivation of moments of filtered crosstalk is given. In Section IV, based on the derived moments pdf's are estimated using a maximum entropy approach. A comparison of theoretical pdf's with simulated and measured pdf's is also presented. Section V is devoted to the performance analysis of optical systems disturbed by interferometric crosstalk. Power penalties are computed using the estimated pdf for filtered interferometric crosstalk. Experimental details are presented in Section VI.

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Fig. 1. Schematic diagram of an ASK/DD receiver. At the receiver input $S_s(t)$ represents the optical signal while interferometric crosstalk is denoted by $S_x(t)$.

Experimental results, their discussion and comparison with theory are the topics of Section VII. Finally, in Section VIII summarizing conclusions are presented.

II. SYSTEM MODEL

We consider the case of an optical signal disturbed by a crosstalk interfering source operating at the same nominal wavelength. The optical field of the signal $\vec{S}_s(t)$ and the crosstalk $\vec{S}_x(t)$ is given by their complex amplitude vectors

$$\vec{S}_s(t) = \sqrt{b_k^s} A_s(t) \vec{r}_s e^{j\phi_s(t)} \quad (1)$$

$$\vec{S}_x(t) = \sqrt{\epsilon b_k^x} A_x(t) \vec{r}_x e^{j\phi_x(t)} \quad (2)$$

where ϵ is the crosstalk parameter: the ratio of leakage crosstalk to signal power. The indicator b_k is introduced to represent the binary symbols: $b_k \in \{\varrho, 1\}$ ($0 \leq \varrho < 1$). For the case of perfect extinction the ratio $\varrho = 0$. The variable $\phi_{s,x}$ is the phase of the signal and interferer, respectively. The vectors $\vec{r}_s$ and $\vec{r}_x$ are unit vectors representing the signal and interferer polarization state, respectively.

We consider an ASK/DD receiver whose schematic diagram is depicted in Fig. 1. The output of the photodetector $I_{sh}(t)$ is a shot noise process characterized by a photoelectron intensity $\lambda(t)$, which normalized can be written as [5]

$$\lambda(t) = \frac{1}{2} |\vec{S}_s(t) + \vec{S}_x(t)|^2 \quad (3)$$

where the factor "1/2" comes from the complex notation.

The receiver thermal noise, denoted by $I_{th}(t)$, is modeled as an additive, zero mean, white Gaussian stochastic process. It is assumed that the optical pulses are of identical shape and confined in the time interval $[0, T]$, i.e., no intersymbol interference (ISI) is assumed. For a transmitted binary "one"

$$m = \frac{1}{2} \int_0^T |A(t)|^2 dt$$

photons are contained in an optical pulse of duration T and for a binary "zero" ϱm photons are in the optical pulse.

The postdetection filter is assumed to be a finite time integrator over the interval $[0, T]$. With no loss of generality we consider the time interval $[0, T]$ ($k = 0$) and denote the decision variable by $Z = Z(t=T)$

$$Z = \int_0^T [I_{sh}(t) + I_{th}(t)] dt = X_{sh} + X_{th}. \quad (4)$$

X_{th} is a zero mean, Gaussian distributed random variable (RV) with variance σ_{th}^2 given by [15]

$$\sigma_{th}^2 = \frac{2K_B T_k T}{q_e^2 R_L} \quad (5)$$

K_B being the Boltzmann's constant, T_k denotes absolute temperature, q_e the electron charge, and R_L the receiver resistance load.

The moment generating function (MGF) of the decision variable is given by

$$M_Z(s) = E\{e^{sZ}\} = M_{sh}(s)M_{th}(s) \quad (6)$$

where M_{th} is the MGF for a zero-mean Gaussian variable with variance σ_{th}^2

$$M_{th}(s) = e^{s^2 \sigma_{th}^2 / 2}. \quad (7)$$

$M_{sh}(s)$ is the MGF of X_{sh} : the filtered shot noise contribution to the decision variable Z . The product of MGF in (6) is a consequence of the stochastic independence of the shot and thermal noise.

The filtered shot noise is well modeled by a doubly stochastic Poisson process with intensity $\lambda(t)$. Hence, for the case of an integrator postdetection filter, M_{sh} is given by

$$M_{sh}(s) = M_\Lambda(e^s - 1) \quad (8)$$

where $M_\Lambda(s) = E\{e^{s\Lambda}\}$ and $\Lambda = \int_0^T \lambda(t) dt$ is the Poisson parameter [12].

The signal and the interferer are assumed to exhibit aligned state of polarization (worst case) and perfect bit alignment. With the above mentioned assumptions the parameter Λ takes the form

$$\Lambda = m(b_0^s + \epsilon b_0^x) + 2m\sqrt{b_0^s b_0^x} \epsilon \times \underbrace{\frac{1}{T} \int_0^T \xi(t) dt}_\gamma \quad (9)$$

where the function $\xi(t)$ is given by

$$\xi(t) = \cos[\phi_s(t) - \phi_x(t - \tau_d)] \quad (10)$$

in which τ_d is the interferometric delay time.

