Phase-Induced Intensity Noise in Digital Incoherent All-Optical Tapped-Delay Line Systems

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***Abstract*—In this paper, the authors analyze conditions under which they can be certain on the intensity addition of a given device, such as tapped-delay lines, used in digital incoherent all-optical communication systems. A general expression for phase-induced intensity noise that is applicable to all types of semiconductor lasers is derived by defining an optical self-SNR expression that can be used to analyze and measure phase-induced intensity noise. The result shows that in order to have a minimal phase-induced intensity noise in most digital optical incoherent systems, a large optical self-SNR, e.g., 20 dB or more, is needed. This in turn is shown to place a limit on the maximum rate of processing in a typical incoherent optical system even neglecting the bandwidth limitation of the photodetector. Furthermore, it is shown that the maximum rate of processing depends on the laser autocorrelation function and laser coherence time.**

***Index Terms*—Autocorrelation function, coherence time, optical self-SNR, phase noise, processing time.**

I. Introduction

COMMUNICATIONS through optical fiber links have many advantages over other methods due to its large bandwidth, low attenuation, immunity to interference, and high security. There are many distinct forms of fiber-optic transmission systems [1]–[7], but in general, they can be categorized mainly into two groups, namely coherent and incoherent systems.

In coherent optical systems, the system is based on the coherence of optical laser sources. Even though an ideal optical coherent system provides more sensitivity to the required number of received photons, they suffer usually from their sources of not being ideal. It is understood that in order to decrease the effect of nonideal sources, we should decrease the integration time of the integrator at the receiver of a common coherent receiver [1]–[7]. However, on the other hand, incoherent systems are based on an incoherent addition of optical intensities at the photodetector's output. Based on this assumption, many structures have been proposed [8]. In general, the operational performance of any optical system is influenced by various internal- and external-noise sources [9]. Therefore, a complete analysis of the system performance involves consideration of all the relevant noise sources. Random phase, which is the source of phase-induced intensity noise in many optical devices that induces intensity fluctuation of the output intensity of a photodetector for coherent and incoherent communications or optical sensor applications, has been extensively studied and analyzed (e.g., [1]–[17]). However, in this paper, we focus on the effect of random phase on incoherent optical systems, where we add intensities at the photodetector's output. We drive a general expression for any laser source in any structure and simplify our results for special cases. We obtain the noisy term autocorrelation function and its corresponding power spectrum. Our results are applicable to any incoherent system that is based on intensity addition.

In Section II of this paper, optical-signal model is discussed. The problem analyzed in this paper is defined and presented in Section III. Section IV presents the system analyses of our proposed problem by defining and calculating its so-called self-SNR. In Section V, some special but important examples are considered and discussed. In Section VI, a few applications of our results are discussed. Section VII compares the coherent and incoherent systems from the perspective of their corresponding processing time. Section VIII concludes the paper.

II. Optical-Signal Model

In general, optical signals that are produced by laser sources are random processes with characteristics that depend on the laser type. This randomness in a laser output can have a quantum origin, or it could be a result from external disturbances [20], [21]. In an exact model, the amplitudes or their corresponding intensities and the phases of optical signals vary randomly. Due to damping of amplitude fluctuation in semiconductor lasers, we can neglect this effect and safely assume that the randomness in the optical field is due to the phase fluctuation [20], [22]. Hence, we can write the optical-signal field $E(t)$ as

$$E(t) = \sqrt{I_0} e^{j(\omega_0 t + \phi(t) + \theta)} \tag{1}$$

where I_0 represents instantaneous intensity, and it is assumed to be a constant parameter; ω_0 is the optical frequency, $\phi(t)$ is the random phase of the light with zero initial condition; θ is the initial phase of the laser; and $j \triangleq \sqrt{-1}$.

The random-phase process $\phi(t)$ is assumed to have a zero-mean Gaussian probability density function with an arbitrary coherence function. In our final simplified model, we assume that $\phi(t)$ is a Wiener–Levy process [18]–[23] that best models

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many outputs of semiconductor lasers. We also define the structure function of the random phase as [18]

$$D_{\phi}(t_1, t_2, \ldots, t_n, t_{n+1}, \ldots, t_{2n}) \triangleq E\left\{(\phi(t_1)+\phi(t_2)+\cdots+\phi(t_n)-\phi(t_{n+1})-\cdots-\phi(t_{2n}))^2\right\} \quad (2)$$

where $E\{\cdot\}$denotes the expectation operation. In Appendix A, we show the reasons for needing this function and also obtain its form for random-phase processes with arbitrary correlation function and n. However, even though the random-phase process is not a stationary process, the structure function depends only on the difference time instants, as shown in Appendix A. The constant phase θ is assumed to be a random variable with uniform distribution on $[-\pi, \pi]$.

III. Problem Definition

In many optical communication systems or devices, such as optical receivers, we are in a situation where the input to the photodetector is the sum of a few optical signals. Since photodetectors act as square-law devices on input fields [18], [22], [24], in reality in many incoherent systems, we may not have the exact intensity addition of the optical signals at the photodetector's output. In this paper, we attempt to measure the inaccuracy associated with the above intensity addition due to phase-induced intensity noise in any incoherent system. Note that this type of phase-induced intensity noise occurs only when more than one optical signal is incident on the photodetector surface, and this results into a completely different intensity noise produced by the fiber chromatic dispersion, as analyzed in [27].

We consider a general structure for an incoherent system. This structure is shown in Fig. 1. In this figure, we assume that optical signals from different sources pass through different fiber-optic tapped-delay lines (TDLs), split by optical splitters, and are recombined by optical combiners prior to photodetection. Also, all the optical elements such as splitters, fiber delay lines, combiners, and couplers to the photodetector are assumed to be ideal, and all nonlinear effects are neglected. Thus, all the passive elements act like linear time-invariant devices [19]. The statistical behavior of the incident light at the input of each TDLs is assumed to be in the form of (1), and the variation or fluctuation of its corresponding intensity is neglected. The photodetector is modeled as an ideal square-law device [22], [24] with quantum efficiency equal to one, and for the sake of mathematical simplicity, the shot-noise effect is neglected. Following the squaring of the input light in the desired system, we proceed by processing the detected light. The processing part of the system, as an example, can be a filtering operation or any other processing. In most digital optical systems, especially for receivers in the direct detection, the processing part is an integrate-and-dump device with integration time T_{p}. We denote T_{p} to be the processing time of the desired system. Fig. 1 shows this hypothetical model.

IV. System Analysis

The input optical signal on each TDL can be written as

$$E_{\mathrm{in}}^{(i)}(t) = \sqrt{I_i} e^{j(\omega_0 t + \phi_i(t) + \theta_i)}, \quad i \in \{1, 2, \ldots, N\} \quad (3)$$

where i denotes the ith TDL. Furthermore, we assume that for each pair of optical signals, where $i \neq j \in \{1, \ldots, N\}$, their center frequencies ω_0 are equal, and their corresponding random phases $\{\phi_i(t), \theta_i\}$ and $\{\phi_j(t), \theta_j\}$ are mutually statistically independent. Furthermore, we assume that optical signals from different sources have exactly the same polarization that corresponds to the worst case scenario in our analysis. The number of branches in the ith TDL is equal to w_i. Each branch in each TDL delays the split incident field with a predetermined delay. The splitting ratio in the jth branch of the ith TDL is denoted by $\sqrt{\eta_j^{(i)}}$. Note that, in general, we can have $\sum_{j=1}^{w_i} \eta_j^{(i)} < 1$ for a nonideal TDL that corresponds to a lossy device. The total number of TDLs, which are independent sources, is assumed to be N. From the above discussion, the impulse response of the ith TDL can be written as

$$h_{\mathrm{TDL}}^{(i)}(t) \triangleq \sum_{j=1}^{w_i} \sqrt{\eta_j^{(i)}} \delta\left(t - \tau_j^{(i)}\right) \quad (4)$$

where $\delta(\cdot)$ denotes Dirac-delta function. Therefore, for the output of each TDL, we have

$$E_{\mathrm{out}}^{(i)}(t) = E_{\mathrm{in}}^{(i)}(t) \otimes h_{\mathrm{TDL}}^{(i)}(t) = \sum_{j=1}^{w_i} \sqrt{\eta_j^{(i)}} E_{\mathrm{in}}^{(i)}\left(t - \tau_j^{(i)}\right) \quad (5)$$

where $\otimes$ denotes the convolution operation. From (3)–(5), and the system model given in Fig. 1, the total input field to the photodetector is the sum of the TDL output and can be expressed as

$$\begin{aligned} E_{\mathrm{tot}}(t) &= \sum_{i=1}^{N} E_{\mathrm{out}}^{(i)}(t) \\ &= \sum_{j=1}^{w_1} \sqrt{I_j^{(1)}} e^{j\left(\omega_0\left(t-\tau_j^{(1)}\right)+\phi_1\left(t-\tau_j^{(1)}\right)+\theta_1\right)} \\ &\quad + \cdots + \sum_{j=1}^{w_N} \sqrt{I_j^{(N)}} e^{j\left(\omega_0\left(t-\tau_j^{(N)}\right)+\phi_N\left(t-\tau_j^{(N)}\right)+\theta_N\right)} \end{aligned} \quad (6)$$

where $I_j^{(i)} \triangleq I_i \eta_j^{(i)}$. For the detected light at the photodetector's output, we have

