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Transfer Function Equalization Enhanced Phase Noise in Generalized Carrier Assisted Differential Detection Receivers

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Abstract *We analyze the equalization enhanced phase noise (EEPN) in carrier-assisted differential detection (CADD) and its dependence on the receiver transfer function. For CADD, by using optical filters instead of a pure optical delay, the EEFN effect could be greatly alleviated when using the transmitter lasers with a large linewidth. ©2022 The Author(s)*

Introduction

There has been much interest in advanced direct detection (DD) capable of optical field recovery analogous to coherent detection from both academia and industry. In conjunction with the well-developed digital signal processing (DSP), the advanced DD could offer unprecedented performance in receiver sensitivity, channel impairment resilience, and spectral efficiency compared with conventional IM/DD systems. Despite the powerful DSP for high receiver performance, the DSP-based receivers possess their own issues. In coherent detection, the presence of the local oscillator (LO) phase noise prior to the DSP-enabled chromatic dispersion (CD) compensation impedes the perfect equalization of the accumulated CD, which results in additional noise referred to as equalization enhanced phase noise (EEPN) [1]. The EEPN impairment is analytically found to scale with the laser linewidth, CD as well as signal baud rate in coherent detection. Moreover, the EEPN could not be mitigated with any linear filter since it has almost an identical spectrum as the transmitted signal [2]. Consequently, the EEPN impairment imposes another constraint on the laser linewidth for LO in coherent transmission systems. In DD systems, the tight requirements on the wavelength stability and laser linewidth are greatly relaxed due to the essential self-homodyne detection. In consequence, un-cooled laser sources with large linewidths, such as distributed feedback (DFB) lasers, could be employed for DD. However, in the advanced DD systems, like Kramers-Kronig receiver (KKR) [3] and Stokes vector receiver (SVR) [4], the self-coherent optical carrier propagating along with the signal is normally needed to linearize the optical channel. Due to the accumulated CD-induced walk-off, the phase noise of the optical carrier and information-

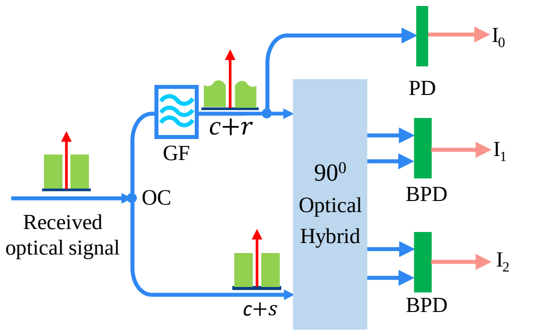

Fig. 1: Generalized CADD receiver structure. GF: generalized optical filter. OC: optical coupler. PD: photodetector.

bearing signal has discrepancies. As a result, the residual phase noise arises from the signal-carrier beating during photodetection and is further aggravated by the DSP-enabled channel equalization. Therefore, it is imperative to investigate the laser linewidth tolerance of advanced DD schemes and give some guidance on the selection of laser sources for DD-based short-reach optical networks. The EEPN impact on the performance of KKR and SVR has been researched [5-6]. Recently, to bridge the gap between coherent detection and DD, CADD [7-8] has been proposed to retrieve the complex-valued double sideband (DSB) signal as shown in Fig. 1. Except for the accumulated CD compensation, CADD needs to equalize the receiver transfer function, which is distinguished from KKR and SVR. Therefore, the residual phase noise could be further enhanced by the transfer function equalization in CADD receivers. In this paper, we analyze the transfer function equalization enhanced phase noise (TF-EEPN) in both the delay-based and micro-ring resonators (MRR)-based CADD receivers and numerically investigate its impact on a 60-Gbaud 16-QAM OFDM signal with respect to the laser linewidth, transmission reach, baud rate, and different bandwidth optical filters.

