# Analysis of Homodyne Crosstalk in Optical Networks Using Gram–Charlier Series

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***Abstract*— Homodyne crosstalk with the same wavelength as the signal causes severe system performance degradation in optical networks by beating with the desired signal. Gaussian approximation is found to overestimate the system degradation. A correction to Gaussian approximation, Gram–Charlier series is used to analyze homodyne crosstalk. Both bit error rate (BER) and power penalty are calculated for multiple homodyne interferers.**

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

## I. Introduction

MULTIWAVELENGTH optical networks will be an essential technology for the future information infrastructure. Wavelength division multiplexing (WDM) is used in optical networks to fully utilize the bandwidth of a single-mode optical fiber. In optical networks, optical signal add–drop is performed by wavelength routers. A fundamental difficulty of the wavelength router is homodyne crosstalk from neighboring input ports or upstream nodes, causing severe degradation in system performance. Homodyne crosstalk has identical or very close wavelength to that of the signal, is difficult to be eliminated by filtering, beats with the desire signal and generates a new kind of noise at the receiver [1]–[18].

Even for a single interferer, previous analysis of homodyne crosstalk was largely based on Gaussian approximation [1], [5]–[8], though there were reports and evidences that this assumption is incorrect [9]–[18]. Representing a worst-case assumption and serving well for conservative system design [5], [7], [11], [13]–[18], the Gaussian approximation is only valid for a large number of more or less the same intensity and statistically independent interferers [5], [8]–[10]. Therefore, a non-Gaussian model may better estimate the system perfomance [9]–[17]. Furthermore, a non-Gaussian model can be used to verify the condition of the validity of the Gaussian approximation.

Non-Gaussian model had been developed for a single interferer by series expansion [13]–[14] and for many interfers by modified Chernoff bound [9], saddle-point approximation [15]–[16], and numerical integration or simulation [10]–[12], [17]. However, most of the methods of [10]–[12], [15]–[17] require complicated numerical calculation to evaluate the system performance. The main contribution of this paper is the derivation of an analytical series expansion based bit error rate (BER) expression for multiple homodyne interferers. The coefficients of the series can be evaluated by popular software or algorithmically.

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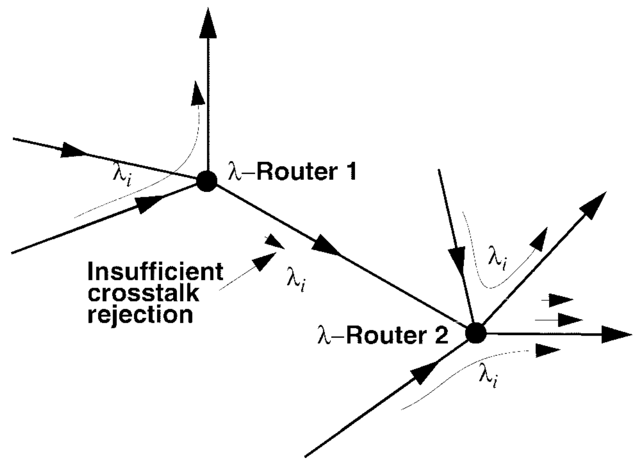


Fig. 1. Example of an optical network configuration that may induce homodyne crosstalk interference.

Here, Gram–Charlier series is used as a correction to the Gaussian approximation for homodyne crosstalk having multiple interferers. The Gram–Charlier series, may be considered as a correction of Gaussian approximation, expresses an arbitrary probability density function as an infinite series whose leading term is a Gaussian distribution. The Gram–Charlier series has been used to evaluate the performance of optical transmission systems [19], [20]. The advantage of Gram–Charlier series is that all series coefficient can be evaluated from the moments of the random variable [21].

The remaining parts of this paper will discuss the general property of homodyne crosstalk, Gram–Charlier series of homodyne crosstalk, and also present some numerical results.