$$i_{\mathrm{PD}}(t) = \left|E_{\mathrm{tot}}(t)\right|^2. \quad (7)$$

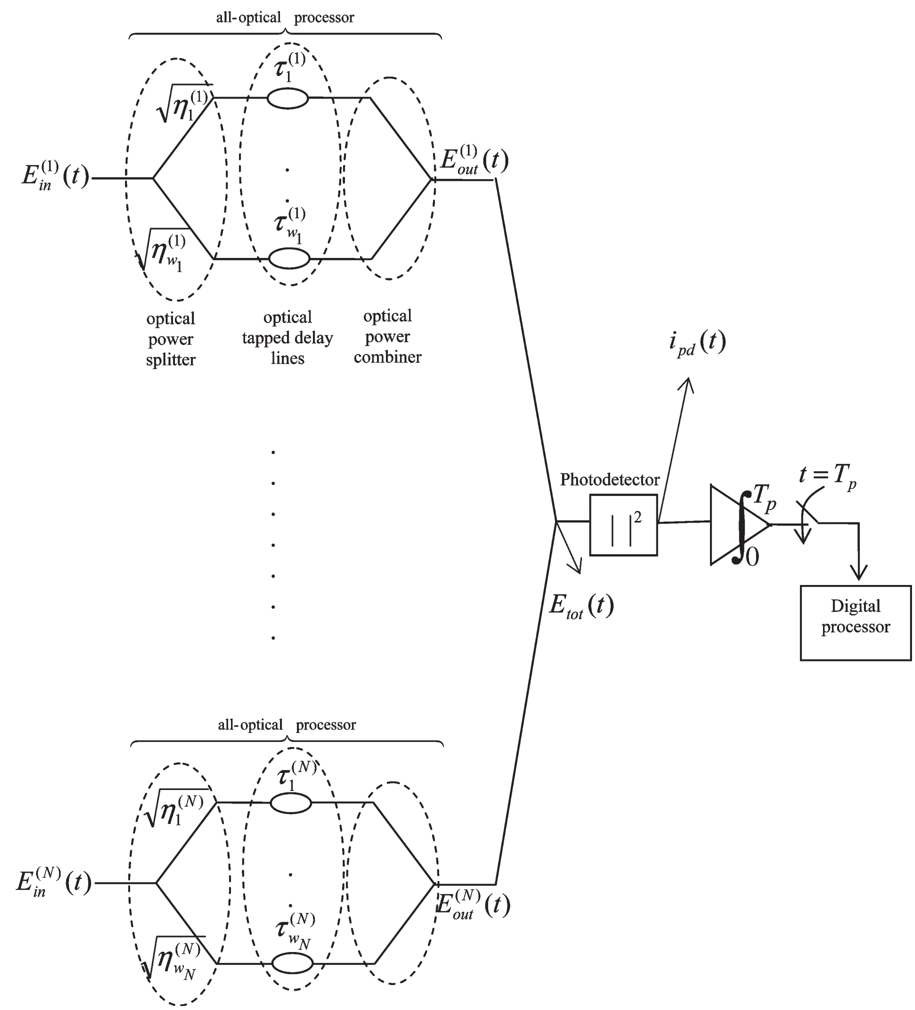

Fig. 1. Model for incoherent all-optical-signal processing. As we stated, each optical signal from an independent laser source will pass through an all-optical processor based on an optical-power splitter, fiber-optic TDLs, and optical power-combiner. After deliberately shifting each signal, they are recombined and detected by a photodetector, which acts like a square-law device. Note that all the elements are assumed to be ideal and act linearly in intensity. Also, the coupling between the fiber and the detector is assumed to be ideal.

To obtain (7), we note that for each term in (6), we can use the following equality

$$\left|\sum_{j=1}^{w_i}\sqrt{I_j^{(i)}}e^{j\left(\omega_0\left(t-\tau_j^{(i)}\right)+\phi_i\left(t-\tau_j^{(i)}\right)+\theta_i\right)}\right|^2 = \sum_{j=1}^{w_i} I_j^{(i)} + 2\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i}\sqrt{I_{j_1}^{(i)}I_{j_2}^{(i)}} \times\cos\left(\omega_0\left(\tau_{j_2}^{(i)}-\tau_{j_1}^{(i)}\right)+\phi_i\left(t-\tau_{j_1}^{(i)}\right)-\phi_i\left(t-\tau_{j_2}^{(i)}\right)\right). \quad (8)$$

The overall detected intensity $i_{\rm PD}(t)$ can be written mainly as the sum of two terms: one representing incoherent addition of each TDL's output signal and the other the effect of crossterms due to photodetection process. The basic assumption in incoherent optical systems is that the detected light can be expressed as the sum of intensities of the input lights only. But as we can see, in general, this is not true. We can write the detected light as the sum of two terms (9), shown at the bottom of the next page.

The first term I, i.e., incoherent addition, is the sum of intensities of each input light $\sqrt{\eta_j^{(i)}}E_{\rm in}^{(t)}(t-\tau_j^{(i)})$ to the photodetector, and the second term, i.e., $\mathrm{CT}(t) = C_1(t) + C_2(t)$, is due to the squaring effect of the receiver photodetector. In systems such as interferometers and coherent optical systems, $C_1(t) + C_2(t)$ is the desired part of the detected signal. However, in incoherent optical systems, this is the phase-induced intensity-noise term, and it is considered undesirable since it reduces the performance of such systems.

To study the effect of phase-induced intensity-noise term $\mathrm{CT}(t)$ on the overall detected intensity signal $i_{\rm PD}(t)$, we first evaluate its corresponding autocorrelation function. As shown in Appendix B, this autocorrelation function can be written as

$$R_{\rm CT}(t+\tau,t) = R_{C_1}(t+\tau,t) + R_{C_2}(t+\tau,t) \quad (10)$$

where we have (11) and (12), shown at the bottom of the next page.

The variance of the phase-induced intensity-noise term can be easily obtained from its autocorrelation function by setting $\tau = 0$. This variance can be typically large. However, in most incoherent optical systems, prior to electrical processing on the intensity-addition term, which is the first term of (9), we preprocess the detected light. This preprocessing, as shown in

Fig. 1, can be a filtering. Thus, the important parameter for the electrical processing part is the power of the filtered phase-induced intensity-noise term. We assume that the filter in question is a linear system with an impulse response $h_F(t)$. Thus, from Wiener–Khinchin theorem [19] in stochastic process, this filtered power can be obtained from the following equation:

$$\begin{aligned}\text{Power of CT} = P_{\mathrm{CT}} &= R_{\mathrm{CT}}(\tau) \otimes \rho(\tau)|_{\tau=0} \\ &= \int_{-\infty}^{\infty} S_{\mathrm{CT}}(f)\, |H_F(f)|^2 \, df \end{aligned} \tag{13}$$

where $\rho(\tau) \triangleq h_F(\tau) \otimes h_F(-\tau)$; $S_{\mathrm{CT}}(f) \triangleq \Im\{R_{\mathrm{CT}}(\tau)\}$; $H_F(f) \triangleq \Im\{h_F(\tau)\}$; and $\Im\{\cdot\}$ denotes Fourier transformation.

As we can observe from (13), the evaluation of the power of crossterm $\mathrm{CT}(t)$ is not a simple task in general. In Section V, we simplify our results with an actual assumption used in the incoherent digital optical systems. Prior to that, we define a new SNR function as a key parameter for our future analysis. By definition, the SNR, which is referred to as self-SNR, is the ratio of the filtered signal component power to the power

$$\begin{aligned} i_{\mathrm{PD}}(t) = & \underbrace{\sum_{j=1}^{w_1} I_j^{(1)} + \sum_{j=1}^{w_2} I_j^{(2)} + \cdots + \sum_{j=1}^{w_N} I_j^{(N)}}_{\text{Incoherent Addition} \triangleq \mathrm{I}} \\ & \underbrace{+ 2 \sum_{i=1}^{N} \sum_{j_1=1}^{w_i-1} \sum_{j_2=j_1+1}^{w_i} \sqrt{I_{j_1}^{(i)} I_{j_2}^{(i)}} \cos\left(\omega_0 \left(\tau_{j_2}^{(i)} - \tau_{j_1}^{(i)}\right) + \phi_i\left(t - \tau_{j_1}^{(i)}\right) - \phi_i\left(t - \tau_{j_2}^{(i)}\right)\right)}_{\text{crossterms from interproducts of dependent optical light signals} \triangleq C_1(t)} \\ & \underbrace{+ 2 \sum_{i_1=1}^{N-1} \sum_{i_2=i_1+1}^{N} \sum_{j_1=1}^{w_{i_1}} \sum_{j_2=1}^{w_{i_2}} \sqrt{I_{j_1}^{(i_1)} I_{j_2}^{(i_2)}} \cos\left(\omega_0\left(\tau_{j_2}^{(i_2)} - \tau_{j_1}^{(i_1)}\right) + \phi_{i_1}\left(t - \tau_{j_1}^{(i_1)}\right) - \phi_{i_2}\left(t - \tau_{j_2}^{(i_2)}\right) + \theta_{i_1} - \theta_{i_2}\right)}_{\text{crossterms from external products of independent optical light signals} \triangleq C_2(t).} \end{aligned} \tag{9}$$