Conditioning on the value of γ the MGF for Λ is given by

$$M_{\Lambda|\gamma}(s, \gamma) = \exp[sm(b_0^s + \epsilon b_0^x)] \exp[2sm\sqrt{b_0^s b_0^x} \epsilon \gamma]. \quad (11)$$

The variable γ takes values in the interval $[-1, 1]$. Denoting the pdf of γ by $f_\gamma(\cdot)$ the unconditioned MGF for Λ can be written as

$$M_\Lambda(s) = \int_{-1}^1 M_{\Lambda|\gamma}(s, \tilde{\gamma}) f_\gamma(\tilde{\gamma}) d\tilde{\gamma}. \quad (12)$$

The pdf function $f_\gamma(\cdot)$ can be estimated from the moments of γ by using a maximum entropy approach [13]. Based on the knowledge of the MGF we can compute error probabilities by the so-called saddlepoint approximation as outlined in Section V.

III. MOMENT CHARACTERIZATION OF FILTERED INTERFEROMETRIC CROSSTALK

The laser phase [function $\phi_{s,x}(t)$ in (1) and (2)] is modeled as Wiener (Brownian motion) process whose autocorrelation is given by

$$R(t_1, t_2) = 2\pi\Delta\nu \min(t_1, t_2) = \beta \min(t_1, t_2) \quad (13)$$

where $\Delta\nu$ equals the 3-dB bandwidth of the Lorentzian shaped laser power spectrum [14].

The phase difference $\Delta\phi(t) = \phi_s(t) - \phi_x(t - \tau_d)$ is also a Wiener process, Gaussian distributed with zero mean and autocorrelation function given by

$$R_{\Delta\phi}(\tau) = \begin{cases} \beta(\tau_d - |\tau|), & |\tau| \leq \tau_d \\ 0, & |\tau| > \tau_d \end{cases} \quad (14)$$

The autocorrelation function of the process $\xi(t)$ is related to the autocorrelation of the process $\Delta\phi(t)$ in the following way ([15], Section VIII-C2)

$$R_{\xi}(\tau) = \frac{1}{2} e^{(-[R_{\Delta\phi}(0) + R_{\Delta\phi}(\tau)])} + \frac{1}{2} e^{(-[R_{\Delta\phi}(0) - R_{\Delta\phi}(\tau)])} \quad (15)$$

Substitution of (14) in (15) yields

$$R_{\xi}(\tau) = \begin{cases} \frac{1}{2} e^{-\beta|\tau|} [1 + e^{-2\beta(\tau_d - |\tau|)}], & |\tau| \leq \tau_d \\ e^{-\beta|\tau|}, & |\tau| > \tau_d \end{cases} \quad (16)$$

The autocorrelation functions (14) and (16) are used to derive the moments of filtered interferometric crosstalk.

A. The Moments

The filtered crosstalk [cf., (9)] is denoted by

$$\gamma = \frac{1}{T} \int_0^T \xi(t) dt = \frac{1}{T} \int_{t-T}^t \xi(t_1) dt_1. \quad (17)$$

The mean, first moment, of the variable γ is easily derived

$$\mu_1 = E\{\gamma\} = \frac{1}{T} \int_0^T E\{\cos[\Delta\phi(t)]\} dt = \exp\left(-\frac{\sigma_{\Delta\phi}^2}{2}\right). \quad (18)$$

By observing (18) and (16) we find that the process $\xi(t)$ is a wide-sense stationary stochastic (WSS) process. Thus, the second moment for γ can be found by [16]

$$\mu_2 = E\{\gamma^2\} = \frac{2}{T^2} \int_0^T (T - \tau) R_{\xi}(\tau) d\tau. \quad (19)$$

Inserting (16) in (19) it turns out that

$$E\{\gamma^2\} = \frac{1}{(\beta T)^2} [e^{-2\beta\tau_d} (e^{\beta T} - 1 - \beta T) + \beta T - 1 + e^{-\beta T}].$$

A plot of the variance of γ , $\text{Var}\{\gamma\} = E\{\gamma^2\} - (E\{\gamma\})^2$, for different values of β and τ_d is presented in Fig. 2, keeping a fixed value for T . For comparison reasons we use as reference an integrator filter with equivalent bandwidth defined as $Be = (1/T)$. In the sequel, all considered filters are assumed to have the same noise equivalent bandwidth. As we can observe from Fig. 2 the variance of filtered interferometric crosstalk is

Fig. 2. Variance of filtered interferometric crosstalk.

strongly dependent on the relation between the values of β , τ_d , and T . For instance, if we consider the situation for $\beta T \rightarrow 0$ (negligible filtering), we have that the variance of γ increases with $\beta\tau_d$ from its minimum value zero to its maximum value of one-half for $\beta\tau_d \gg 1$. For the case of $\tau_d = 0$ the process $\Delta\phi(t)$ is an standard Brownian motion in contradistinction to a stationary Gaussian process when $\tau_d > 0$. For this particular case the variance of γ is an increasing function of βT .