## II. Homodyne Crosstalk

Homodyne crosstalk may be originated by many different sources. Fig. 1 shows a configuration of an optical network that may induce homodyne crosstalk with similar or identical wavelength to the signal wavelength. While the channel at wavelength $\lambda_i$ at the input of wavelength router 1 should not appear at the input of wavelength router 2, due to insufficient crosstalk rejection in router 1, small amount of crosstalk appears at the input of wavelength router 2 as homodyne crosstalk. Alternatively, two input signals having the same wavelength may appear at different input ports of the same wavelength router (router 2). There is no homodyne crosstalk in ideal case because two signals are routed to different output ports. However, any leaking or insufficient isolation may induce homodyne crosstalk. Those homodyne crosstalks beat with the signal and severely degrade the system performance [1]–[18].

The electrical field intensity of the desired optical signal is assumed to be $E_s(t) = d_s(t)E_s e^{-j\omega_i t - j\varphi_0(t)}$, where $E_s$ is the strength of the signal electric field, $\omega_i$ is the angular frequency of the optical signal, $\varphi_0(t)$ is the random phase due to laser phase fluctuation, $d_s(t) = 0, 1$ is a random process depending on whether ZERO or ONE is transmitted at time $t$. The $N$ small homodyne crosstalk originated from various sources are $E_{x,k}(t) = d_{x,k}(t)\sqrt{x_k}E_s e^{-j\omega_i t - j\varphi_k(t)}, k = 1, \cdots, N$ where $x_k$ are the crosstalk levels in optical power, $\varphi_k(t)$ are the random phases due to laser phase fluctuation, and $d_{x,k}(t)$ are the data transmitted by crosstalk channels.

Without loss of generality, for a unit detector responsivity and for the worst-case assumption of identical polarization of signal and crosstalks, the photocurrent is

$$i(t) = \left| d_s(t)E_s e^{-j\varphi_0(t)} + E_s \sum_{k=1}^{N} d_{x,k}(t)\sqrt{x_k}e^{-j\varphi_k(t)} \right|^2 \tag{1}$$

Ignoring the small terms in the order of $x_k$, the overall receiver noise in the photodetector is [1]–[7]

$$n(t) = \sum_{k=1}^{N} d_s(t)d_{x,k}(t)A_k \cos[\phi_k(t)] + n_g(t) \tag{2}$$

where $A_k = 2\sqrt{x_k}E_s^2$ $k = 1, \cdots, N$, are the crosstalk amplitudes, $\phi_k(t) = \varphi_k(t) - \varphi_0(t), k = 1, \cdots, N$, are random phases, and $n_g(t)$ is the usual Gaussian noise in the receiver. The probability density function (pdf) of $n(t)$ has to be derived to evaluate the BER. However, the pdf is difficult to find. In this section, the characteristic function, the Fourier transform of the pdf, of the noise is first studied. The pdf is evaluated in later sections using the characteristic function.

When ZERO is transmitted by the signal channel, there is no homodyne beating and $n_0(t) = n_g(t)$. The pdf is the well-known Gaussian distribution and the error probability can be evaluated by the complementary error function.

When ONE is transmitted by the signal channel, homodyne beating generates a total noise of

$$n_1(t) = \sum_{k-1}^{N} d_{x,k}(t)A_k \cos[\phi_k(t)] + n_g(t). \tag{3}$$

In each homodyne crosstalk beating, for a random phase of $\phi(t)$, the pdf of $A\cos[\phi(t)]$ is given by $p(x) = (1/\pi)(A^2 - x^2)^{1/2}$ for $-A < x < +A$ [5], [13], [17]–[18], [22] which yields the characteristic function of $J_0(A\omega)$, where $J_0(\cdot)$ is the zero-order Bessel function of first-kind. For each individual homodyne crosstalk, there is no homodyne beating for a probability of 1/2 when the crosstalk channel transmits ZERO. For the other one-half probability for transmitting ONE, homodyne crosstalk generates a beating noise of $A_k \cos[\phi_k(t)]$. Therefore, the characteristic function of the $k$th homodyne crosstalk source, $A_k \cos[\phi_k(t)]$, is