$$\begin{aligned} & R_{C_1}(t+\tau, t) \\ & = 2 \sum_{i=1}^{N} \sum_{j_1=1}^{w_i-1} \sum_{j_3=1}^{w_i-1} \sum_{j_2=j_1+1}^{w_i} \sum_{j_4=j_3+1}^{w_i} \sqrt{I_{j_1}^{(i)} I_{j_2}^{(i)} I_{j_3}^{(i)} I_{j_4}^{(i)}} \\ & \quad \times \left\{ \cos\left(\omega_0\left(\tau_{j_1}^{(i)} + \tau_{j_3}^{(i)} - \tau_{j_2}^{(i)} - \tau_{j_4}^{(i)}\right)\right) e^{-\frac{1}{2} D_{\phi_i}\left(t+\tau-\tau_{j_1}^{(i)}, t-\tau_{j_3}^{(i)}, t+\tau-\tau_{j_2}^{(i)}, t-\tau_{j_4}^{(i)}\right)} \right. \\ & \qquad \left. + \cos\left(\omega_0\left(\tau_{j_1}^{(i)} - \tau_{j_3}^{(i)} - \tau_{j_2}^{(i)} + \tau_{j_4}^{(i)}\right)\right) e^{-\frac{1}{2} D_{\phi_i}\left(t+\tau-\tau_{j_1}^{(i)}, t-\tau_{j_4}^{(i)}, t+\tau-\tau_{j_2}^{(i)}, t-\tau_{j_3}^{(i)}\right)} \right\} \\ & \quad + 2 \sum_{i_1=1}^{N-1} \sum_{i_2=1 \neq i_1}^{N} \sum_{j_1=1}^{w_{i_1}-1} \sum_{j_2=j_1+1}^{w_{i_1}} \sum_{j_3=1}^{w_{i_2}-1} \sum_{j_4=j_3+1}^{w_{i_2}} \sqrt{I_{j_1}^{(i_1)} I_{j_2}^{(i_1)} I_{j_3}^{(i_2)} I_{j_4}^{(i_2)}} \\ & \quad \times \cos\left(\omega_0\left(\tau_{j_1}^{(i_1)} - \tau_{j_2}^{(i_1)}\right)\right) \cos\left(\omega_0\left(\tau_{j_3}^{(i_2)} - \tau_{j_4}^{(i_2)}\right)\right) e^{-\frac{1}{2}\left(D_{\phi_{i_1}}\left(\tau+\tau_{j_1}^{(i_1)}-\tau_{j_2}^{(i_1)}\right) + D_{\phi_{i_2}}\left(\tau+\tau_{j_3}^{(i_2)}-\tau_{j_4}^{(i_2)}\right)\right)} \end{aligned} \tag{11}$$

$$\begin{aligned} & R_{C_2}(t+\tau, t) \\ & = 2 \sum_{i_1=1}^{N-1} \sum_{i_2=i_1+1}^{N} \sum_{j_1=1}^{w_{i_1}} \sum_{j_2=1}^{w_{i_2}} \sum_{j_3=1}^{w_{i_1}} \sum_{j_4=1}^{w_{i_2}} \sqrt{I_{j_1}^{(i_1)} I_{j_2}^{(i_2)} I_{j_3}^{(i_1)} I_{j_4}^{(i_2)}} \\ & \quad \times \cos\left(\omega_0\left(\tau_{j_1}^{(i_1)} - \tau_{j_3}^{(i_1)} - \tau_{j_2}^{(i_2)} + \tau_{j_4}^{(i_2)}\right)\right) e^{-\frac{1}{2}\left(D_{\phi_{i_1}}\left(\tau - \left(\tau_{j_1}^{(i_1)} - \tau_{j_3}^{(i_1)}\right)\right) + D_{\phi_{i_2}}\left(\tau - \left(\tau_{j_2}^{(i_2)} - \tau_{j_4}^{(i_2)}\right)\right)\right)} \end{aligned} \tag{12}$$

of the noise term $\mathrm{CT}(t)$ at the photodetector's output after the filtering process.

$$\mathrm{SNR}_{\mathrm{self}} \triangleq \frac{\text{power of filtered incoherent term}}{\text{power of filtered crossterm}} = \frac{P_I}{P_{\mathrm{CT}}}. \quad (14)$$

We also define the inverse of self-SNR function and denote it as Γ, hence

$$\Gamma \triangleq \mathrm{SNR}_{\mathrm{self}}{}^{-1}. \quad (15)$$

As we discuss in the following sections, working with inverse self-SNR Γ is simpler than self-SNR function itself. Note that the above definition is quite general, since as we discussed, the optical intensity might be a random process. However, in this paper, we will analyze the self-SNR for deterministic intensities only. One can also easily include the effect of the shot-noise process [9], [18].

In general, the self-SNR is a function of the filtering process; however, as it will be shown, it is a meaningful parameter for analyzing the effect of phase-induced intensity noise. The power of phase-induced intensity-noise term depends explicitly on the autocorrelation function of the input optical signals to the TDLs, and this depends on the structure function of their corresponding random-phase process (see Appendix A). However, the autocorrelation functions of the random-phase processes depend on the type of lasers that are used for signal generation. For example, for most semiconductor lasers in optical systems, their corresponding random-phase processes are modeled with Wiener–Levy processes [18], [24], and in some other applications, more precise models for laser output signals are used [17], [21].

V. Time-Averaged Autocorrelation Function

As we discussed in the previous section, the analysis of crossterm $\mathrm{CT}(t)$ in general is difficult, and exact analysis with a closed-form solution seems to be almost impossible. In this section, we employ a common assumption mainly used for incoherent digital optical systems and simplify our expressions for a class of special lasers with Wiener–Levy random phases. In general, the delays in TDLs are not constant and can vary due to thermal variation or other effects. These variations can be very small, but since these delays are multiplied by optical frequency, the resulting variations will be large. Note that optical frequency is on the order of petahertz, and delays in TDLs can be on the order of picoseconds, so variations in delay times for 1% of picoseconds will result in approximately 2π swing in radians for the corresponding cosine functions. Therefore, we can use time-averaged time autocorrelation function as those in [10] and [15]. In sensor applications, this may not be an acceptable or true assumption, but in incoherent optical systems with sources of enough incoherence, this assumption will not change the results significantly [15]. With this assumption, the two terms comprising the crossterm $\mathrm{CT}(t)$ will simplify to (16) and (17), shown at the bottom of the page (see Appendix C). Thus, the power of filtered term can be easily obtained from (16) and (17) in conjunction with (13). All the above relations are applicable to every lasers with arbitrary randomness, i.e., structure function. In the next section, for practical purposes, we consider laser sources having Wiener–Levy random phases (see Appendix A).

In most incoherent digital optical systems, the filtering part of the system is an integrate-and-dump process [24], [26] with an integration time T_{p}. In this case, the power of filtered phase-induced intensity-noise term can be evaluated (see Appendix D) and are as follows:

$$P_{C_1} = 2\sum_{i=1}^{N}\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i} I_{j_1}^{(i)} I_{j_2}^{(i)} \times f\left(\tau_{c_i}, T_{\mathrm{p}}, \left|\tau_{j_1}^{(i)} - \tau_{j_2}^{(i)}\right|\right) \quad (18)$$

$$P_{C_2} = 4\sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\sum_{j_1=1}^{w_{i_1}}\sum_{j_2=1}^{w_{i_2}} I_{j_1}^{(i_1)} I_{j_2}^{(i_2)} T_{\mathrm{p}} \tau_{c_{i_1,i_2}} \times \left(1 - \frac{\tau_{c_{i_1,i_2}}}{T_{\mathrm{p}}}\left(1 - e^{-\frac{T_{\mathrm{p}}}{\tau_{c i1,i2}}}\right)\right) \quad (19)$$

where

$$\tau_{c_{i_1,i_2}} \triangleq \frac{\tau_{c_{i_1}} \tau_{c_{i_2}}}{\tau_{c_{i_1}} + \tau_{c_{i_2}}} \quad (20)$$

and (21), shown at the bottom of the next page.

If we define the following parameters (Γ_{C_1} and Γ_{C_2}) as

$$\Gamma_{C_1} = \sum_{i=1}^{N}\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i} \Gamma_{i,j_1,j_2} \quad (22a)$$

$$\Gamma_{i,j_1,j_2} \triangleq 2\frac{I_{j_1}^{(i)} I_{j_2}^{(i)}}{P_I} f\left(\tau_{c_i}, T_{\mathrm{p}}, \left|\tau_{j_1}^{(i)} - \tau_{j_2}^{(i)}\right|\right) \quad (22b)$$

$$\Gamma_{C_2} = \sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\sum_{j_1=1}^{w_{i_1}}\sum_{j_2=1}^{w_{i_2}} \Gamma_{i_1,i_2,j_1,j_2} \quad (22c)$$

$$R_{C_1}(\tau) = 2\sum_{i=1}^{N}\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i} I_{j_1}^{(i)} I_{j_2}^{(i)} e^{-\frac{1}{2}\left(2D_{\phi_i}\left(\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right)+D_{\phi_i}(\tau)-D_{\phi_i}\left(\tau-\left(\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right)\right)-D_{\phi_i}\left(\tau+\left(\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right)\right)\right)} \quad (16)$$

$$R_{C_2}(\tau) = 2\sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\sum_{j_1=1}^{w_{i_1}}\sum_{j_2=j_1+1}^{w_{i_2}} I_{j_1}^{(i_1)} I_{j_2}^{(i_2)} e^{-\frac{1}{2}\left(D_{\phi_{i_1}}(\tau)+D_{\phi_{i_2}}(\tau)\right)} \quad (17)$$

$$\Gamma_{i_1,i_2,j_1,j_2} \triangleq 4\frac{I_{j_1}^{(i_1)} I_{j_2}^{(i_2)}}{P_I} T_{\mathrm{p}}\tau_{c_{i_1,i_2}}\left(1-\frac{\tau_{c_{i_1,i_2}}}{T_{\mathrm{p}}}\left(1-e^{-\frac{T_{\mathrm{p}}}{\tau_{c_{i_1,i_2}}}}\right)\right) \quad (22d)$$

Power of incoherent term

$$= P_I = \left[T_{\mathrm{p}}\sum_{i=1}^{N}\sum_{j=1}^{w_i} I_j^{(i)}\right]^2 \quad (22e)$$

then the inverse self-SNR will be $\Gamma = \Gamma_{C_1} + \Gamma_{C_2}$.

For other filter shapes where working in spectrum domain is easier, we may need the power spectrum of the crossterm. This spectrum is obtained in Appendix E. Then, (13) can be used for the calculation of the corresponding power.