We are interested in the regime when the interferometric noise is less damaging, i.e., when it has a small variance. It can be seen from Fig. 2 that this occurs when the values of τ_d/T and βT are large. It corresponds to the case of incoherent interferometric noise (interferometric delay time much larger than the light source coherence time) and a laser linewidth larger than the filter bandwidth. The fact that the variance decreases for large values of βT is an important characteristic of filtered interferometric crosstalk. It indicates that one can reduce interferometric crosstalk in optical networks by assuring a high value of $\beta T \equiv \beta/Be$. As the value of the postdetection filter bandwidth is governed by the system bit rate, a high value β/Be can be achieved, for instance, by broadening (phase dithering) the laser spectrum.

The higher moments of γ can be found by the following relation [17]:

$$\mu_k = \frac{k!}{2^{k-1} T^k} \sum_{\mathbf{a}} I_{\mathbf{a}}^{(k)}|_{t=T} \quad (20)$$

in which

$$I_{\mathbf{a}}^{(n)} = \int_0^t e^{\beta b_n t_n} I_{\mathbf{a}}^{(n-1)} dt_n \quad (21)$$

with the initial condition $I_{\mathbf{a}}^{(0)} = e^{c\beta\tau_d}$. The parameters b_n , and c are given by (33) and (34), respectively. See Appendix A for a derivation.

The third moment is found to be equal to

$$\mu_3 = \frac{3}{8(\beta T)^3} \left[\left(1 + \beta T \right) e^{-(9/2)\beta T_d} + \left(1 + \frac{2}{3}(\beta T)^3 - 2\beta T + 2(\beta T)^2 \right) \cdot e^{-(1/2)\beta T_d} + (\beta T - 1) e^{2\beta T - (9/2)\beta T_d} - e^{-(1/2)\beta T_d - 2\beta T} \right].$$

The analytical expressions for higher moments become complex as the order increases. However, the recursion (21) is expeditiously solved by computer programs supporting symbolic integration. We have computed moments up to the twelve order.

In several applications of interest, for instance in WDM networks, the interferometric delay is of a larger magnitude than the laser coherence time ($\beta T_d \gg 1$). This situation is called the incoherent interferometric noise regime. For this case we notice that the terms containing exponentials of $-\beta T_d$ may be neglected and consequently the odd moments of the filtered interferometric crosstalk vanish and the even moments are function of the parameter βT alone. The resulting expression for even moments up to order four are given below

$$\mu_2 = \text{Var} \{ \gamma \} = \frac{1}{(\beta T)^2} [e^{-\beta T} + \beta T - 1] \quad (22)$$

$$\mu_4 = \frac{1}{48(\beta T)^4} [e^{-4\beta T} + 783 + 144(\beta T)^2 - 540\beta T - (240\beta T + 784)e^{-\beta T}]. \quad (23)$$

IV. PROBABILITY DENSITY FUNCTION OF FILTERED INTERFEROMETRIC CROSSTALK

A. Maximum Entropy Approach

The probability density of a random variable can be estimated by a maximum entropy approach based on its known moments [13]. Using this approach we have estimated the pdf of filtered interferometric crosstalk considering a laser source with a 3-dB linewidth of 45 MHz. If we use a filter with an equivalent bandwidth of 34, 141.3, 565.2 MHz, then the corresponding parameter βT is equal to 8.3, 2.0, and 0.5, respectively. In Fig. 3 is presented a plot of the estimated pdf for the three different values of βT . We observe that as the product βT increases the shape of the pdf changes from a two pronged one to a Gaussian like function shape for large values of βT .

The maximum entropy approach can be arbitrarily used for estimating an unknown pdf based on a finite number of moments. We performed computer simulations and experimental measurements to justify the use of the maximum entropy criterion in the performance evaluation of optical systems disturbed by filtered interferometric crosstalk.

B. Computer Simulation

The statistics of filtered crosstalk γ has also been studied with the aid of computer simulations. The simulations are

Fig. 3. Probability density function of filtered crosstalk as a function of βT . The pdf is estimated using a maximum entropy approach.