$$\frac{1 + J_0(A_k\omega)}{2}. \tag{4}$$

All random phases are independent with each other, the characteristic function of $n_1(t)$ in (3) is the product of the characteristic functions of all noise sources

$$\psi_{n1}(\omega) = \exp\left(-\frac{\sigma_0^2\omega^2}{2}\right) \prod_{k-1}^{N} \frac{1 + J_0(A_k\omega)}{2} \tag{5}$$

where $\sigma_0^2$ and $\exp(-\sigma_0^2\omega^2/2)$ are the variance and characteristic function of the receiver Gaussian noise $n_g(t)$, respectively.

In the following section, the BER due to the summation of homodyne crosstalk and Gaussian noise is evaluated according to the characteristic function of the overall noise. The Gram–Charlier series expansion of the characteristic function is derived and the BER is evaluated accordingly.

## III. Gram–Charlier Series

Gram–Charlier series can be used to analyze multiple homodyne interferers. Gram–Charlier series can be easily derived from the characteristic function of the noise.

### A. General Formula of Gram–Charlier Series

Gaussian approximation can be used to approximate the homodyne crosstalk. In Gaussian approximation, the characteristic function is approximated by

$$\psi_{n1}(\omega) \approx \exp\left(-\frac{(\sigma_0^2 + \sigma_I^2)\omega^2}{2}\right) \tag{6}$$

where

$$\sigma_I^2 = \frac{1}{4}\sum_{k=3}^{N} A_k^2 \tag{7}$$

is the total variance of homodyne crosstalk. However, the drawback of using Gaussian approximation is well-known [13]–[18]. Better approximation can be achieved using a particular series expansion called Gram–Charlier series in which

$$\psi_{n1}(\omega) = \exp\left(-\frac{\sigma_t^2\omega^2}{2}\right)\left[1 + \sum_{k=3}^{\infty} c_k (j\omega)^k\right]. \tag{8}$$

The leading term of this series is the characteristic function of a zero-mean Gaussian density with variance of $\sigma_t^2 = \sigma_0^2 + \sigma_I^2$ which is the same as that in (6). Other terms can be used as a correction to the Gaussian approximation.

Taking the inverse Fourier transform of $\psi_{n1}(\omega)$, the pdf is

$$p_{n1}(x) = \frac{1}{\sqrt{2\pi}\sigma_t}\exp\left(-\frac{x^2}{2\sigma_t^2}\right) + \frac{1}{\sqrt{2\pi}\sigma_t} \times \sum_{k=3}^{\infty} \frac{(-1)^k c_k}{\sigma_t^k} H_k\left(\frac{x}{\sigma_t}\right)\exp\left(-\frac{x^2}{2\sigma_t^2}\right) \tag{9}$$

where $H_k(x) = (-1)^k e^{x^2/2} d^k e^{-x^2/2}/dx^k$ is a Hermitian polynomial of order $k$. The error probability or the cumulative tail probability is

$$p_{e1}(d) = \int_{-\infty}^{-d} p_{n1}(x)\,dx = \frac{1}{2}\operatorname{erfc}\left(\frac{d}{\sqrt{2}\sigma_t}\right) + \frac{1}{\sqrt{2\pi}}\sum_{k=3}^{\infty}\frac{c_k}{\sigma_t^k}H_{k-1}\left(\frac{d}{\sigma_t}\right)\exp\left(-\frac{d^2}{2\sigma_t^2}\right). \quad (10)$$

where $d$ is the detection threshold. Compared the Gaussian approximation (6) with the Gram–Charlier series (8), the leading term is the Gaussian approximation and the rest can be considered as correction to the Gaussian approximation.

