Digital Vibration Detection and Localization using Carrier Laser Phase Noise Retrieval in a Conventional Coherent Transponder

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Abstract: We demonstrate digitally recovered carrier laser phase noise corrupted by vibration induced phase perturbations on signaling data without introducing ultranarrow linewidth lasers. We show >10 dB improvements in vibro-perturbation SNR versus bandpass filtering methods. © 2024

1. Introduction

Presently equipment manufacturers and network operators want to both *transmit data* and *sense perturbations* generated on optical transmission systems carrying live traffic. Sensing enhances transmission system functionality (e.g., detecting road traffic) and security (e.g., tampering events) [1]. Fig. 1 illustrates the architecture of a conventional bidirectional coherent optical fiber transmission system. When a point source vibration event occurs, a vibro-acoustic perturbation induces a phase change, via the elasto-optical effect, in the existing propagating optical waveform [2]. This phase perturbation propagates bidirectionally, where z_E (τ_e) and z_W (τ_w) corresponds to the distance (time) the perturbation travels in the East (E) and West (W) directions, respectively. The phase change can be detected via interrogating the consequential phase record introduced onto the pre-existing phase and amplitude changes intrinsic to the propagating optical signaling pulses (illustration shown in Fig. 2).

Because a coherent modem recovers the full electric field of both the perturbation and the optical signaling pulse, a complete phase record can, in principle, be extracted and subsequently used to determine in real time the location of the disturbance. Recently, field trials of vibration detection and localization using modems without resorting to dedicated sensing channels were reported [1,3]. Using a bidirectional transmission scheme and a small DSP overhead, the localization of different events was successfully carried out without reducing data transmission performance. Unfortunately, two narrow-linewidth fiber lasers, which are incompatible with commercial equipment, were employed to reduce the impact of the laser phase noise (PN). A similar field trial of simultaneous communication and vibration sensing was reported wherein the authors used pilot tones co-propagating with the data, and a dedicated counterpropagating continuous wave (CW) signal [4]. Again, narrow-linewidth lasers were employed. Distributed Acoustic Sensing (DAS) is another alternative and widely investigated technique [5]. However, the Rayleigh backscattering this technique relies on is weak and limits its sensing distance to only a few spans [6]. This can potentially lead to expensive replacement of current amplifiers, and requiring dedicated equipment for processing, and allocating spectral resources (e.g., dedicated WDM channels) to sensing probes.

Using a modified dual-polarization I/Q modulator (DP-IQM) architecture, conventional commercially deployed carrier/ Local Oscillator (LO) lasers, and the resulting mathematically derived digital phase change estimates, we present carrier laser phase noise sensitivities exceeding previous reports. Per Fig. 1, the West-East (W-E) and East-West (E-W) transceivers are built using one laser each, functioning as both the carrier and the LO. Focusing on the DP transmitters, the core innovation is the insertion of a known time delay, $\Delta\tau$, on the Y-pol path within both W-E and E-W DP-IQMs. Given a known value of $\Delta\tau$, reconstruction of both the W-E and E-W transmit laser phase noise in the presence of acoustic perturbations is achieved using DSP techniques described below. Specially, for perturbations with bounded frequency components between 10 kHz and 30 kHz and using carrier and LO lasers with 100 kHz or 300 kHz for chromatic dispersion of 1.7 ns/nm or 102 ns/nm, respectively, we demonstrate perturbation signature SNR improvements of 10dB, within the perturbation bandwidth, versus using only bandpass filtering [3].

2. Theoretical analysis

Fig. 1 describes a bidirectional coherent optical fiber transmission system architecture, including our transmitter innovation. First, the W/E laser outputs are divided such that each laser can act as both the carrier (outbound traffic), and L O (in-bound traffic). For the carrier laser path, the power is next split into X-pol and Y-pol branches and then fed into a DP-IQM). A known time delay, $\Delta\tau$, is inserted on the Y-pol path on both the W-E and E-W DP-IQMs. Finally, IQ modulation is applied on both the X-pol and the Y-Pol, followed by combing, and transmitting.