Transfer function equalization enhanced phase noise in CADD receiver

Fig. 1 presents the receiver structure of the generalized CADD. For simplicity, we assume that the self-coherent carrier c and complex-valued DSB signal s have the same phase noise. Therefore, the transmitted signal is denoted as $(c+s)e^{j\varphi(t)}$, where $\varphi(t)$ is the laser phase noise characterized by the laser linewidth β. After the fiber transmission, neglecting the fiber loss and nonlinearity, the received optical signal of the CADD receiver is $(c+s)e^{j\varphi(t)} \otimes h(t)$, where $\otimes$ stands for convolution operation and *h(t)* is the impulse response of the accumulated CD. Ignoring some trivial constants, the captured waveforms via the three photodetectors in the generalized CADD receiver are given by

$$I_0 = \left|(c+s)e^{j\varphi(t)} \otimes h(t) \otimes G(t)\right|^2 \qquad (1)$$

$$I_1 + jI_2 = \left[(c+s)e^{j\varphi(t)} \otimes h(t)\right] \cdot \left[(c+s)e^{j\varphi(t)} \otimes h(t) \otimes G(t)\right]^* \qquad (2)$$

where $G(t)$ is the time-domain impulse response of the generalized filter (GF). Digitally combining Eq. (1) and Eq. (2), a complex-valued DSB signal *R* can be reconstructed as

$$R = (I_1 + jI_2) - I_0 = \left[se^{j\varphi(t)} \otimes h(t) - se^{j\varphi(t)} \otimes h(t) \otimes G(t)\right] \cdot \left[ce^{j\varphi(t)} \otimes h(t)\right] + SSBI \qquad (3)$$

$$SSBI = \left[se^{j\varphi(t)} \otimes h(t) \otimes G(t)\right]^* \cdot \left[se^{j\varphi(t)} \otimes h(t) - se^{j\varphi(t)} \otimes h(t) \otimes G(t)\right] \qquad (4)$$

It is noted that $ce^{j\varphi(t)} \otimes h(t) \otimes G(t)$ is approximated as $ce^{j\varphi(t)} \otimes h(t)$ due to the relatively smaller linewidth of lasers when deriving the Eq. (3). It is known that the accumulated CD could convert the phase noise to amplitude (P2A) noise $n(t)$ [9-10] as

$$ce^{j\varphi(t)} \otimes h(t) = [c + n(t)]e^{j\varphi(t)} \qquad (5)$$

where the P2A $n(t)$ is normally small and neglected in both the following derivation and numerical study. For explanation simplicity, we assume the signal-to-signal beating interference (SSBI) could be mitigated by SSBI, and the constant carrier amplitude c could be estimated and eliminated. To retrieve the transmitted DSB signal, the equalized DSB signal is given by

$$s^{eq}(t) = s(t)e^{j\varphi(t)} \otimes [h(t) - h(t) \otimes G(t)]e^{-j\varphi(t)} \otimes [h(t) - h(t) \otimes G(t)]^{-1} \qquad (6)$$

Therefore, the transfer function for the CADD receiver is $T(t) = h(t) - h(t) \otimes G(t)$. The phase noise average of a short block of signal-carrier signals or an OFDM symbol can be represented as φ_0. Hence, Eq. (6) could be rewritten as

$$s^{eq}(t) = s(t)e^{j\Delta\varphi} \otimes T(t)e^{-j\Delta\varphi} \otimes T^{-1}(t) \qquad (7)$$

where $\Delta\varphi = \varphi(t) - \varphi_0$ represents the residual phase noise. As such, there is no need for phase noise compensation in the evaluation. Taking Taylor expansion in $\Delta\varphi$ for Eq. (7), we have

$$s^{eq}(t) = s(t)e^{j\Delta\varphi} - js(t)e^{j\Delta\varphi} \otimes T(t)\Delta\varphi(t) \otimes T^{-1}(t) \qquad (8)$$

The first term is the desired linear signal, which includes the residual phase noise. This residual phase noise for OFDM demodulation could generate intercarrier interference. The second term in Eq. (8) is the TF-EEPN due to the non-exchangeable multiplication and convolution operations. We find that the EEPN in CADD could be further aggravated compared to the coherent detection. However, it is difficult to quantitatively analyze the TF-EEPN like the EEPN in the coherent detection-based transmission systems. Considering the limitation of the experimental characterization requiring various lasers, the numerical analysis is performed to investigate the TF-EEPN impact on both the pure optical delay and optical filter-based CADD receivers.