VI. Some Special Cases

Case I—Independent Phases: In this case, we assume that the number of branches in each TDL is equal to one with no loss ($\eta_j^{(i)} = w_i^{-1} = 1$), also the signal intensities at the input of TDLs are equal ($I_i = I_0$), the coherence time of the optical signals are assumed to be identical ($\tau_{c_i} = \tau_{\mathrm{c}}$), then the inverse self-SNR Γ will be independent of the signal intensities, and we have

$$\Gamma = \mathrm{SNR}_{\mathrm{self}}^{-1} = \frac{\tau_{\mathrm{c}}}{T_{\mathrm{p}}}\left(1-\frac{1}{N}\right)\left(1-\frac{\tau_{\mathrm{c}}}{2T_{\mathrm{p}}}\left(1-e^{-2\frac{T_{\mathrm{p}}}{\tau_{\mathrm{c}}}}\right)\right). \quad (23)$$

As we can see from this equation, the self-SNR depends explicitly on two parameters, namely the number of interfering signals before the photodetector and laser coherence time to processing time ratio. When the number of signals or TDLs is one, i.e., $N = 1$, there is no phase-induced intensity noise $\mathrm{SNR}_{\mathrm{self}} = \infty$, $\Gamma = 0$, as expected. However, when the number of TDLs increases, the inverse self-SNR Γ also increases. But the difference gets smaller for larger number of signals and fixed laser coherence time to processing time. This is due to the fact that the power of the phase-induced intensity-noise term is proportional to $N(N-1)$, whereas the power of the desired incoherent term is proportional to N^2, and for large N, we can approximate the first with N^2. That is, when the number of interfering signals is large, the only important parameter will be the laser coherence time to processing time ratio. This in turn implies that in an incoherent optical system, the phase-induced intensity noise can be neglected for $\tau_{\mathrm{c}}/T_{\mathrm{p}} \ll 1$, i.e., low laser coherence times to processing time. We can also approximate the inverse self-SNR in terms of $\beta = \tau_{\mathrm{c}}/T_{\mathrm{p}}$ and can be expressed as follows:

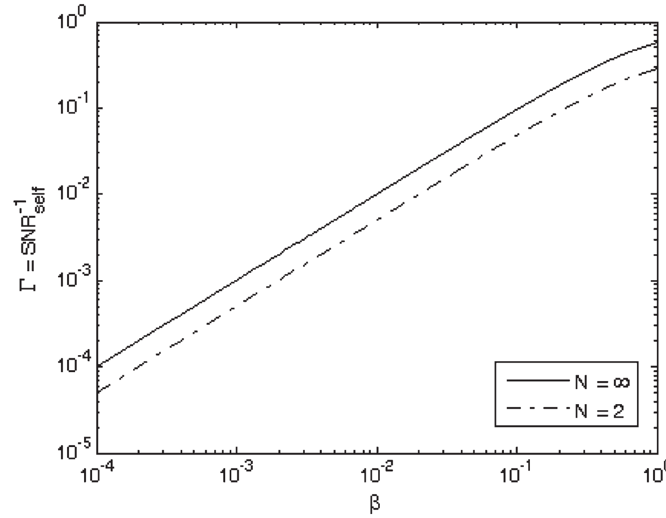

Fig. 2. Inverse self-SNR as a function of the normalized laser coherence time by processing time for two extreme cases when the number of input pulses N is equal to infinite (solid line) and when the number N is equal to two (dashed line).

$$\Gamma = \mathrm{SNR}_{\mathrm{self}}^{-1} \cong \left(1-\frac{1}{N}\right)\begin{cases}\beta\left(1-\frac{\beta}{2}\right) \approx \beta, & \beta < 1\\ \beta(1-0.4323\beta), & \beta \sim 1\\ \leq 1, & \beta > 1.\end{cases} \quad (24)$$

As we can observe from (24), $\beta < 1$ corresponds to a region of low phase-induced intensity noise. In this region, β and the inverse self-SNR Γ are linearly related. Fig. 2 shows Γ as a function of β. For large values of β, the signal corresponds to a coherent signal. In such a case, the self-SNR can be easily upper bounded as in (24). This is obvious because in coherent regime, the random-phase process can be assumed to be equal for time instants t and $t+\tau$. In this situation, the correlation function of the crossterm will have its maximum value, which is $N(N-1)$, and is constant. Therefore, in Fig. 2, the gamma function is plotted for values of $\beta \leq 1$ only. Note that the phase-induced intensity noise cannot be completely eliminated from detector's output. This is due to the fact that the phase-to-intensity term is proportional to the incident signal intensity, and thus, it is an intrinsic system noise due to photodetection.

$$f\left(\tau_{c_i}, T_{\mathrm{p}}, \left|\tau_{j_1}^{(i)} - \tau_{j_2}^{(i)}\right|\right) \triangleq \begin{cases} T_{\mathrm{p}}\tau_{c_i}\left(1-\frac{\tau_{c_i}}{2T_{\mathrm{p}}}\left(1-e^{-2\frac{T_{\mathrm{p}}}{\tau_{c_i}}}\right)\right), & \left|\tau_{j_1}^{(i)} - \tau_{j_2}^{(i)}\right| \geq T_{\mathrm{p}}\\ T_{\mathrm{p}}^2\left(1-\frac{\left|\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right|}{T_{\mathrm{p}}}\right)^2 e^{-2\frac{\left|\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right|}{\tau_{c_i}}} + T_{\mathrm{p}}\tau_{c_i}\left(1-\frac{\tau_{c_i}}{2T_{\mathrm{p}}}+e^{-2\frac{\left|\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right|}{\tau_{c_i}}}\left(\frac{2\left|\tau_{j_1}^{(i)}-\tau_{j_2}^{(i)}\right|-\tau_{c_i}}{2T_{\mathrm{p}}}-1\right)\right), & \text{o.w.}\end{cases} \quad (21)$$

However, theoretically and from (23), the exact elimination of phase-to-intensity noise occurs $\tau_c = 0$, which is not possible, and we neglect this case.

Case II—Dependent Phases: In this case, we assume that there is only one TDL, i.e., $N = 1$, one all-optical processor, in the incoherent structure, and the number of its branches is equal to w. Also, for simplicity, the coupling coefficient of the branches is assumed to be equal, i.e., $\eta_j = w^{-1}$. This implies that the intensity of optical signal at each branch output will be the same. With these assumptions, the self-SNR can be easily extracted from (22). We have

$$\Gamma = \sum_{i_1=1}^{w-1} \sum_{i_2=i_1+1}^{w} \Gamma_{i_1,i_2} \quad \text{or} \quad \text{SNR}_{\text{self}}^{-1} = \sum_{i_1=1}^{w-1} \sum_{i_2=1}^{w} \text{SNR}_{i_1,i_2}^{-1} \tag{25a}$$

$$\Gamma_{i_1,i_2} \triangleq \text{SNR}_{i_1,i_2}^{-1} \tag{25b}$$

and (26), shown at the bottom of the page.

Note that (26) depends explicitly on four important parameters: the number of branches in TDL w, laser coherence time τ_c, processing time T_p, and the relative delay time between input signals in the corresponding branches at the photodetector's input in TDL. Note that since $N = 1$, this implies that all the signals belong to the same optical source. We define normalized delay difference for two branches as follows:

$$\Delta_{i_1,i_2} \triangleq \frac{|\tau_{i_1} - \tau_{i_2}|}{\tau_c}. \tag{27}$$

Using (27) and the previously defined parameter for β, we can express (26) as (28), shown at the bottom of the page.

For an in-depth discussion on this case, we further divide this case into three special cases and discuss each separately.

1) In this case, the difference between two delays in their corresponding branches in TDL is assumed to be constant and also greater than the processing time, i.e., $\Delta_{i_1,i_2} \cdot \tau_c > T_p$. Therefore, the inverse self-SNR can be simplified as follows:

$$\Gamma = \left(1 - \frac{1}{w}\right) \beta \left(1 - \frac{\beta}{2}\left(1 - e^{-\frac{2}{\beta}}\right)\right). \tag{29}$$

This result can be easily obtained using (25) and (28) in connection with the above assumption. As we can see in this case, Γ depends only on β. This result is analogous to the independent phases, which were analyzed in case I. This means that when the delay difference is greater than the processing time, the delayed versions of an optical signal act independently as two optical signals with independent random phases. For accurate intensity addition, we need to decrease β as in case I. With decreasing β, we can be more certain on the intensity addition. Another important point is the linear relation that exists between Γ and β, which is once again analogous to the independent case. Note that in this case, when the number of branches is equal to one, i.e., $w = 1$, there will also be no phase-induced intensity noise.

2) In this case, we assume that all the delay differences are smaller than the processing time and where they are also identical $\Delta_{i_1,i_2} = \Delta$. In this case, the inverse self-SNR Γ can be easily derived from (28) and (25) with the above conditions, and we have

$$\Gamma = \left(1 - \frac{1}{w}\right)\left[(1-\beta\Delta)^2 e^{-2\Delta} + \beta\left(1 - \frac{\beta}{2} + e^{-2\Delta}\left(\beta\Delta + \frac{\beta}{2} - 1\right)\right)\right]. \tag{30}$$

We observe that in this situation, the inverse self-SNR can be dominated by delay differences. In order to have a large self-SNR function or small Γ, we should first choose the coherence time in such a way that the first term in the bracket in (30) becomes negligible. Then, choose the processing time to laser coherence time in such a way that the second term will become smaller than the desired value indicating the accuracy in incoherent addition.