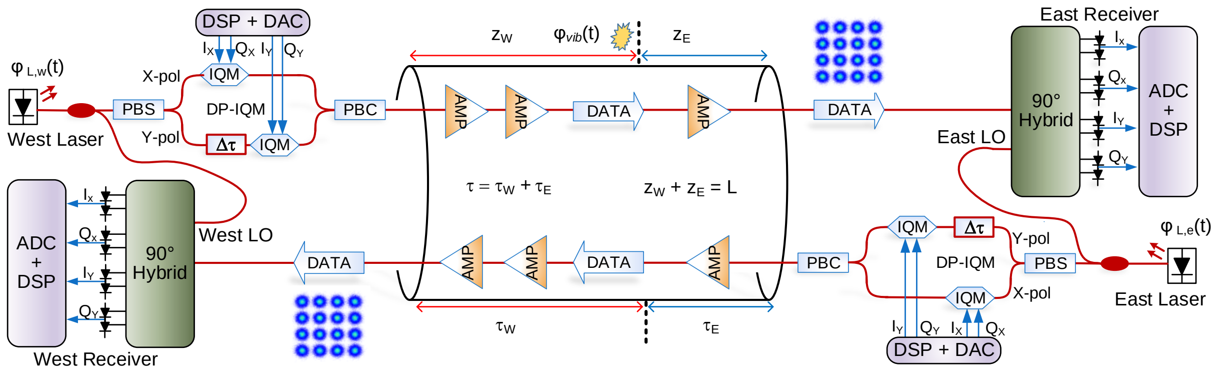

Fig. 1. Schematic of the proposed method with an additional time delay $\Delta\tau$ in the DP-IQM.

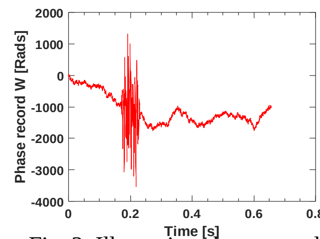

Fig. 2: Illustrative phase record induced by fiber perturbation.

Assume $E_w(t) = A_w e^{j(\omega_w t + \varphi_{L,w}(t))}$ and $E_e(t) = A_e e^{j(\omega_e t + \varphi_{L,e}(t))}$ are the electrical fields of the W and E laser outputs, respectively, wherein ω_w and ω_e are the optical angular frequencies of the W and E lasers and $\varphi_{L,w}(t)$and $\varphi_{L,e}(t)$ are their temporal laser phase noise.

Consider a scenario in which a perturbation in the form of a vibration acts locally and simultaneously on both the W-E and E-W fiber pairs. The vibrational perturbation induces a differing optical path length change for data traveling W-E vs. E-W. The perturbation also induces an optical phase variation of $\varphi_{vib}(t)$ on the carrier laser. We assume z_w and z_e represent the distances from the W transmitter and the E transmitter respectively, to the perturbation location. There is a corresponding propagation time of τ_w and τ_e, for the perturbation to reach the W and E receivers, respectively. We next define $L = z_w + z_e$ and $\tau = \tau_w + \tau_e$.

Taking E-W (*ew*) transmission as an example and neglecting chromatic dispersion (CD) without loss of generality, the electrical fields of the two polarizations (X and Y) of the received signal at the W receiver can be written as:

$$E_{X,ew}(t) = (A_{X,ew}(t) + n_{X,ew}(t)) \cdot e^{j(\omega_e t + \varphi_{X,e}(t) + \varphi_{vib}(t-\tau_w) + \varphi_{L,e}(t-\tau) + \varphi_{X,n,ew}(t))} \cdot e^{-\left(j\omega_w t + \varphi_{L,w}(t)\right)}, \quad (1)$$

$$E_{Y,ew}(t) = (A_{Y,ew}(t) + n_{Y,ew}(t)) \cdot e^{j(\omega_e t + \varphi_{Y,e}(t) + \varphi_{vib}(t-\tau_w) + \varphi_{L,e}(t-\tau-\Delta\tau) + \varphi_{Y,n,ew}(t))} \cdot e^{-\left(j\omega_w t + \varphi_{L,w}(t)\right)}, \quad (2)$$