In theory, the detection threshold of the receiver can be adjusted for optimal performance. In practice, the detection threshold may be fixed at the middle of the "eye" by amplitude estimation because no threshold is optimal for all noise conditions. If the detection threshold is in the middle, the BER of the system is equal to

$$p_b = \frac{1}{4}\operatorname{erfc}\left(\frac{d}{\sqrt{2}\sigma_0}\right) + \frac{1}{2}p_{e1}(d) \quad (11)$$

where the first term is for a signal at ZERO level and the second term is for a signal at ONE level, assuming an extinction ratio of infinity, $d = I_1/2$ is the threshold of detection and $I_1$ is the photocurrent at ONE level. The corresponding Gaussian approximation is

$$p_b \approx \frac{1}{4}\operatorname{erfc}\left(\frac{d}{\sqrt{2}\sigma_0}\right) + \frac{1}{4}\operatorname{erfc}\left(\frac{d}{\sqrt{2}\sigma_t}\right). \quad (12)$$

In the noise expression of (3) to derive the BER, the beating of homodyne crosstalk with each other is ignored. The beating of homodyne crosstalk with signal generates a crosstalk amplitude of $A_k = 2\sqrt{x_k}E_s^2$. The beating of homodyne crosstalk with each other (including self-beating) generates a crosstalk amplitude of $\sqrt{x_k x_j}E_s^2$ which is a factor of $\sqrt{x_k}$ smaller then signal and crosstalk beating. For an usual crosstalk level less than $-20$ dB, the beating of homodyne crosstalk with each other is at least 10 dB smaller than the beating of homodyne crosstalk with signal and thus can be ignored in the BER evaluation.

### *B. Gram–Charlier Series for Homodyne Crosstalks*

The series coefficients $c_k, k = 3, 4, \cdots$, are required in the Gram–Charlier series. Compared the characteristic function of (5) with the series expression (8), the coefficients can be evaluated according to

$$1 + \sum_{k=3}^{\infty} c_k (j\omega)^k = \prod_{k=1}^{N} \frac{1 + J_0(A_k\omega)}{2}\exp\left(\frac{A_k^2\omega^2}{8}\right). \quad (13)$$

First of all, we would like to find the series expansion of the normalized function

$$\varphi(\omega) = \frac{1 + J_0(\omega)}{2}\exp\left(\frac{\omega^2}{8}\right) = 1 + \sum_{k=3}^{\infty}\alpha_k\omega^{2k}. \quad (14)$$

TABLE I
THE COEFFICIENTS OF GRAM–CHARLIER SERIES

| | $\alpha_k$ | $(-1)^k c_{2k}$ |
|---|---|---|
| $k=3$ | $\frac{1}{2^{10}3^2}$ | $\alpha_3\sum_i A_i^6$ |
| $k=4$ | $\frac{1}{2^{14}3^2}$ | $\alpha_4\sum_i A_i^8$ |
| $k=5$ | $\frac{13}{2^{18}3^2 5^2}$ | $\alpha_5\sum_i A_i^{10}$ |
| $k=6$ | $\frac{41}{2^{22}3^4 5^2}$ | $\alpha_6\sum_i A_i^{12} + \alpha_3^2\sum_{i\neq j} A_i^6 A_j^6$ |
| $k=7$ | $\frac{131}{2^{24}3^4 5^2 7^2}$ | $\alpha_7\sum_i A_i^{14} + \alpha_3\alpha_4\sum_{i\neq j} A_i^6 A_j^8$ |
| $k=8$ | $\frac{107}{2^{30}3^4 5^2 7^2}$ | $\alpha_8\sum_i A_i^{16} + \alpha_4^2\sum_{i\neq j} A_i^8 A_j^8 + \alpha_3\alpha_5\sum_{i\neq j} A_i^6 A_j^{10}$ |