Results and discussion

To study the TF-EEPN in CADD receivers, a numerical analysis is conducted for both delay-based and optical filter-based CADD receivers. With an 80-GSa/s sampling rate, a 60-Gbaud 16-QAM signal is employed for the performance evaluation of the CADD receivers, which achieves a 240-Gb/s raw source rate. The transmitted signals are formatted in OFDM with a 4096-point DFT, in which 3072 subcarriers are filled with 16-QAM symbols. As the SSBI concentrates in the low-frequency region and the transfer function *T(t)* has a null at the DC component, a 5-GHz guard band is deployed in the middle of the DSB signal spectrum, which represents only 8.3% spectrum redundancy. For the optical filter-based CADD receiver, the MRRs with different bandwidths are deployed. The characteristic and digital estimation methods of these optical filters can be found in [8]. For the delay-based CADD receiver, a 27-ps pure optical delay is employed. The SBBI iterative mitigation algorithm is based on the symbol decision [11]. The OSNR penalty from the TF-EEPN in the CADD receiver is illustrated in Fig .2. The OSNR penalty is measured by using a 1.5×10^{-2} binary hard-decision FEC (HD-FEC) threshold. To signify the TF-EEPN effects in the CADD receiver, the EEPN in coherent detection systems is also presented in Fig. 2 for comparison by assuming the same phase noise for both the transmitter laser and LO. To investigate the TF-EEPN induced OSNR penalty in CADD-based transmission systems, we select the typical parameters such as linewidth, transmission distance, and baud rate for performance evaluation. In Fig. 2(a), the linewidth tolerance of