where $A_{i,ew}(t)$ represents the amplitude information, $n_{i,ew}(t)$ is the accumulated amplitude noise, $\varphi_{ie}(t)$ is the phase information, and $\varphi_{i,n,ew}(t)$ is the accumulated PN excluding the laser phase contributions; *i*=X, Y polarization. After coherent detection and analog-to-digital conversion, the digitized baseband signals are fed into a standard coherent Rx DSP stack to compensate for transceiver and fiber impairments such as CD and polarization mode dispersion (PMD). Within the DSP stack, the Carrier Phase Recovery (CPR) algorithm estimates and compensates for the carrier PN. The CPR is used to independently estimate the carrier PN of each polarization, with the resulting digital phase estimates being give by:

$$\varphi_{X,ew}[n] = \varphi_{Le}[n-N] - \varphi_{Lw}[n] + \varphi_{X,n,ew}'[n] + \varphi_{vib}[n-N_w], \quad (3)$$

$$\varphi_{Y,ew}[n] = \varphi_{Le}[n-N-\Delta N] - \varphi_{Lw}[n] + \varphi_{Y,n,ew}'[n] + \varphi_{vib}[n-N_w], \quad (4)$$

where $\varphi_{X,n,ew}'[n]$ and $\varphi_{Y,n,ew}'[n]$ include accumulated PN and equalization enhanced phase noise (EEPN). Next, we perform a difference operation between $\varphi_{Y,ew}[n]$ and $\varphi_{X,ew}[n]$ and obtain:

$$\Delta\varphi_{Y,X,ew}[n] = \varphi_{Le}[n-N-\Delta N] - \varphi_{Le}[n-N] + \varphi_{X,n,ew}'[n] - \varphi_{Y,n,ew}'[n]. \quad (5)$$

We find that the inverse of a transfer function:

$$H[\omega] = e^{-j\omega N} - e^{-j\omega(N+\Delta N)}, \quad (6)$$

can be applied to the frequency response of $\Delta\varphi_{Y,X,ew}[n]$ to reconstruct the E-W Tx laser PN $\varphi_{Le}[n]$. Applying the same operation to the W-E data yields the W-E Tx laser PN, $\varphi_{Lw}[n]$. Finally, the vibro-perturbation phase is recovered by subtracting the laser PN contribution based on the estimated W and E laser PN.

3. Results and discussion

Here, we study the performance of the proposed method. W and E laser PN are emulated using Wiener processes with a Lorentzian linewidth of 100 kHz or 300 kHz. 100-Gbaud 16-QAM signaling is applied on the DP-IQMs shown in Fig. 1 for 0.14 msecs. Pulse-shaping using a root-raised cosine filter with a roll-off factor of 0.1 is applied, and a 3-dB bandwidth limit of 50 GHz is imposed. To investigate EEPN, DP signals are launched into SMF having a CD of either 1.7 ns/nm or 102 ns/nm. Complex additive white Gaussian noise is applied to emulate accumulated system noise, and this noise is maintained at the same magnitude irrespective of choices of CD and linewidth.

The applied perturbation is modeled to have frequency content between 10 kHz and 30 kHz using a brick-wall bandpass filter (BPF). A 100 MHz frequency offset (FO) between the carrier laser and the LO is assumed for both directions. CD compensation, FO compensation, and independent MIMO equalizers interleaved with pilot symbol-based CPR for each channel are applied to the received signals. In simulation, the SMF AWGN level is fixed, the received16-QAM SNR range is bounded between 15 and 20 dB, and differing values of CD and linewidths are studied. Finally, independently tracked phases on each channel are processed to reveal the phase of the perturbation.

The effectiveness of the proposed method is numerically demonstrated in Fig. 3. Fig. 3(a) compares the retrieved and applied Tx laser PN waveforms. During PN retrieval, a discrete Fourier transform is applied to Eq. (5). An optimized low-pass filter is used to reject the unwanted high frequency noise peaks arising due to singularities of the inverse transfer function which depends on the installed $\Delta\tau$. We define two types of SNR performance metrics i) Tx PN retrieval SNR, and ii) perturbation SNR. The former is defined as the ratio of the applied Tx PN average power divided by noise average power. The latter is defined as the ratio of the average power of applied perturbation phase magnitude divided by the noise average power.