Using the series expansion of

$$J_0(z) = \sum_{k=0}^{\infty}\frac{(-1)^k}{(k!)^2}\left(\frac{z}{2}\right)^{2k} \quad \text{and} \quad \exp(z) = \sum_{k=0}^{\infty}\frac{z^k}{k!} \quad (15)$$

after some algebra

$$\alpha_k = 0, \quad k = 1, 2$$
$$\alpha_k = \frac{1}{2^{3k}k!} + \frac{1}{2^{3k+1}}\sum_{i=1}^{k}\frac{(-1)^i 2^i}{(i!)^2(k-i)!}, \quad k = 3, 4, \cdots. \quad (16)$$

The first six nonzero coefficients of $\alpha_k$ are shown in Table I. All coefficients are small. The method of coefficient evaluation of (16) is almost the same as that in [21].

The Gram–Charlier series of the characteristic function $\psi_{n1}(\omega)$ is

$$1 + \sum_{k=3}^{\infty} c_k(j\omega)^k = \prod_{j=1}^{N}\left(1 + \sum_{k=3}^{\infty}\alpha_k(A_j\omega)^{2k}\right). \quad (17)$$

The coefficients of $c_k$ can be found by comparing the left- and right-hand side of (17). The first six nonzero coefficients of $c_k$ are shown in Table I. All coefficients are function of the crosstalk amplitudes $A_j$ and the coefficients $\alpha_k$.

### *C. Evaluation of Gram–Charlier Coefficients*

Given the crosstalk levels from different channels or the crosstalk amplitude of $A_k, k = 1, \cdots, N$, the error probability can be evaluated according to (10). In practice, using many choices of powerful symbolic mathematical software,[1] the coefficients $c_k$ can be found by using Taylor expansion of the right hand side of (13). Tens of those Gram–Charlier series coefficients can be evaluated within minutes using most symbolic mathematical software.

[1] The author has tried the series expansion in Mathematica and the Taylor expansion in the symbolic Maple toolbox of Matlab. For ten homodyne crosstalk sources, it takes about two minutes on a SUN Ultra 1 to an order of 50 for about 25 nonzero coefficients.

If a symbolic mathematical software is not available, a recursive algorithm can be used to evaluate all the Gram–Charlier coefficients with the following steps:

1) find all coefficient $\alpha_k$ using (16);
2) calculate the coefficient of one homodyne interferer by $c_{2k}^{(1)} = (-1)^k \alpha_k A_1^{2k}$;
3) recursively evaluate to $N$ homodyne interferers using the following formula:

$$c_{2k}^{(l)} = \sum_{i=0}^{k} c_{2i}^{(l-1)} (-1)^k \alpha_{k-i} A_l^{2(k-i)}, \quad l = 2, \cdots, N. \tag{18}$$

In the recursive formula of (18), the Gram–Charlier coefficients of $l$ homodyne interferers are evaluated from the Gram–Charlier coefficients of $l-1$ homodyne interferers and the crosstalk amplitude of the $l$th homodyne interferer. The formula can be applied recursively to find the Gram–Charlier coefficients of any number of homodyne interferers.

The required number of Gram–Charlier coefficients depends very much on the ratio of crosstalk variance $\sigma_I^2$ to Gaussian noise variance $\sigma_0^2$. In general, the required number of Gram–Charlier coefficients increases as the ratio $\sigma_I/\sigma_0$ increases. Numerical results show that about 20 nonzero coefficients are adequate in most numerical computations. In general, because the pdf is close to Gaussian distribution as the number of interferers increase, the required number of Gram–Charlier coefficients decreases.

## IV. Numerical Results

The extent of performance degradation due to homodyne crosstalk depends very much on the number of crosstalk interferers. Fig. 2 shows BER as a function of signal-to-Gaussian-noise ratio, $d/\sigma_0$, for different number of crosstalk interferers. The total signal-to-crosstalk ratio is assumed to be $-25$ dB and each crosstalk interferer is assumed to have the same crosstalk amplitude. Gaussian approximation represents the worst-case estimation that is valid when the number of homodyne interferers increases. Gaussian approximation has insignificant difference with the Gram–Charlier series when the number of interferers is more than ten. However, when the number of interferers is smaller, the Gaussian approximation overestimates the BER with a large margin. Fig. 2 also shows the theoretical results from [13] for one interferer. Although Gram–Charlier series, as a correction to Gaussian approximation, is considered least accurate for single-interferer, negligible difference is found as compared to [13].