Fig. 4. Statistics of filtered interferometric crosstalk as a function of βT . Simulations results for a seventh-order Butterworth digital filter, using 10^6 samples.

performed in the following way. A process $\Delta\phi(t)$ is generated with a corresponding variance βT_d . Then the functional $\xi(t)$ is formed. Further, the process ξ is passed through a filter. The filter used is a seventh-order Butterworth digital filter. The filtered samples are then analyzed in a frequency histogram yielding an estimate of the probability density function of the filtered crosstalk. The simulated pdf of filtered crosstalk for the values of $\beta T = 0.5, 2.0$, and 8.3 with a fixed value $\beta T_d = 50.0$ is displayed in Fig. 4. It is observed again that the statistics changes from a two-pronged shape for small values of βT (wide bandwidth filter) to a Gaussian-like shape for larger values of βT (narrower bandwidth filter). This agrees well with the simulation results in [18].

Fig. 5. Statistics of filtered interferometric crosstalk. Measured results for the incoherent regime. The 3-dB laser linewidth is 45 MHz. The filter bandwidth is (a) 2500 MHz ($\beta T = 0.11$) and (b) 34 MHz ($\beta T = 8.3$).

C. Measured pdf

Measured probability density functions of filtered interferometric crosstalk are shown in Fig. 5. Details of the experimental setup are presented in Section VI. The incoherent regime ($\beta\tau_d \gg 1$) is assured in the experiment. The laser 3-dB linewidth, continuous-wave (CW) operation, is measured to be 45 MHz. Two filters are used: 1) a filter with a 3-dB bandwidth of 2500 MHz. This case correspond, approximately, to having a value $\beta T = 0.11$ and 2) a filter with 34 MHz 3-dB bandwidth ($\beta T = 8.3$). The measured pdf's confirm the theoretical results (incoherent regime) on the reshaping of the statistics from a two pronged function to a Gaussian like shape as the filter bandwidth becomes smaller than the light source 3-dB linewidth; as βT increases. This result is in agreement with measurements reported by others workers in the field [1], [18], [19].

V. PERFORMANCE ANALYSIS

The question is to evaluate the average error probability for an ASK/DD system. The error probability, given that a binary "one" is transmitted is

$$q_-(\alpha) = P_{r1}(Z < \alpha)$$

where α denotes the decision threshold. Similarly, the error probability, given a binary "zero" is transmitted is

$$q_+(\alpha) = P_{r0}(Z > \alpha).$$

Assuming that the symbols are *a priori* equally probable, the average error probability is

$$P_e = \frac{1}{2} [q_-(\alpha) + q_+(\alpha)]. \quad (24)$$

A. Analysis by Saddlepoint Approximation

The saddlepoint approximation (SPA) has been proposed by Helstrom [20], as an efficient and numerically simple tool for analyzing communication systems. The SPA has shown a reasonably high degree of accuracy in the analysis of optical communication systems, e.g., [21].

As shown in [20] the tail probability $q_+(\alpha)$, and $q_-(\alpha)$, are approximately equal to

$$q_+(\alpha) \approx \frac{\exp[\Phi(s_0)]}{\sqrt{2\pi\Phi''(s_0)}} \quad \text{and} \quad q_-(\alpha) \approx \frac{\exp[\Phi(s_1)]}{\sqrt{2\pi\Phi''(s_1)}} \quad (25)$$

respectively, the so-called *saddlepoint approximation*. The function $\Phi(s)$ is related to the MGF for Z , $M_Z(s)$ by

$$\Phi(s) = \ln[M_Z(s)] - s\alpha - \ln|s|. \quad (26)$$

The parameters s_0 , and s_1 are the positive and negative root, respectively, of the equation

$$\Phi'(s) = 0 \quad (27)$$

and $\Phi''(s_{0,1})$ stands for the second derivative of (26) at $s = s_{0,1}$. (See [20] or [15] for further details.) The error probability is minimized by adjusting the detection threshold α . The optimum value of α and the parameters s_0, s_1 may be found numerically by solving an appropriate set of equations [15].

B. Gaussian Approximation

For simplicity reasons, in the performance analysis of a variety of communications systems, it is often assumed that the interfering noises are Gaussian distributed. We proposed to consider the filtered interferometric noise to be Gaussian distributed with mean zero and variance given by (22) instead of having a variance equal to one-half as assumed in previous analyzes, e.g., [2], [3]. This assumption simplifies the performance evaluation. It is found that the proposed Gaussian approximation yields reasonable good results for (small) crosstalk values ϵ that does not result in large power penalties (less than 2 dBm); see Figs. 7 and 8.

Until now we have considered the case of interferometric noise arising from a single interferer. In many applications, as in multichannel WDM networks, there will be a multiple number of interferers. Although in this work we do not present experimental results for the case of multiple interferers, in Appendix B we show how to include N sources of interferometric noise in the performance analysis.

VI. EXPERIMENT

The measurement setup to verify the theory is schematically given in Fig. 6. At the transmitter side, two light sources modulation schemes are used, namely, direct modulation in Fig. 6(a) and external modulation in Fig. 6(b). In Fig. 6(a) a distributed feedback (DFB) laser which has a CW-linewidth of 45 MHz is modulated directly by an electrical pulse pattern

Fig. 6. Experimental setup used to measure power penalties due to filtered interferometric crosstalk. Two light source modulation schemes are used: (a) direct modulation and (b) external modulation.

generator with nonreturn-to-zero (NRZ) signals. The generated pseudorandom binary signals have a bit-rate of 622 Mb/s and their pattern is repeated after $2^7 - 1$ bits. By this direct modulation scheme we have obtained optical signals of an average extinction ratio of 15 dB.