The approximation of Γ for small values of β and Δ can be derived from (31) as such (see Figs. 3 and 4), we have

$$\Gamma = \left(1 - \frac{1}{w}\right) \begin{cases} e^{-2\Delta} + \beta(1 - e^{-2\Delta}), & \beta \ll 1 \\ \beta\left(1 - \frac{\beta}{2}\right), & \Delta > 5 \end{cases}. \tag{31}$$

We can see that for reducing the effect of the delay difference term, we need to choose Δ to be at least five,

$$\Gamma_{i_1,i_2} \triangleq \frac{2}{w^2} \begin{cases} \frac{\tau_c}{T_p}\left(1 - \frac{\tau_c}{2T_p}\left(1 - e^{-2\frac{T_p}{\tau_c}}\right)\right), & T_p \le |\tau_{i_1} - \tau_{i_2}| \\ \left(1 - \frac{|\tau_{i_1}-\tau_{i_2}|}{T_p}\right)^2 e^{-2\frac{|\tau_{i_1}-\tau_{i_2}|}{\tau_c}} + \frac{\tau_c}{T_p}\left(1 - \frac{\tau_c}{2T_p} + e^{-2\frac{|\tau_{i_1}-\tau_{i_2}|}{\tau_c}}\left(\frac{\tau_c + 2|\tau_{i_1}-\tau_{i_2}|}{2T_p} - 1\right)\right), & \text{o.w.} \end{cases} \tag{26}$$

$$\Gamma_{i_1,i_2} \triangleq \frac{2}{w^2} \begin{cases} \beta\left(1 - \frac{\beta}{2}\left(1 - e^{-\frac{2}{\beta}}\right)\right), & \beta\Delta_{i_1,i_2} \ge 1 \\ (1 - \beta\Delta_{i_1,i_2})^2 e^{-2\Delta_{i_1,i_2}} + \beta\left(1 - \frac{\beta}{2} + e^{-2\Delta_{i_1,i_2}}\left(\Delta_{i_1,i_2} + \frac{\beta}{2} - 1\right)\right), & \text{o.w.} \end{cases} \tag{28}$$

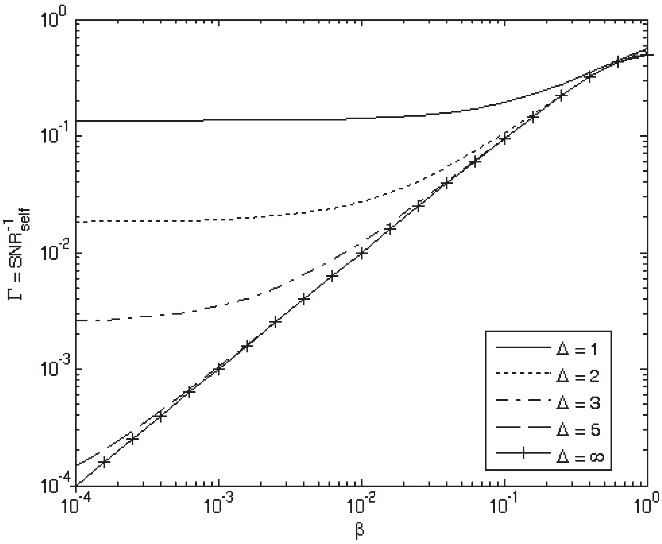

Fig. 3. Gamma function versus β for various values of Δ and with $w = \infty$. As it can be observed from this figure, when Δ increases, the gamma function approaches to a more linear relation with respect to β.

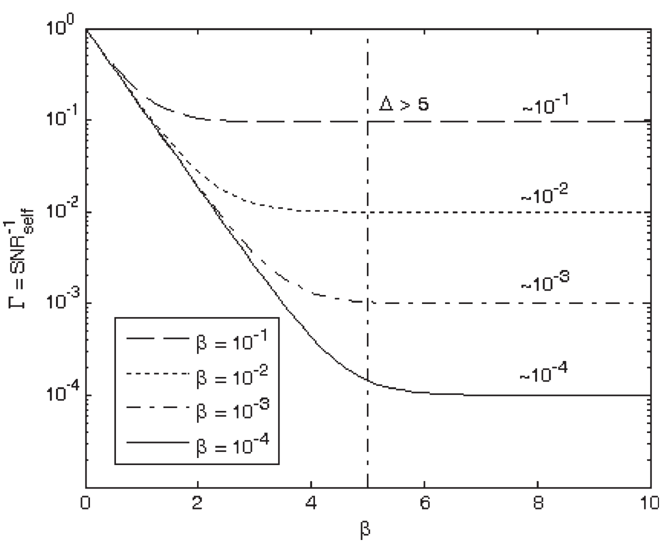

Fig. 4. Gamma function versus Δ for various values of β. As can be observed for values of $\Delta \geq 5$, the value of the Gamma function becomes independent from Δ and can be stated as a function of β only.

i.e., $\Delta > 5$. With this choice, the effect of the first term in (30) becomes negligible on the order of -5 dB, and the dominant term will be the second term. This term is similar to case I and also to case 1). With the constraint used for the first term, the only important parameter for the remaining second term will be β. Thus, for improving the self-SNR in this case, we need to control the second term by decreasing β after reducing the effect of the first term by appropriate choice on delay difference Δ. This result however shows that for this case, the delay difference is important, but its effect can be easily reduced by choosing a laser coherence time to be at least five times smaller than Δ. But with this selection for the delay differences, the inverse self-SNR depends explicitly and linearly on β. Note also that in this case, as in other previous cases when the number of interferences is one, there will be no phase-induced intensity noise, i.e., $\mathrm{SNR}_{\mathrm{self}} = \infty, \Gamma = 0$. In this section, we have assumed that all the delay differences are equal. In real situations, they are not equal but can be smaller than the processing time. From our discussion in such cases, we can easily substitute Δ with its minimum possible value so that $\Delta = \min_{i_1,i_2}\{\Delta_{i_1,i_2}\}$, as shown in the following section.

3) In this case, some delay differences are greater than the processing time and some are smaller. However, theoretically or in practice, there may exist a situation where some delay differences are zero. But for our analysis, we do not consider this situation, because in this case, we can model two branches in Fig. 1 by one branch with intensity four times the former. However, for this case then, the assumption of identical intensities (equal coupling coefficient, $\eta_j = w^{-1}$) will not be satisfied. Thus, assume that from the total number of terms in Γ, w_1 terms have delay differences that are smaller than the processing time, and for the others, say w_2, the processing time is smaller than the delay differences. Obviously, we have $w_1 + w_2 = w(w-1)/2$. For the total Γ, we can write

$$\Gamma = \frac{2}{w^2}\sum_{j=1}^{w_1} \underbrace{e^{-2\Delta_j}\left[(1-\beta\Delta_j)^2+\beta\left(\Delta_j\beta+\frac{\beta}{2}-1\right)\right]}_{\text{depends on } \beta \text{ and } \Delta_j}$$
$$+\underbrace{\frac{2}{w^2}\left(\sum_{j=1}^{w_1}\beta\left(1-\frac{\beta}{2}\right)+\sum_{j=1}^{w_2}\beta\left(1-\frac{\beta}{2}\left(1-e^{-\frac{2}{\beta}}\right)\right)\right)}_{\text{depends on } \beta \text{ only}}. \quad (32)$$

It can be observed from the above equation that the total inverse self-SNR Γ can be expressed via two terms, as in (32). One term depends on the normalized delay differences Δ_j, and the other as a function of the normalized coherence time β. The effect of delay differences can be easily minimized by a small increase in the normalized delay difference (see 2) in case II in this section). On the other hand, in incoherent optical systems, the normalized laser coherence time is comparatively small so that we have $\beta < 1$. In this case, we can neglect the term multiplied by the exponential factor, i.e., $e^{-2\Delta_j}$ in (32). The above discussion implies that, in more general situation, we can neglect the effect of the delay differences and approximate the total inverse self-SNR as

$$\Gamma \cong \left(1-\frac{1}{w}\right)\beta\left(1-\frac{\beta}{2}\right) \approx \left(1-\frac{1}{w}\right)\beta. \quad (33)$$

The discussion in obtaining (33) is the same as in cases 1) and 2).

VII. Applications of the Above Results: Perspective to System Design

In most incoherent optical digital communication systems, the basic assumption is that at the receiver's photodetector

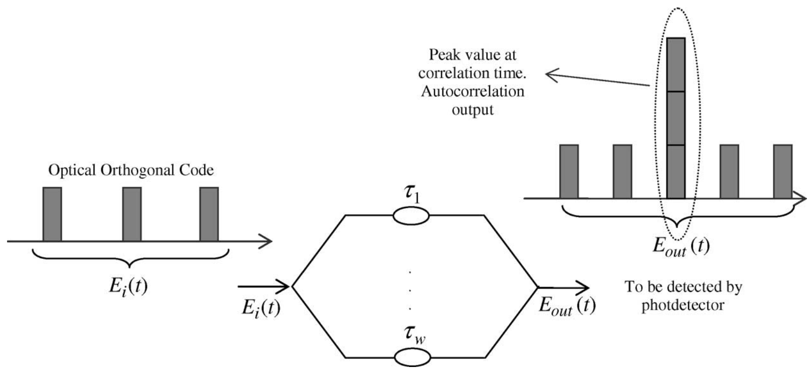

Fig. 5. All-optical encoder/decoder structure based on TDL for an optical CDMA system using OOC. Note that in the above example, the number of branches is equal to the code weight w.

output, we have the sum of a few positive optical signals, i.e., intensity addition. Based on this assumption, new codes for incoherent and positive optical systems and multiple-access networks were proposed [8]. However, as the speed of the processing in these classes of systems increases, the processing time per signal or pulse of the system decreases. But, as it is becoming apparent from previous sections, as the system speed increases, the intensity-addition assumption becomes less acceptable, and one needs to combat or remedy this degrading effect. This issue becomes even more acute in incoherent optical multiple-access networks. In these systems, we usually encode the data stream with a higher speed optical codes [8], [25], [26]. This implies that for a given coherence time of a laser, the processing time of the system will be lower bounded, and the maximum achievable rate of information also will be upper bounded. The reason is obvious from our previous discussion in Section VI. As we showed in all cases, the important parameter for accuracy in incoherent addition will be the normalized laser coherence time to the processing time ratio β, and this parameter should be as small as possible, which implies that for a specified laser coherence time, the processing time should be larger than a fixed constant as will be discussed in the following.