Fig. 3 shows the power penalty as a function of crosstalk level for different number of interferers. For many interferers, the crosstalk amplitude of each interferer is assumed to be identical for simplicity. The required SNR to achieve a BER of $10^{-9}$ is $q = d/\sigma_0 = 6$ without homodyne crosstalk. With homodyne crosstalk, if the required SNR to achieve a BER of $10^{-9}$ is $q$, the power penalty is defined as $10 \cdot \log_{10}(q/6)$. Fig. 3 also shows that Gaussian approximation is a good model for many interferers but not a good model for small number of interferers. For example, Gaussian approximation provides a power penalty of 3 dB at a crosstalk level of about $-23$ dB but the accurate model shows a crosstalk level of about $-17$ dB for the same penalty. For the number of interferers more than ten, the results from Gaussian approximation and Gram–Charlier series are very close to each other. The results from [13] for single interferer are also shown for comparison for crosstalk levels of $-30$, $-25$, and $-20$ dB. The power penalties provided by Gram–Charlier series are shown to have insignificant difference with that from [13].

The Gram–Charlier series can also be used to study multiple homodyne crosstalk sources having different crosstalk levels. Fig. 4 shows BER as a function of SNR with four homo-

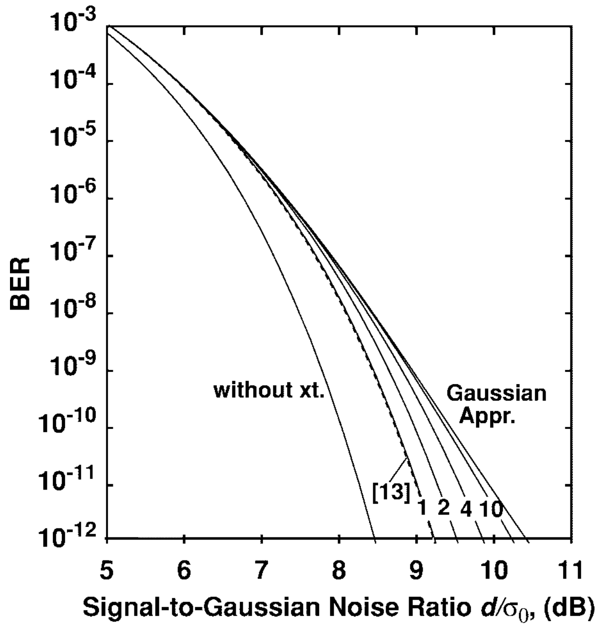


Fig. 2. BER as a function of signal-to-Gaussian noise ratio $d/\sigma_0$ for a total crosstalk level of $-25$ dB with different number of homodyne interferers and Gaussian approximation.The dash-line curve is the single-interferer result from [13].