In the external modulation scheme, Fig. 6(b), lightwaves coming from the DFB laser are coupled into a lithium niobate (LiNbO_3) modulator. The modulator is driven by the 622 Mb/s $2^7 - 1$ pseudorandom electrical signals. The resulting optical signals have an improved extinction ratio of 20 dB. Besides that, the spectral broadening or chirp which is very common in directly modulated laser is reduced. We have observed that the spectral width of external modulation is determined mainly by the modulation speed, i.e., 622 MHz whereas in direct modulation the combined effect of adiabatic and transient chirp makes the spectrum wider than that of external modulation. Measurements of the spectrum for the direct modulated light source case yielded values in the range from 1.9 to 2.4 GHz.

After the transmitter, the lightwaves are splitted to form a signal and a crosstalk path by a Mach-Zehnder structure with one of its arm 7 km longer than the other. The difference in the arm-length is intended to decorrelate information signals from crosstalk. The state of polarization of the information signal with respect to the crosstalk is matched to produce a worst case condition at the detection. In the crosstalk path a variable optical attenuator is located for crosstalk power adjustment relative to the signal power. Another attenuator is placed after the Mach-Zehnder structure to vary optical signal powers coupled to an optical detector for bit error rate (BER) evaluation.

As detector, a broad-band optical-to-electrical (O/E) converter followed by electrical filtering is used for studying the statistics of filtered signal-to-crosstalk beating noise. But for BER-evaluation and power penalty analyzes a receiver module with a more sensitive InGaAs p-i-n photodetector incorporating also a high-gain electrical transimpedance amplifier is employed. The detector's sensitivity is around -30 dBm for a BER of 10^{-9} . The BER and power penalties measurements are performed using an optimized decision-threshold. The resulting BER values are lower than those obtained with a fixed threshold.

Fig. 7. Measured power penalties for the external light source modulation case (marks). The solid line represents the theoretical result (moment based) while the dotted line is the Gaussian approximation result.

VII. RESULTS AND DISCUSSION

A. External Modulation

Measured power penalties for an externally modulated light source, at a BER of 10^{-9} , as a function of the crosstalk power ϵ is presented in Fig. 7 (marks). The 3-dB laser linewidth is found to be mainly determined by the modulation rate. In Fig. 7 the solid line represents the theoretical result while the dotted line is the result by the Gaussian approximation. We can observe in Fig. 7 good agreement between theory and experiment. The Gaussian approximation gives reasonable good result for small values of ϵ that result in small power penalties while for large values of ϵ this approximation yields too pessimistic results.

B. Direct Modulation

The spectral line of light sources like a DFB laser is considerably broadened under direct modulation, e.g., [22] and [23]. This is due to the laser dynamics during the transitions from

Fig. 8. Measured power penalties for a directly modulated light source (marks). The solid line represents the theoretical result (moment based) while the dotted line is the Gaussian approximation result.

one power level to another. This spectral broadening, “chirp,” is a key differentiating property of directly modulated lasers from externally modulated lasers that experience negligible or smaller spectral broadening.

Interferometric noise arising from directly modulated DFB light sources has been shown to be bit-sequence dependent [24]. This fact together with the (dynamics) transient and adiabatic chirp properties of directly modulated sources make the analysis of interferometric noise a more complex task than in the case of externally modulated light sources. In the performance analysis, we proceed by assigning to the 3-dB laser linewidth the average measured value $\Delta\nu = 2.2$ GHz.

The spectral broadening by the direct modulation results in a larger value βT than in the case of an externally modulated source. Hence the resultant reduction in variance of the filtered interferometric crosstalk [cf., (22)] suggest that lower power penalties will be incurred. This is actually confirmed by the experiment. In Fig. 8 is displayed the measured power penalties for a directly modulated source (marks). Comparing with the results for the external modulated source (Fig. 7) the system with a directly modulated source experiences less power penalties due to filtered interferometric crosstalk. These results are in good agreement with previous observations by other authors [4], [8]. Interferometric noise reduction by broadening the spectrum (by, e.g., phase dithering or phase noise modulation) has already being proposed and exploited [9]–[11].

In Fig. 8 are also displayed the theoretical, moments based, results (solid line) and the results by the Gaussian approximation (dotted line). Good agreement between theory and experiment is also observed. As in the previous case (Fig. 7), the Gaussian approximation gives a reasonable good result for small values of ϵ . The experimental results show that power penalties are kept less than 1 dBm if the crosstalk parameter ϵ is better than -23 dB for a directly modulated source, and better than -26 dB for an externally modulated

source. The theoretical, simulations and experimental results clearly indicate that significant interferometric noise reduction is possible if the laser 3-dB bandwidth is larger than the postdetection filter bandwidth.