Fig. 3(b) shows the perturbation phase waveforms of Fig. 3(a) including the applied perturbation phase, the recovered perturbation phase after BPF (10-30 kHz), and the recovered perturbation phase with BPF and the proposed method based on retrieval of W and E laser PN via the processing of captured phase at two ends. The perturbation phase after using the proposed method shows a perturbation SNR improvement of 13.5 dB compared to the case using only BPF. In Fig. 3(c) and Fig. 3(d), we further examine the performance of the proposed method by sweeping the $\Delta\tau$ from 2 ns to 7 ns, as a function of laser PN (100 kHz or 300 kHz Tx/LO laser linewidths), and CD (1.7 ns/nm or 102 ns/nm). In Fig. 3(c), Tx laser PN retrieval performs better since a larger $\Delta\tau$ leads to stronger differential phase. Additionally, the retrieval performance shows larger degradation at a 300 kHz Tx/LO linewidth compared to the 100 kHz Tx/LO linewidth case because of stronger EEPN at higher LO linewidths. Fig. 3(d) shows the corresponding perturbation SNR improvement versus BPF achieving 19.7 dB.

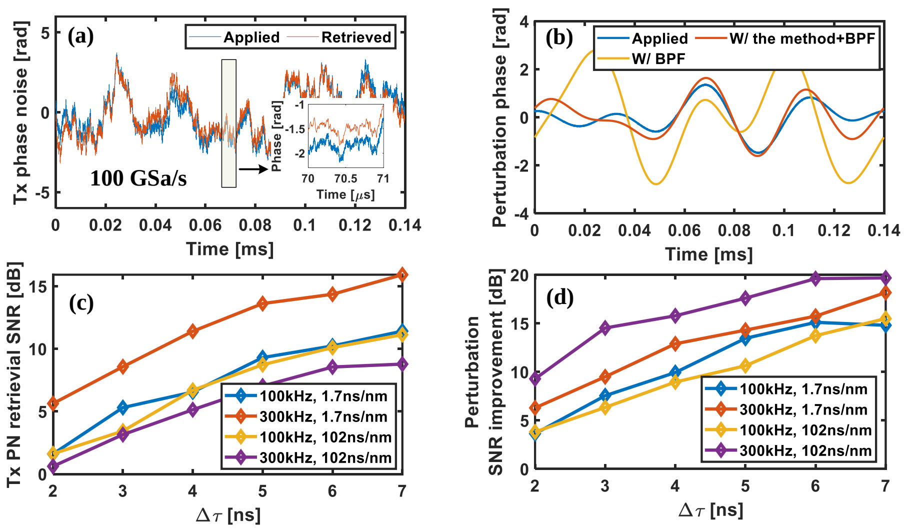

Fig. 3. Simulation results of the proposed method. (a) The applied 100-kHz linewidth Tx laser PN vs its retrieval at the Rx for a CD of 1.7 ns/nm and $\Delta\tau$ of 5 ns. (b) The waveform of the applied perturbation phase, the recovered perturbation phase with BPF, and the recovered perturbation phase with the proposed method and BPF for a CD of 1.7 ns/nm and $\Delta\tau$ of 5 ns. (c) The influence of $\Delta\tau$ on the Tx laser PN retrieval. (d) The influence of $\Delta\tau$ on the perturbation SNR improvements after using the proposed method with BPF over using BPF only.

4. Conclusion

In conclusion, we demonstrate through design, mathematics, analysis, and simulaiton a new method to digitally recovered carrier laser phase noise corrupted by vibration induced phase perturbations on signaling data without introducing ultranarrow linewidth lasers. We show >10 dB improvements in vibro-perturbation SNR versus bandpass filtering methods for perturbations with frequency components bounded between 10 kHz and 30 kHz.

5. References

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