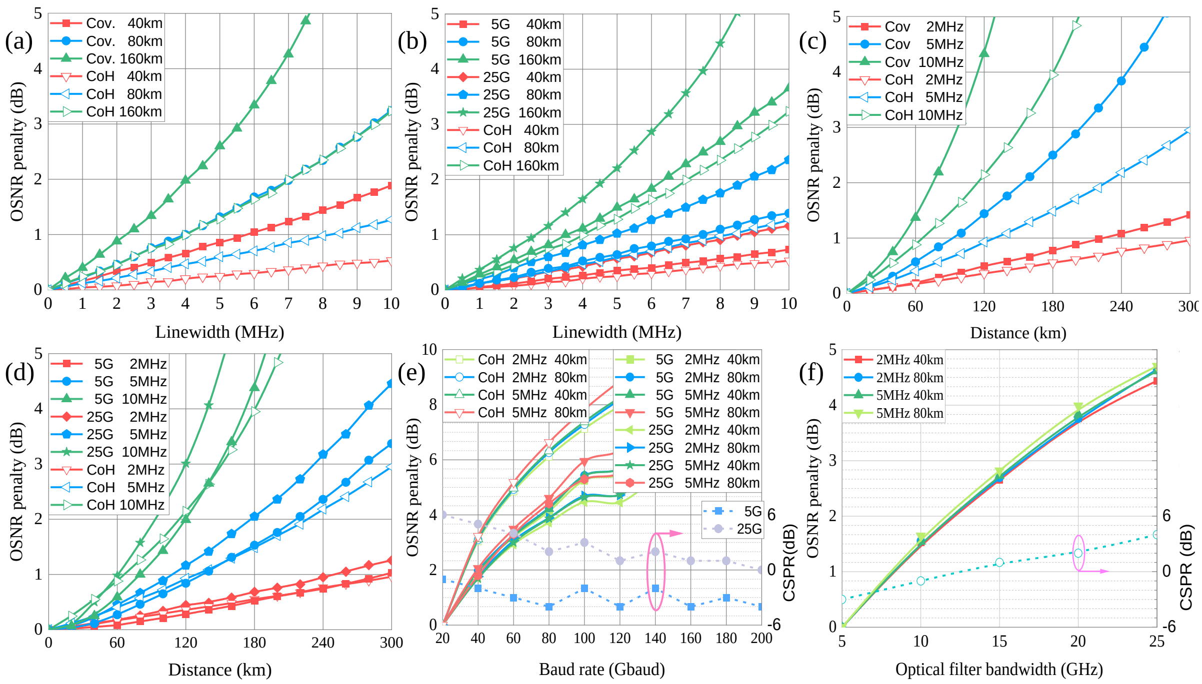

Fig. 2: OSNR penalty as a function of the linewidth (a, b) and transmission distance (c, d) for delay- and MRR-based CADD receivers, respectively. OSNR penalty and the required CSPR as a function of the baud rate (e) and MRR bandwidth (f) for MRR-based CADD receiver. CoH: coherent detection. Cov: conventional pure optical delay-based CADD.

the delay-based CADD receiver is 6 MHz to be below the 1-dB OSNR penalty under 40-km transmission while it is reduced to 2 MHz for 160-km transmission. However, in Fig. 2(b), the linewidth tolerance of the MRR-based CADD receivers is more than 10 MHz for using 5-GHz MRR and 40-km optical fiber while it is decreased to 8.5 MHz for using 25-GHz MRR. When the transmission distance is 160 km, the linewidth tolerance for using 5- and 25-GHz MRR is 3.5 and 2.5 MHz, respectively. In Fig. 2(c), the transmission reach for the delay-based CADD receiver using 2-MHz linewidth lasers can be up to 220 km but it is shrunk to 50 km for using a 10-MHz linewidth laser. In Fig. 2(d), the transmission reach for the CADD receiver using 5-GHz MRR and 2-MHz linewidth lasers can be up to 300 km while it is decreased to 80 km for using 10-MHz linewidth lasers. Nevertheless, when using 25-GHz MRR and 10-MHz linewidth lasers, the allowable transmission reach is decreased to 60 km. Therefore, as presented in Figs. 2(a-d), the TF-EEPN induced OSNR penalty is more severe than the coherent systems and increases quadratically with the linewidth and transmission distance while the EEPN in coherent systems scales linearly. Compared with the delay-based CADD receiver, the TF-EEPN induced OSNR penalty is greatly alleviated by using the narrow-bandwidth MRR for the CADD receiver because the delay-based CADD receiver has a stronger SSBI and the SSBI in MRR-based CADD is greatly reduced by using narrow-bandwidth optical filters. To further investigate the TF-EEPN under different baud rates, we only perform the analysis for the MRR-based CADD since the baud rate for the delay-based CADD is mainly determined by its periodical transfer function [1]. In Fig. 2(e), the TF-EEPN resulted OSNR penalty for using MRR is a non-convex function of baud rate. When increasing the baud rate, the OSNR penalty in coherent detection systems increases faster than the MRR-based CADD receiver, which could be attributed to the reduced CSPR requirements for high baud rate and the deployed guard band for CADD receivers. In Fig. 2(f), the OSNR penalty of using 5-GHz MRR is used as the benchmark and the TF-EEPN resulted OSNR penalty is a quasi-linear function of the optical bandwidth of the used MRR for CADD receivers. All these results manifest that the narrower-bandwidth MRR is more preferred for CADD receivers to restrict the EEPN impacts.

Conclusions

In this paper, we investigate the TF-EEPN in the CADD receivers and quantify its OSNR penalty with respect to the laser linewidth, transmission distance, baud rate, and different-bandwidth optical filters. When using the large-linewidth lasers for CADD systems, the TF-EEPN induced OSNR penalty is more severe than the coherent systems. Compared with the delay-based approach, the TF-EEPN could be greatly alleviated in the CADD receivers using narrow-bandwidth optical filters. The numerical results in this paper could provide some guidance on the parameter selection for CADD systems.

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