VIII. CONCLUSIONS

This paper presents a statistical analysis for filtered interferometric noise which takes into account the relation between the laser (signal and crosstalk) 3-dB bandwidth and the postdetection filter bandwidth. The impact of interferometric crosstalk on the performance of optical networks turns out to be strongly dependent on this relation, for instance, significant interferometric noise reduction is possible if the laser 3-dB bandwidth is larger than the postdetection filter bandwidth. This operating situation can be achieved by broadening (phase dithering) the laser spectrum. Research on the topic is in progress.

This paper also gives insights, both by an accurate statistical analysis and experiment, on why ASK/DD systems with directly modulated light sources incurred less power penalties due to interferometric noise than systems using externally modulated sources. The reason being the different resulting relation between the laser 3-dB bandwidth and the postdetection filter bandwidth.

The presented theoretical analysis has shown good consistency with experimental results from an ASK/DD system using externally, and directly modulated light sources.

APPENDIX A DERIVATION OF MOMENTS

In this Appendix a derivation for the moments of the variable γ is given. We follow closely the presentation by Roudas [17]. The moment of order k , $E\{\gamma^k\}$, is given by

$$\mu_k = \frac{1}{T^k} \int_{t-T}^t \int_{t-T}^t \cdots \int_{t-T}^t E\{\cos \Delta\phi(t_1) \times \cos \Delta\phi(t_2) \times \cdots \times \cos \Delta\phi(t_k)\} dt_1 dt_2 \cdots dt_k. \quad (28)$$

Using trigonometric identities and the representation for $\cos(\cdot)$ as the real part of an exponential function we have

$$\begin{aligned} \mu_k = & \frac{1}{2^{k-1} T^k} \\ & \cdot \left[\text{Re} \left\{ \int_{t-T}^t \int_{t-T}^t \cdots \int_{t-T}^t E\{\exp(j[\Delta\phi(t_1) \right. \right. \\ & \quad \left. \left. + \cdots + \Delta\phi(t_2) + \Delta\phi(t_k)])\} dt_1 dt_2 \cdots dt_k \right\} \right. \\ & + \text{Re} \left\{ \int_{t-T}^t \int_{t-T}^t \cdots \int_{t-T}^t E\{\exp(j[\Delta\phi(t_1) \right. \\ & \quad \left. + \Delta\phi(t_2) - \cdots + \Delta\phi(t_k)])\} dt_1 dt_2 \cdots dt_k \right\} \\ & + \cdots + \text{Re} \left\{ \int_{t-T}^t \int_{t-T}^t \cdots \int_{t-T}^t E\{\exp(j[\Delta\phi(t_1) \right. \\ & \quad \left. - \Delta\phi(t_2) - \cdots + \Delta\phi(t_k)])\} dt_1 dt_2 \cdots dt_k \right\} \left. \right]. \end{aligned} \quad (29)$$

We observe that the integrands are the characteristic function of a sum of zero mean Gaussian variables $\Delta\phi(t_1), \Delta\phi(t_2), \dots, \Delta\phi(t_k)$ which is given by [25]

$$\begin{aligned} & \mathbb{E} \left\{ \exp \left(j \sum_{k=1}^N u_k \Delta\phi(t_k) \right) \right\} \\ &= \exp \left[-\frac{1}{2} \sum_{k,l=1}^N u_k u_l R_{\Delta\phi}(t_k, t_l) \right]. \end{aligned} \quad (30)$$

Arranging the integration variables in increasing order, i.e., $t_1 < t_2 < \dots < t_k$ it can be shown that

$$\begin{aligned} \mu_k &= \frac{k!}{2^{k-1} T^k} \\ & \cdot \left[\text{Re} \left\{ \int_{t-T}^t \int_{t-T}^{t_k} \dots \int_{t-T}^{t_2} \mathbb{E} \{ \exp (j [\Delta\phi(t_1) \right. \right. \\ & \quad \left. \left. + \dots + \Delta\phi(t_2) + \Delta\phi(t_k)]) \} dt_1 dt_2 \dots dt_k \right\} \right. \\ & + \text{Re} \left\{ \int_{t-T}^t \int_{t-T}^{t_k} \dots \int_{t-T}^{t_2} \mathbb{E} \{ \exp (j [\Delta\phi(t_1) \right. \\ & \quad \left. + \Delta\phi(t_2) - \dots + \Delta\phi(t_k)]) \} dt_1 dt_2 \dots dt_k \right\} \\ & + \dots + \text{Re} \left\{ \int_{t-T}^t \int_{t-T}^{t_k} \dots \int_{t-T}^{t_2} \mathbb{E} \{ \exp (j [\Delta\phi(t_1) \right. \\ & \quad \left. - \Delta\phi(t_2) - \dots - \Delta\phi(t_k)]) \} dt_1 dt_2 \dots dt_k \right\} \left. \right]. \end{aligned} \quad (31)$$

