Simultaneous communications and vibration sensing over a single 100-km deployed fiber link by fiber interferometry

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Abstract: We demonstrate simultaneous 60 GBaud 16-QAM transmissions and vibration sensing over a single 100-km deployed fiber link. Vibration localization is realized by extracting the phases of a co-propagating pilot and a counter-propagating tone. © 2023 The Authors

1. Introduction

Recently, there are increasing interest to enable optical fiber networks to support simultaneous communications and sensing capability. This is because sensing on one hand can provide proactive fault detection of optical fibers which ensures stable data transmission. On the other hand, developing sensing capabilities for deployed fiber networks is a cost effective way to enable various physical environment and human activity monitoring, Internet of Things for smart city applications and dramatically increase the value of deployed fiber links. A common approach to integrate distributed acoustic sensing (DAS) with communications is to separate them in frequency so that the sensing signals occupy a different part of the spectrum and do not affect the communication signals at all [1-3]. To take a step further and develop sensing capabilities using communication signals, state of polarization (SOP) monitoring of transmission data was proposed for proactive fault detection but event localizations are challenging and the sensitivity is limited due to the property of signal polarization states [4,5]. Compared with SOP, optical phase is better for vibration detection due to its high sensitivity. Ip et al. demonstrated successful vibrations detection and localization by extracting and comparing the phases from bidirectional communication signals on a single fiber and conventional bidirectional links [6]. As research in sensing systems typically analyze multiple vibration signatures embedded on different signals from a single fiber whose correlations (hence localization capability) are stronger than those from bidirectional links in the first place, it will be beneficial to develop low cost, low implementation complexity distributed sensing solutions on a single fiber with typical unidirectional communications traffic and the sensing signals do not affect communication system performance.

In this paper, we propose to use a pilot tone co-propagating with the communication signal, a counter-propagating continuous wave (CW) tone from a small portion split from the local oscillator (LO) at the receiver side, and fiber interferometry at the transmitter as a simple vibration sensing solution without the need of complex digital signal processing algorithms and additional expensive components. Through retrieving and correlating the phases of the pilot tone and counter-propagating CW, vibrations can be successfully detected and localized for a 60 GBaud PM 16-QAM system transmitted over a 100-km deployed fiber link across different parts of Hong Kong. The influence of sensing signals to communication system performance is negligible as long as the CW power level is relatively low. The proposed scheme provides a cost-effective way to add sensing function to deployed optical communication links.

2. Operating principle and Experimental setup

The deployed fiber loop network consists of four standard single-mode fiber links: green line (from Hong Kong Polytechnic University(PolyU) to a data center in Tseung Kwan O), purple line (from Tseung Kwan O to City University of Hong Kong(CityU)), red line (from CityU to a data center in Chai Wan) and blue line (from Chai Wan to PolyU). The fiber link routes are shown in Fig.1(a) and (b). The transmitter and receiver are co-located in the lab at PolyU. The total length of this fiber loop is 98.9 km and the loop passes through the busiest street in Hong Kong, rural mountainous areas as well as under the sea.

The experimental setup for the proposed sensing scheme is shown in Fig.1 (c). Two fiber lasers (NKT X15) are used to reduce both the frequency and phase noise of the pilot and CW tone. A 4-channel 92-GSa/s digital-to-analog converter (DAC) modulates a 60-Gbaud 16-QAM signal as shown in Fig.1(a) onto the carrier via IQ modulators. A pilot tone at 35.16 MHz is added to the 16-QAM through the DAC. Moreover, we set the power of the pilot to be 33dB lower than the data in order to eliminate the influence of the pilot on the data detection. Next, a 95/5 coupler is used to split a small portion of CW tone from the LO at the receiver. The 5% light is coupled back into the fiber link via a circulator. A tunable optical attenuator is inserted between the circulator and the coupler to investigate the influence of the counter-propagated CW tone. Since the total link loss is about 30 dB, we add a bidirectional optical fiber amplifier that is composed of two EDFAs at the CityU site. At the transmitter, the laser power is divided equally for data transmission and LO for sensing. Since the Rayleigh backscattering from the transmitted data will influence the sensing performance, narrow optical bandpass filter is first used to reduce the Rayleigh noise as much as possible, followed by another EDFA and bandpass filter to amplify the CW signal. After beating with the LO and heterodyne detection, the phase of CW signal can be successfully retrieved. The frequency difference between two NKT lasers are adjusted to be 21.2 MHz so that low speed/bandwidth ADC can be used for sensing. To simulate external disturbance-induced vibrations, a 10-m fiber at the transmitter end was wrapped around a piezoelectric transducer (PZT) to imitate external vibrations. A spur like signal was applied to the PZT. Since the pilot tone and CW light propagate in opposite directions, vibrations can be located by cross-correlating the received phase waveforms of the CW and pilot tones and identify its peak. In a practical setting, GPS can be used to align the timing of the two received phase waveforms [7].