In optical systems, the processing time is directly related to the specified receiver structure [26]. For an incoherent optical system, we need to be in regions where $\beta \ll 1$. Therefore, for a desired self-SNR, one can easily calculate the required β from the approximation discussed in the previous section, e.g., (24), (29), and (33). If we need for the self-SNR to be ξ, the required β will be approximately $\xi^{-1}(1-(\mathrm{Nw})^{-1})^{-1}$, with Nw showing the total number of optical signals or pulses at the photodetector's input. From this relation and neglecting the effect of $1-(\mathrm{Nw})^{-1} \sim 1$, we can write

$$\beta \times \xi = 1. \tag{34}$$

Substituting β from (24), we have

$$\tau_{\mathrm{c}} = \frac{T_{\mathrm{p}}}{\xi}. \tag{35}$$

Equation (35) easily relates the processing time of the system T_{p} to the coherence time of the laser and the desired or required self-SNR. For typical values of laser coherence time in incoherent optical systems 10–100 ps and acceptable self-SNR 20 dB or more, the maximum rate of the system that is proportional to the inverse of the minimum processing time will be 1 GHz for 10 ps or 100 MHz for a 100-ps laser coherence time. With this limitation, it seems that many incoherent optical structures may not operate as well as we expect. In other words, increasing the system accuracy from the intensity-addition point of view will decrease the maximum acceptable processing rate and vice versa. In many applications, 1 GHz or 100 MHz may be an acceptable processing rate, but take note that in some others, such as multiple-access networks depending on decoding structure, processing time may be equal to the chip time [8], [25], [26], and therefore, 1 GHz or 100 MHz may not be an acceptable range.

To gain more insight on the application of our results based on the structure introduced in Fig. 1, we discuss an important application, namely IM/DD-based optical code-division multiple-access (CDMA) system. Assume that we have a CDMA system using optical orthogonal codes (OOC) with characteristic (F, w, λ_{a}, λ_{c}), where F, w, λ_{a}, and λ_{c} are the code length, code weight, and maximum of auto- and cross-correlation values, respectively [25]. For such class of networks, their corresponding optical encoder/decoder can be designed based on all-optical processor TDL structure introduced in Fig. 1. For example, for all-optical decoder based on TDL structures, the delays are selected such that we have the maximum correlation value when matched with its corresponding OOC (see Fig. 5). Thus, the number of branches is equal to the code weight. Thus, after decoding by the desired decoder, we have the addition of w optical pulses at the correlation time from the corresponding desired user's OOC. Also, there may be other interfering undesired optical pulses added to the desired w optical pulses at the correlation time from other users. If we assume that the ith interfering user can interfere with w_i, $i \in \{2, 3, \ldots, N\}$ pulses of the desired OOC signal, then (9) corresponds to the detected light in the presence of interfering users with $w_i \leq \lambda_{\mathrm{c}}$, where λ_{c} is the maximum cross-correlation value between the OOCs. Thus, our analysis based on the model introduced in Fig. 1 can be easily applied to optical CDMA systems, and degradation due to the phase-induced intensity noise in such multiple-access systems can be analyzed using the mathematical models introduced in this paper. Note that depending on the receiver structure used for optical CDMA, the processing time can be equal to the chip time or bit time, and our models can be easily extended to these various cases [26].

Another important incoherent intensity-based system where phase-induced intensity noise is of concern is a simple ON–OFF keyed bit-rate limiter (BRL) for controlling the maximum allowable transmission rate of the users [13], [28]. In such cases, we can set the delays of the branches equal to the delays in BRL and use the results developed in this paper.

VIII. Coherent Versus Incoherent Systems

In previous sections, we obtained a self-SNR for random-phase processes based on Wiener–Levy for an arbitrary coherence time. As we deduce from (33) and (34), the ratio of the laser coherence time to the system processing time plays an important role in setting a basic condition on the accuracy of an incoherent digital optical system. This parameter, which we denote as β, is a well-known parameter in coherent optical communication systems [1]–[7]. The analysis on coherent optical communication systems shows that in order to obtain a good performance, β should be as high as possible. One intuitive reason for this result on such coherent optical systems can be described as follows: As the coherence time of the laser decreases, we need a larger filter bandwidth (or smaller integration time) to collect more power because of the spreading effect of the random-phase process in the power spectrum of the received signal. Note that in such systems, the desired term is the phase-induced intensity crossterm, and the incoherent term is the undesirable term. Hence, the methods for decreasing the effect of the random-phase process finally result in decreasing processing time that a typical coherent system receives. However, from (32), we observe that in an incoherent system, for ensuring the intensity addition for a specified laser coherence time, the processing time of the system should increase, which is exactly the opposite of coherent systems. Therefore, in an incoherent system that works with processing time $T_{\rm p}$, the coherence time of our laser $\tau_{\rm c}$ should be much smaller than $T_{\rm p}$. As β decreases, we will be more certain on the intensity addition at the photodetector's output. For an incoherent system, we want to have $\beta \ll 1$. In this case, the crossterm power to the incoherent power term, which is the desired term, will be approximately proportional to β. This implies that the processing time must be much larger than the coherence time of laser, for example, 100 times for $\mathrm{SNR}_{\rm self} \cong 20$ dB, where in coherent systems, we should choose β as high as possible (100 or more) [2], [7] to eliminate the random-phase effect at its receiver. This comparison shows that in coherent systems, we have no choice but to have a very high processing rate, which is proportional to the system data rate, but in incoherent systems based on the structure given in Fig. 1, we have no choice but to have a low processing rate that is also proportional to the data rate.

IX. Conclusion

In this paper, we discussed and analyzed conditions under which we can be certain on intensity addition of optical signals. We define a self-SNR function that in the special case of Wiener–Levy phase model can be easily calculated from (20)–(22). We showed that for fixed processing time, the coherence time of the laser must be much smaller, and for a fixed coherence time, the processing time of the system must be much larger. This implies that in systems that we are dealing only with intensities, the rate of processing cannot be larger from a preset value, which depends on the accuracy we require for the system. As the accuracy increases, the maximum achievable rate decreases in a reverse manner. For a desired accuracy, one can correspond it to the normalized laser coherence time in (35) and so calculate the maximum possible rate for the desired laser coherence time. This shows an important limiting factor in digital incoherent optical systems.

Appendix A

In this section, we derive the nth-order correlation function of optical signal and also relate this to the corresponding nth-order random-phase-process structure function. Prior to doing this, note that in general, the nth-order autocorrelation function of a random process is defined by time averaging, but in the case of an ergodic process, we can use ensemble averaging instead [18]–[20]. Thus, we first describe the autocorrelation function of an optical signal in the form of (A4), which is shown below, in terms of structure function. From the definition, we have

$$R_E(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n}) \triangleq E\left\{E(t_1)\times\cdots\times E(t_n)\times E^*(t_{n+1})\times\cdots\times E^*(t_{2n})\right\} \quad \text{(A1)}$$

substituting $E(t)$ from (3) into (A1), we have

$$R_E(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n}) \triangleq I_0^n E\left\{e^{j(\phi(t_1)+\cdots+\phi(t_n)-\phi(t_{n+1})-\cdots-\phi(t_{2n}))}\right\} \quad \text{(A2)}$$

and the random phase has a Gaussian density function with zero mean. Also, for such a random process, say $n(t)$, we can write

$$E\left\{e^{jn(t)}\right\} = \Phi_n(s=j) = e^{-\frac{\sigma_n^2}{2}} \quad \text{(A3)}$$

where from the definition, $\Phi_n(s)$ and σ_n correspond to the characteristic function and variance of our zero-mean Gaussian random process $n(t)$. Thus, we can write

$$\begin{aligned} R_E(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n}) &\triangleq I_0^n e^{\frac{-E\left\{(\phi(t_1)+\cdots+\phi(t_n)-\phi(t_{n+1})-\cdots-\phi(t_{2n}))^2\right\}}{2}} \\ &= I_0^n e^{-\frac{D_\phi(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n})}{2}} \end{aligned} \quad \text{(A4)}$$

so we proceed by calculating the structure function for any order of n. In this case, we have

$$\begin{aligned} D_\phi(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n}) &= E\left\{[\phi(t_1)+\cdots+\phi(t_n)-\phi(t_{n+1})-\cdots-\phi(t_{2n})]^2\right\} \\ &= \sum_{i=1}^{n} E\left\{[\phi(t_i)-\phi(t_{i+n})]^2\right\} \\ &\quad + 2\sum_{i_1=1}^{n-1}\sum_{i_2=i_1+1}^{n} E\left\{[\phi(t_{i_1})-\phi(t_{i_1+n})] \times [\phi(t_{i_2})-\phi(t_{i_2+n})]\right\} \end{aligned} \quad \text{(A5)}$$

but simply for any four time instants t_a, t_b, t_c, and t_d, we have the following equality:

$$2\left(\phi(t_a)-\phi(t_c)\right)\left(\phi(t_d)-\phi(t_b)\right)=\left(\phi(t_c)-\phi(t_d)\right)^2 +\left(\phi(t_a)-\phi(t_b)\right)^2-\left(\phi(t_a)-\phi(t_d)\right)^2-\left(\phi(t_c)-\phi(t_b)\right)^2 \quad \text{(A6)}$$

by substituting this into (A5) and letting $t_a = t_{i_1}$, $t_c = t_{i_1+n}$, $t_b = t_{i_2+n}$, and $t_d = t_{i_2}$, we have

$$\begin{aligned} D_\phi(t_1,\ldots,t_n,t_{n+1},\ldots,t_{2n}) &= \sum_{i=1}^{n} D_\phi(t_i,t_{i+n}) \\ &+ \sum_{i_1=1}^{n-1}\sum_{i_2=i_1+1}^{n}\left[D_\phi(t_{i_1},t_{i_2+n})+D_\phi(t_{i_1+n},t_{i_2})\right. \\ &\left. -D_\phi(t_{i_1},t_{i_2})-D_\phi(t_{i_1+n},t_{i_2+n})\right] \quad \text{(A7)} \end{aligned}$$

where by definition, we have

$$D_\phi\left(t_a,t_b\right)=E\left\{\left[\phi(t_a)-\phi(t_b)\right]^2\right\}. \quad \text{(A8)}$$

Depending on the laser type and the model used for random phase, the structure function can be different. In a special case, where the random phase is modeled with Wiener–Levy process [19], [24], it can be easily shown that with the increment independent characteristics of Wiener–Levy process, the structure function can be written as follows [18], [19]:

$$D_\phi(t_a,t_b)=2\frac{|t_a-t_b|}{\tau_{\mathrm{c}}}. \quad \text{(A9)}$$

In the special cases when $t_a = t+\tau$ and $t_b = t$, which correspond to $n = 2$, the second-order coherence function will be achieved. Also, note that the structure function also depends on the difference of sample times, therefore even for a nonstationary random phase as Wiener–Levy case, the autocorrelation is only a function of the correlation time τ.