Let denote by $\mathbf{a} = (a_1, a_2, \dots, a_k)$ the set of signs $+1$ or -1 in front of the variables $\Delta\phi(t_1), \Delta\phi(t_2), \dots, \Delta\phi(t_k)$. We consider the general case, $t_1 < t_2 < \dots < t_k$, for which we get

$$\begin{aligned} & \mathbb{E} \{ e^{j(a_1 \Delta\phi(t_1) + a_2 \Delta\phi(t_2) + \dots + a_k \Delta\phi(t_k))} \} \\ &= e^{(\beta \sum_{n=1}^k b_n t_n + c \beta \tau_d)} \end{aligned} \quad (32)$$

in which

$$b_n = \begin{cases} -1 + \sum_{l=1}^n a_l - \sum_{l=n+1}^k a_l & 1 < n < k-1 \\ -1 + a_k \sum_{l=1}^k a_l & n = k \end{cases} \quad (33)$$

and the term c is given by

$$c = \frac{k}{2} - \sum_{n=1}^k a_n \sum_{l=1}^n a_l. \quad (34)$$

Considering a particular set $\mathbf{a}$ and substituting (32) in (31), we have that

$$\begin{aligned} I_{\mathbf{a}} &= \int_{t-T}^t \int_{t-T}^{t_k} \dots \int_{t-T}^{t_2} \mathbb{E} \{ \exp (j [a_1 \Delta\phi(t_1) \\ & \quad + \dots + a_2 \Delta\phi(t_2) + a_k \Delta\phi(t_k)]) \} dt_1 dt_2 \dots dt_k \\ &= e^{c \beta \tau} \int_{t-T}^t e^{\beta b_k t_k} \int_{t-T}^{t_k} e^{\beta b_{k-1} t_{k-1}} \dots \int_{t-T}^{t_2} e^{\beta b_1 t_1} dt_1 \\ & \quad \cdot dt_2 \dots dt_k. \end{aligned}$$

The integrals in (35) obey the following recursive relation:

$$I_{\mathbf{a}}^{(n)} = \int_0^t e^{\beta b_n t_n} I_{\mathbf{a}}^{(n-1)} dt_n \quad (35)$$

with the initial condition $I_{\mathbf{a}}^{(0)} = e^{c \beta \tau_d}$.

Finally, the μ_k moment can be expressed as

$$\mu_k = \frac{k!}{2^{k-1} T^k} \sum_{\mathbf{a}} I_{\mathbf{a}}^{(k)}|_{t=T}. \quad (36)$$

APPENDIX B

PERFORMANCE ANALYSIS FOR MULTIPLE CROSSTALK INTERFERERS

This Appendix shows how to extend the performance analysis in order to include N sources of interferometric crosstalk. We proceed by following [5] in which we have that the average error probability, P_e , given a detection threshold α , is given by a weighted statistical average of the error probability $P_r(\alpha, \mu)$ for each value μ , binomially distributed, of interferers being simultaneously a digital "one" (see [5, eq. (22)]). Given a value μ , the MGF for Λ , $M_{\Lambda}(s)$, consists of the product of the MGF for all the resultant signal and crosstalk beat terms; see (21) in [5]. The MGF $M_{\Lambda}(s)$ is evaluated in a similar way as in (12) observing that we need now to determine the pdf for a sum of independent identically distributed (i.i.d) random variables (RV) of the type in (17). The performance analysis comprises the following steps.

- 1) Given a value μ determine the number of terms signal-to-crosstalk, crosstalk-to-crosstalk, beating terms in Λ ; taking into account the extinction ratio ϱ .
- 2) For each resulting sum of RV of type (17) compute its pdf. This is done in the following way: compute the moments for each RV in the sum as shown in Section III-A (eventually for different values of βT). Compute the cumulants by the standard relations between moments and cumulants [26]. The cumulants for a sum of i.i.d random variables is given by the sum of the cumulants of each RV in the sum. Compute the moments of the sum from the cumulants [26]. Based on the moments estimate the pdf by the maximum entropy approach.
- 3) Evaluate the error probability by the SPA (see Section V-A) based on the MGF $M_{\Lambda}(s)$ (using the estimated pdf computed in step 2).
- 4) Finally, the average error probability, P_e , is evaluated.

Using the above procedure the performance analysis accounts for data statistics, interferometric crosstalk statistics, extinction ratio, shot noise and thermal noise. The Gaussian approximation, proposed in Section V-B, will simplify the analysis, requiring less computing time. It is expected that for a large number of interferers the Gaussian approximation, via the Central Limit Theorem, will yield results closed to those obtained by the accurate statistical approach.