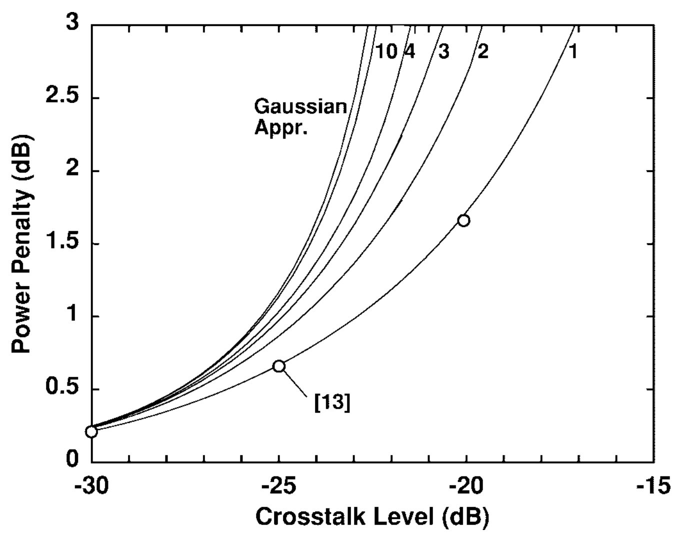


Fig. 3. Power penalty as a function of crosstalk level for different number of interferers and Gaussian approximation. The circles are power penalties from exact analysis for single interferer [13].

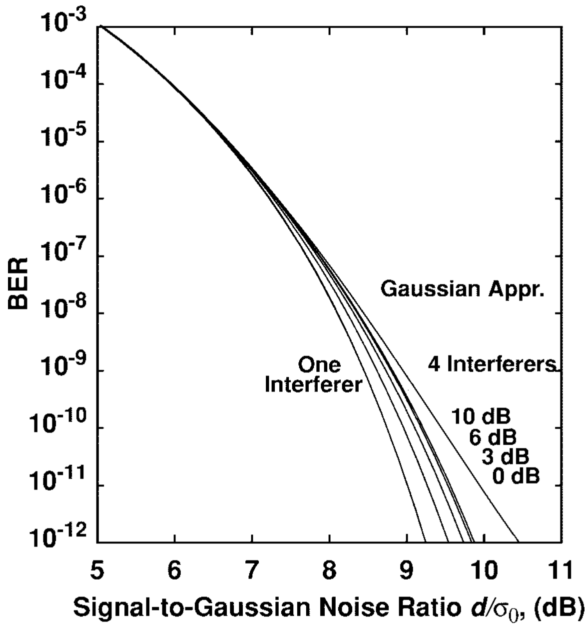


Fig. 4. BER as a function of signal-to-Gaussian noise ratio, $d/\sigma_0$ for a total crosstalk level of $-25$ dB. There are a total of four homodyne interferers with different crosstalk levels.

dyne crosstalk sources in which three of them have identical crosstalk level and one of them is dominated with 3, 6, and 10 dB larger crosstalk level than the other three interferers. For a total crosstalk level of $-25$ dB, Fig. 4 also shows results of one interferer and four equal interferers, all the same as Fig. 2, for comparison. In practice, usually all interferers have different crosstalk level and usually one or two of them may be dominated. As shown in Fig. 4, if one of the crosstalk sources become dominant crosstalk, the performance approaches that of a single interferer. If the stronger crosstalk is only 3 dB larger than the other three interferers are, the performance is very close to that provided by equal crosstalk level.

From Figs. 2–4, Gaussian approximation is always the worse-case approximation and may be used in practice for a conservative system design. As shown in [5] by numerically evaluating the pdf for multiple interferers, as the number of interferers increases, by the central limit theorem, the combined pdf approaches a Gaussian distribution provided that the variances of individual interferer are more or less the same. Figs. 2–3 show that the number of interferers must be larger than about ten to render the validity of Gaussian approximation. For a single interferer, from Figs. 2–3, the Gram–Charlier series has insignificant difference with an exact analysis in [13].

## V. Conclusion

Optical networks may be seriously degraded by homodyne crosstalk having the same wavelength as the signal. Usually used to evaluate system BER degraded by homodyne crosstalk, Gaussian approximation overestimates the performance degradation, especially when the number of homodyne crosstalk sources is small. Gram–Charlier series, which may be considered as a correction to Gaussian approximation, is used to derive the probability density function and the error probability for multiple homodyne interferers. Gaussian approximation is very close to the Gram–Charlier series if the system has more than ten homodyne crosstalk sources having more or less the same crosstalk level. With multiple homodyne crosstalk sources, the system performance may be close to single interferer case if one of the homodyne crosstalk sources is the dominant source.

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