APPENDIX B

In obtaining the autocorrelation function, we first arrange the total output terms. Hence, we have

$$\begin{aligned} i_{\mathrm{PD}}(t) &= \left|E_{\mathrm{out}}^{(1)}(t)+E_{\mathrm{out}}^{(2)}(t)+\cdots+E_{\mathrm{out}}^{(N)}\right|^2 \\ &= \sum_{i=1}^{N}\left|E_{\mathrm{out}}^{(i)}\right|^2+2\sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\mathrm{Real}\left\{E_{\mathrm{out}}^{(i_1)}E_{\mathrm{out}}^{*(i_2)}\right\}. \end{aligned} \quad \text{(B1)}$$

By substituting (3), (5), and (8) into (B1) and rearranging the terms, we can write the crossterm as the summation of two terms, namely $\mathrm{CT}(t) = C_1(t) + C_2(t)$, so that we have

$$\begin{aligned} C_1(t) &= 2\sum_{i=1}^{N}\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i}\sqrt{I_{j_1}^{(i)}I_{j_2}^{(i)}} \\ &\times\cos\left(\omega_0\left(\tau_{j_2}^{(i)}-\tau_{j_1}^{(i)}\right)\right. \\ &\left.+\phi_i\left(t-\tau_{j_1}^{(i)}\right)-\phi_i\left(t-\tau_{j_2}^{(i)}\right)\right) \end{aligned} \quad \text{(B2)}$$

$$\begin{aligned} C_2(t) &= 2\sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\sum_{j_1=1}^{w_{i_1}}\sum_{j_2=1}^{w_{i_2}}\sqrt{I_{j_1}^{(i_1)}I_{j_2}^{(i_2)}} \\ &\times\cos\left(\omega_0\left(\tau_{j_2}^{(i_2)}-\tau_{j_1}^{(i_1)}\right)+\phi_{i_1}\left(t-\tau_{j_1}^{(i_1)}\right)\right. \\ &\left.-\phi_{i_2}\left(t-\tau_{j_2}^{(i_2)}\right)+\theta_{i_1}-\theta_{i_2}\right). \end{aligned} \quad \text{(B3)}$$

In confirming (11), we should note that each term in $C_1(t)$does not have any random phase with uniform distribution, but each term in $C_2(t)$ has two random phases with uniform distribution. Thus, the expectation of the cross product of these two terms will be zero. This means that for the autocorrelation of the noisy term, we should only calculate the autocorrelation of each terms separately. By using the autocorrelation function definition, we have

$$\begin{aligned} R_{C_1}(\tau) &= 4\sum_{i_1=1}^{N}\sum_{i_2=1}^{N}\sum_{j_1=1}^{w_{i_1}-1}\sum_{j_3=1}^{w_{i_2}-1}\sum_{j_2=j_1+1}^{w_{i_1}}\sum_{j_4=j_3+1}^{w_{i_2}}\sqrt{I_{j_1}^{(i_1)}I_{j_2}^{(i_1)}I_{j_3}^{(i_2)}I_{j_4}^{(i_2)}} \\ &\times E\left\{\cos\left(\omega_0\left(\tau_{j_2}^{(i_1)}-\tau_{j_1}^{(i_1)}\right)+\phi_{i_1}\left(t+\tau-\tau_{j_1}^{(i_1)}\right)\right.\right. \\ &\left.-\phi_{i_1}\left(t+\tau-\tau_{j_2}^{(i_1)}\right)\right) \\ &\times\cos\left(\omega_0\left(\tau_{j_4}^{(i_2)}-\tau_{j_3}^{(i_2)}\right)+\phi_{i_2}\left(t-\tau_{j_3}^{(i_2)}\right)\right. \\ &\left.\left.-\phi_{i_2}\left(t-\tau_{j_4}^{(i_2)}\right)\right)\right\}. \end{aligned} \quad \text{(B4)}$$

Therefore, in (B4), we should obtain the expectation in the summation. This expectation also can be easily calculated using the Gaussian properties of random phases. As in Appendix A, for a constant number χ_0 and zero mean Gaussian random process χ, we can write

$$E\left\{\cos(\chi+\chi_0)\right\}=\cos(\chi_0)e^{\frac{-\sigma_\chi^2}{2}}. \quad \text{(B5)}$$

With this equality similar to Appendix A, the desired expectation, say X_1, can be written as follows:

$$\begin{aligned} X_1 &= \frac{1}{2}\cos\left(\omega_0\left(\tau_{j_1}^{(i_1)}+\tau_{j_3}^{(i_2)}-\tau_{j_2}^{(i_1)}-\tau_{j_4}^{(i_2)}\right)\right)e^{-\frac{\sigma_1^2}{2}} \\ &+\frac{1}{2}\cos\left(\omega_0\left(\tau_{j_1}^{(i_1)}+\tau_{j_4}^{(i_2)}-\tau_{j_2}^{(i_1)}-\tau_{j_3}^{(i_2)}\right)\right)e^{-\frac{\sigma_2^2}{2}} \end{aligned} \quad \text{(B6)}$$

where by definition

$$\sigma_1^2 \triangleq E\left\{\left[\phi_{i_1}\left(t+\tau-\tau_{j_1}^{(i_1)}\right)+\phi_{i_2}\left(t-\tau_{j_3}^{(i_2)}\right)\right.\right.$$
$$\left.\left.-\phi_{i_1}\left(t+\tau-\tau_{j_4}^{(i_1)}\right)-\phi_{i_2}\left(t-\tau_{j_4}^{(i_2)}\right)\right]^2\right\} \qquad \text{(B7a)}$$

$$\sigma_2^2 \triangleq E\left\{\left[\phi_{i_1}\left(t+\tau-\tau_{j_1}^{(i_1)}\right)+\phi_{i_2}\left(t-\tau_{j_4}^{(i_2)}\right)\right.\right.$$
$$\left.\left.-\phi_{i_1}\left(t+\tau-\tau_{j_2}^{(i_1)}\right)-\phi_{i_2}\left(t-\tau_{j_3}^{(i_2)}\right)\right]^2\right\}. \qquad \text{(B7b)}$$

However, $\sigma_1^2$and σ_2^2 can be easily related to the structure functions as calculated in Appendix A; therefore, we will have (B8a) and (B8b), shown at the bottom of the page.

Note that the two random phases $\phi_{i_1}(\cdot)$ and $\phi_{i_2}(\cdot)$ are independent for $i_1 \neq i_2$. In a similar way, for the second term $R_{C_2}(\tau)$, we need to evaluate the following expectation:

$$X_2 \triangleq \frac{1}{2}\cos\left(\omega_0\left(\tau_{j_1}^{(i_1)}-\tau_{j_3}^{(i_2)}+\tau_{j_4}^{(i_3)}-\tau_{j_3}^{(i_4)}\right)\right)$$
$$\times e^{-\frac{\sigma_3^2}{2}}\delta(i_1-i_2)\delta(i_3-i_4) \qquad \text{(B9)}$$

where by definition, we have

$$\sigma_3^2 \triangleq E\left\{\left[\phi_{i_1}\left(t+\tau-\tau_{j_1}^{(i_1)}\right)+\phi_{i_2}\left(t-\tau_{j_4}^{(i_2)}\right)\right.\right.$$
$$\left.\left.-\phi_{i_3}\left(t+\tau-\tau_{j_3}^{(i_{31})}\right)-\phi_{i_4}\left(t-\tau_{j_4}^{(i_4)}\right)\right]^2\right\}$$
$$= D_{\phi_{i_1}}\left(t+\tau-\tau_{j_1}^{(i_1)}, t-\tau_{j_3}^{(i_1)}\right)$$
$$+ D_{\phi_{i_3}}\left(t+\tau-\tau_{j_2}^{(i_2)}, t-\tau_{j_4}^{(i_2)}\right) \qquad \text{(B10)}$$

and

$$\delta(i-j) = \begin{cases} 1, & i=j \\ 0, & \text{o.w.} \end{cases} \qquad \text{(B11)}$$

Appendix C

In this section, we discuss the mechanism by which we time average (11) and (12) in order to obtain (16) and (17). It is important to note that by reducing our expressions from (11) and (12) to (16) and (17), it allows us to carry out and follow our discussions in an analytical form rather than numerical form. As we stated before, due to the variation in the delays in TDLs τ_i^j and also due to a large value of optical frequency ω_0, the terms including cosines will oscillate even for small variation of delays. Therefore, a small percent in picosecond variation in the delays will result in approximately 2π radian swing, i.e., we have $\omega_0\Delta\tau_i^j \sim 2\pi$, while this change in the time delays has approximately no effect on the value of the exponential terms, which include the characteristic function in (11) and (12), and especially, the characteristic functions. This means that the result of the time-averaged autocorrelation function exists only for terms of summations in (11) and (12) that their corresponding variations cancel one another. This condition only occurs for each cosine term when its argument is equal to zero, i.e., the argument without considering the variation in the delays be equal to zero. In this condition, the cosine term will be equal to "one," and the delays are such that their corresponding variations cancel each other. Thus, for the time-averaged case, we only need to find conditions in which the cosine terms are independent from the variations. For $R_{C_1}(\tau)$, we first set all the cosine terms equal to "one," which is a constant value, and then test if there could be conditions under which it could exist. Then, we set the condition in the corresponding correlation function and try to further simplify it. For $R_{C_1}(\tau)$, we have (C1), shown at the bottom of the page.