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REFERENCES

- [1] M. Tur and E. L. Goldstein, "Dependence of error rate on signal-to-noise ratio in fiber-optic communication systems with phase-induced intensity noise," *J. Lightwave Technol.*, vol. 7, pp. 2055–2057, Dec. 1989.
- [2] 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. 657–700, May 1994.
- [3] E. L. Goldstein and L. Eskildsen, "Scaling limitations in transparent optical networks due to low-level crosstalk," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 93–94, Jan. 1995.
- [4] P. T. Legg, M. Tur, and I. Andonovic, "Solution paths to limit interferometric noise induced performance degradation in ASK/direct detection lightwave networks," *J. Lightwave Technol.*, vol. 14, pp. 1943–1953, Sept. 1996.
- [5] I. T. Monroy and E. Tangdiongga, "Performance evaluation of optical cross-connects by saddlepoint approximation," *J. Lightwave Technol.*, vol. 16, pp. 317–323, Mar. 1998.
- [6] W. D. Cornwell and I. Andonovic, "Interferometric noise for a single interferer: comparison between theory and experiment," *Electron. Lett.*, vol. 32, pp. 15001–15002, Aug. 1996.
- [7] K. Ho *et al.*, "Exact analysis of homodyne crosstalk penalty in WDM networks," *IEEE Photon. Technol. Lett.*, vol. 10, pp. 457–458, Mar. 1998.
- [8] L. Eskildsen *et al.*, "Interferometric noise limitations in fiber-amplifier cascade," *Electron. Lett.*, vol. 29, pp. 2040–2041, Nov. 1993.
- [9] P. K. Pepeljugoski and K. Y. Lau, "Interferometric noise reduction in fiber-optic links by superposition of high frequency modulation," *J. Lightwave Technol.*, vol. 10, pp. 957–963, July 1992.
- [10] A. Yariv, H. Blauvelt, and S. Wu, "A reduction of interferometric phase-to-intensity conversion noise in fiber links by large index phase modulation of the optical beam," *J. Lightwave Technol.*, vol. 10, pp. 978–981, July 1992.
- [11] F. W. Willems and W. Muys, "Suppression of interferometric noise in externally modulated lightwave AM-CATV systems by phase modulation," *Electron. Lett.*, vol. 29, pp. 2062–2063, Nov. 1993.
- [12] S. D. Personick, "Applications for quantum amplifiers in simple digital optical communication systems," *Bell Systems Tech. J.*, vol. 52, pp. 117–133, Jan. 1973.
- [13] M. Kavehrad and M. Joseph, "Maximum entropy and the method of moments in performance evaluation of digital communications systems," *IEEE Trans. Commun.*, vol. COM-34, pp. 1183–1189, Dec. 1986.
- [14] A. Mooradian, "Laser linewidth," *Phys. Today*, vol. 38, pp. 48–48, May 1985.
- [15] G. Einarsson, *Principles of Lightwave Communications*. New York: Wiley, 1996.
- [16] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, 2nd ed. New York: McGraw-Hill, 1991.
- [17] I. Roudas, "Conception optimale d'un système optique cohérent CPFSK avec récepteur différentiel," Ph.D. dissertation, Ecole Nationale Supérieure des Télécommunications, Paris, France, Jan. 1995.
- [18] A. Arie, M. Tur, and E. L. Goldstein, "Probability-density function of noise at the output of a two-beam interferometer," *J. Opt. Soc. Amer. A*, vol. 8, pp. 1936–1942, Dec. 1991.
- [19] M. Tur and E. L. Goldstein, "Probability distribution of phase-induced intensity noise generated by distributed feed-back lasers," *Opt. Lett.*, vol. 15, pp. 1–3, Jan. 1990.
- [20] C. Helstrom, "Approximate evaluation of detection probabilities in radar and optical communications," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 14, pp. 630–640, July 1978.
- [21] ———, "Performance analysis of optical receivers by saddlepoint approximation," *IEEE Trans. Commun.*, Jan. 1979, pp. 186–190.
- [22] R. A. Linke, "Modulation induced transient chirping in single frequency lasers," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 593–597, June 1985.
- [23] K. Petermann, "Laser diode modulation and noise," in *Advances in Optoelectronics*. New York: Kluwer Academic, 1988.
- [24] M. Tur *et al.*, "Sequence dependence of phase-induced intensity noise in optical networks that employ direct modulation," *Opt. Lett.*, vol. 20, pp. 359–361, Feb. 1995.
- [25] E. Wong and B. Hajek, *Stochastic Processes in Engineering Systems*. Berlin, Germany: Springer, 1985.
- [26] E. Biglieri, "A recursive method for computing the coefficients of the Gram-Charlier series," *Proc. IEEE*, pp. 251–252, Feb. 1972.

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