As we observe for $R_{C_1}(\tau)$, there is only one possible situation for the cosine terms to be equal to "one." This situation occurs only when we have $j_1 = j_3$ and $j_2 = j_4$. In (C1), note that the index j_2 starts from $j_1 + 1$ and also j_4 from $j_3 + 1$. This implies that we never have $\tau_{j_1}^{(i)} + \tau_{j_3}^{(i)} - \tau_{j_2}^{(i)} - \tau_{j_4}^{(i)} = 0$

$$\sigma_1^2 = \begin{cases} D_{\phi_{i_1}}\left(t+\tau-\tau_{j_1}^{(i_1)}, t-\tau_{j_3}^{(i_2)}, t+\tau-\tau_{j_2}^{(i_1)}, t-\tau_{j_4}^{(i_2)}\right), & i_1 = i_2 \\ D_{\phi_{i_1}}\left(t+\tau-\tau_{j_1}^{(i_1)}, t+\tau-\tau_{j_2}^{(i_1)}\right)+D_{\phi_{i_2}}\left(t-\tau_{j_3}^{(i_2)}, t-\tau_{j_4}^{(i_2)}\right), & \text{o.w.} \end{cases} \qquad \text{(B8a)}$$

$$\sigma_2^2 = \begin{cases} D_{\phi_{i_1}}\left(t+\tau-\tau_{j_1}^{(i_1)}, t-\tau_{j_4}^{(i_2)} t+\tau-\tau_{j_2}^{(i_1)}, t-\tau_{j_3}^{(i_2)}\right), & i_1 = i_2 \\ D_{\phi_{i_1}}\left(t+\tau-\tau_{j_1}^{(i_1)}, t+\tau-\tau_{j_2}^{(i_1)}\right)+D_{\phi_{i_2}}\left(t-\tau_{j_3}^{(i_2)}, t-\tau_{j_4}^{(i_2)}\right), & \text{o.w.} \end{cases} \qquad \text{(B8b)}$$

$$\text{for } C_1 \begin{cases} \cos\left(\omega_0\left(\tau_{j_1}^{(i)}+\tau_{j_3}^{(i)}-\tau_{j_2}^{(i)}-\tau_{j_4}^{(i)}\right)\right) = \text{cte} \Rightarrow \text{impossible} \\ \cos\left(\omega_0\left(\tau_{j_1}^{(i)}+\tau_{j_4}^{(i)}-\tau_{j_2}^{(i)}-\tau_{j_3}^{(i)}\right)\right) = \text{cte} \overset{\text{iff}}{\Leftrightarrow} j_1 = j_3, j_2 = j_4 \\ \cos\left(\omega_0\left(\tau_{j_1}^{(i_1)}-\tau_{j_2}^{(i_1)}\right)\right)\cos\left(\omega_0\left(\tau_{j_3}^{(i_2)}-\tau_{j_4}^{(i_2)}\right)\right) = \text{cte} \Rightarrow \text{impossible.} \end{cases} \qquad \text{(C1)}$$

as well as $\tau_{j_1}^{(i_1)} - \tau_{j_2}^{(i_1)} = 0$ and $\tau_{j_2}^{(i_2)} - \tau_{j_4}^{(i_2)} = 0$. Similarly, for $R_{C_2}(\tau)$, we can write

$$\text{for C}_2 \begin{cases} \cos\left(\omega_0\left(\tau_{j_1}^{(i_1)} - \tau_{j_3}^{(i_1)} + \tau_{j_2}^{(i_2)} - \tau_{j_4}^{(i_2)}\right)\right) \\ = \text{cte} \overset{\text{iff}}{\Leftrightarrow} j_1 = j_3, \quad j_2 = j_4. \end{cases} \tag{C2}$$

By inserting these limitations in the general formulas in (11) and (12), the simplified time-averaged autocorrelation functions (16) and (17) are obtained.

APPENDIX D

By neglecting the shot-noise effect, the incoherent term of (9) is deterministic. Thus, its autocorrelation function will be constant. This implies that we have

$$R_I(\tau) = \left[\sum_{i=1}^{N}\sum_{j=1}^{w_i} I_j^{(i)}\right]^2 \tag{D1}$$

with a power spectrum defined as

$$S_I(f) = \left[\sum_{i=1}^{N}\sum_{j=1}^{w_i} I_j^{(i)}\right]^2 \delta(f). \tag{D2}$$

Therefore, the power of the filtered-term signal is

$$P_I = \int_{-\infty}^{\infty} S_I(f)\,|H_F(f)|^2\,df. \tag{D3}$$

For the special case of integration and dump filter with integration time equal to T_p, we have

$$|H_F(f)|^2 = T_\text{p}^2\left(\frac{\sin(\pi f T_\text{p})}{\pi f T_\text{p}}\right)^2. \tag{D4}$$

Hence

$$P_I = \left[T_\text{p}\sum_{i=1}^{N}\sum_{j=1}^{w_i} I_j^{(i)}\right]^2. \tag{D5}$$

For the phase-induced intensity-noise term, we first evaluate two important integrals, namely

$$I_1 \triangleq \int_{-T_\text{p}}^{T_\text{p}} T_\text{p}\left(1 - \frac{|\tau|}{T_\text{p}}\right) e^{-2\frac{|\tau|}{\tau_\text{c}}}\,d\tau \tag{D6a}$$

$$I_2 \triangleq \int_{-T_\text{p}}^{T_\text{p}} T_\text{p}\left(1 - \frac{|\tau|}{T_\text{p}}\right) e^{-\frac{\left(2|\tau| - \left|\tau - \tau_{j_1,j_2}^{(i)}\right| - \left|\tau + \tau_{j_1,j_2}^{(i)}\right|\right)}{\tau_\text{c}}}\,d\tau$$

$$\text{where} \quad \tau_{j_1,j_2}^{(i)} \triangleq \left|\tau_{j_1}^{(i)} - \tau_{j_2}^{(i)}\right|. \tag{D6b}$$

The first integral I_1 can be easily evaluated by integration by part, and the second integration I_2 can be evaluated using the first integral I_1, so we have (D7a) and (D7b), shown at the bottom of the page.

Using these integrals and substituting in the averaged autocorrelation function, (25) and (26) can be obtained.

APPENDIX E

In this section, we obtain the power spectrum of autocorrelation functions in (16) and (17). By using Wiener–Khinchin theorem for stochastic random process, the power spectrum is the Fourier transform of its autocorrelation function. However, the overall power spectrum of the noisy term is very difficult, but in the case of time averaged, it can be derived easily by its definition. To do this, we only need to evaluate two simple Fourier transforms as follows:

$$F_1(f) \triangleq \Im\left\{e^{-2\frac{|\tau|}{\tau_\text{c}}}\right\} = \frac{\tau_\text{c}}{1 + (\pi\tau_\text{c} f)^2} \tag{E1}$$

$$\begin{aligned} F_2(f) &\triangleq \Im\left\{e^{-\frac{1}{\tau_\text{c}}\left(2|\tau| - \left|\tau - \tau_{j_1,j_2}^{(i)}\right| - \left|\tau + \tau_{j_1,j_2}^{(i)}\right|\right)}\right\} \\ &= \frac{\tau_\text{c}}{1 + (\pi\tau_\text{c} f)^2}\left\{e^{2\frac{\tau_{j_1 j_2}^{(i)}}{\tau_\text{c}}} - \cos\left(2\pi f \tau_{j_1,j_2}^{(i)}\right) + \pi\tau_\text{c} f \sin\left(2\pi f \tau_{j_1,j_2}^{(i)}\right)\right\} \\ &\quad - 2\tau_{j_1,j_2}^{(i)} \sin c\left(2\tau_{j_1,j_2}^{(i)} f\right) \end{aligned} \tag{E2}$$

where from definition, we have $\text{sinc}(x) \triangleq \sin(\pi x)/\pi x$. Thus, the power spectrum of the noisy term can be easily obtained using the above equations, so we have

$$S_\text{CT}(f) = S_{C_1}(f) + S_{C_2}(f) \tag{E3}$$

$$I_1 = T_\text{p}\tau_\text{c}\left(1 - \frac{\tau_\text{c}}{2T_\text{p}}\left(1 - e^{-2\frac{T_\text{p}}{\tau_\text{c}}}\right)\right) \tag{D7a}$$

$$I_2 = \begin{cases} e^{-2\frac{\tau_{j_1,j_2}^{(i)}}{\tau_\text{c}}} I_1, & \tau_{j_1,j_2}^{(i)} \geq T_\text{p} \\ 2T_\text{p} e^{2\frac{\tau_{j_1,j_2}^{(i)}}{\tau_\text{c}}} \int_0^{\tau_{j_1,j_2}^{(i)}} \left(1 - \frac{\tau}{T_\text{p}}\right) e^{-\frac{2}{\beta}}\,d\tau + 2T_\text{p}\int_{\tau_{j_1,j_2}^{(i)}}^{T_\text{p}} \left(1 - \frac{\tau}{T_\text{p}}\right) d\tau, & \text{o.w.} \end{cases} \tag{D7b}$$

where $S(\cdot)$ is used for power spectrum, and using (E1) and (E2) in conjunction with (16) and (17), we can write

$$S_{C_1}(f) = 2\sum_{i_1=1}^{N-1}\sum_{i_2=i_1+1}^{N}\sum_{j_1=1}^{w_{i_1}}\sum_{j_2=1}^{w_{i_2}} I_{j_1}^{(i_1)} I_{j_2}^{(i_2)} F_1(f) \tag{E4}$$

and

$$S_{C_2}(f) = 2\sum_{i=1}^{N}\sum_{j_1=1}^{w_i-1}\sum_{j_2=j_1+1}^{w_i} I_{j_1}^{(i)} I_{j_2}^{(i)} e^{-2\frac{\tau_{j_1,j_2}^{(i)}}{\tau_c}} F_2(f). \tag{E5}$$

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