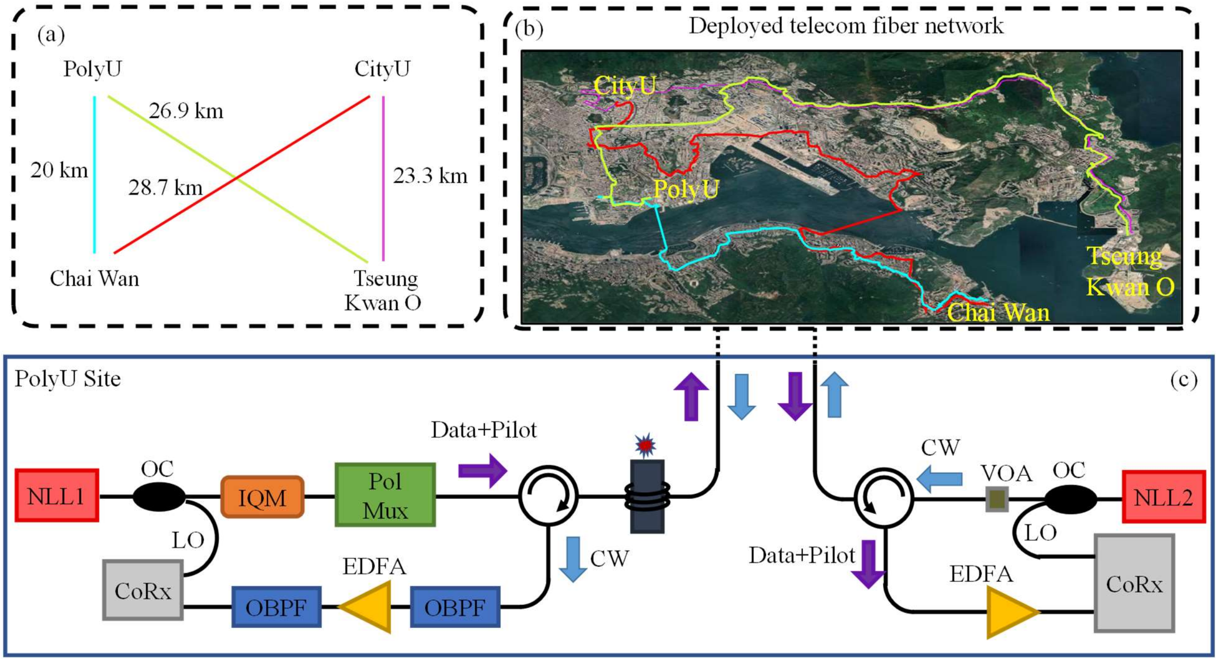

Fig. 1. (a) Routine of the deployed fiber link (b) Map of the deployed fiber network and (c) Experimental setup of the proposed integrated sensing and communication system.

3. Results and discussions

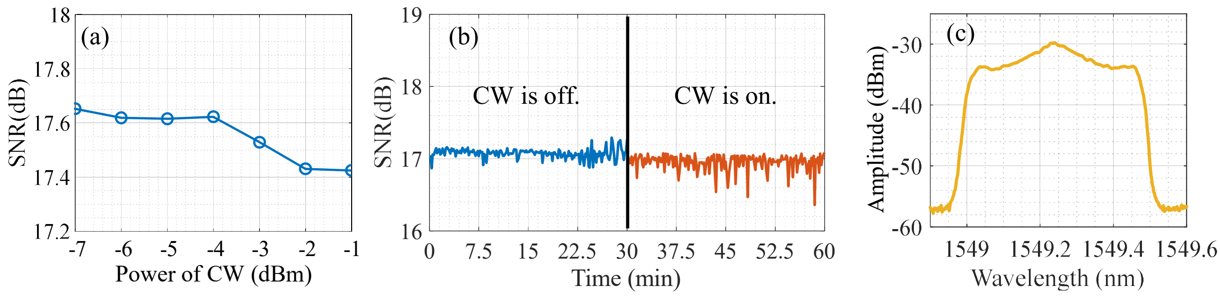

Fig. 2. (a) Measured SNRs of the 16 QAM signal when the power of CW is increased from -7 dBm to -1dBm; (b) Long-term SNR as the counter-propagated CW light is switched on or off; (c) Optical spectrum of the 16 QAM signal at the receiver when CW is on.

To verify that the proposed fiber interferometric sensing scheme is compatible to single-fiber unidirectional communication systems, we first investigate the impact of the counter-propagating CW tone on the signal-to-noise ratio (SNR) of the 16-QAM signal and the results are shown in Fig. 2(a) when the launched power of the CW tone is increased from -7 dBm to -1 dBm. We can see that as the launch power of CW decreases, the SNR of the 16-QAM signal will improve. We then set the CW launched power to be –7 dBm and measured the long-term variations of SNR of the 16-QAM signal when the CW tone is switched off or on. The SNR results are shown in Fig. 2(b), from which we can see that the effect of sensing on communication is neglectable. Fig. 2(c) shows the spectrum of the 16-QAM signal at the receiver end when the CW is on. Although the Rayleigh backscattering from CW tone is inevitable, this back-reflected power can be made much smaller than that of data and not degrade communications performance as long as the CW power is made to a relatively low level. To detect and localize the external vibration, the CW and pilot tone phases $\phi_C(t)$ and $\phi_P(t)$ are retrieved and are shown in Fig. 3(a). One can clearly see the vibration induced phase fluctuations. But due to laser phase noise and environmental vibrations caused by various human activities around the fiber route along the city, the phase traces show a slow fluctuation, which can decrease the correlation between two vibration-induced phase signals and degrade the vibration localization accuracy. Hence, we apply a high pass-filter by calculating the self difference $\Delta\phi_{C(P)}(t) = \phi_{C(P)}(t) - \phi_{C(P)}(t - \Delta\tau)$ to the original phase signals. Here $\Delta\tau$ is a digital time delay which determines the cutoff frequency [8] and is set to 0.4 ms in our studies. Fig. 3(b) shows the phase signals after high-pass filtering, where obvious time delay can be observed between these two signals. The vibration location can be estimated by cross correlating $\Delta\phi_C(t)$ and $\Delta\phi_P(t)$ and identifying the peak location as shown in Fig. 3(c). 50 repeated measurement trials are conducted to characterize the localization accuracy. The mean estimated vibration location is 99.048 km, in agreement with expectations (98.9 km) plus the total lengths of all the fibers in EDFAs, PZT, circulators and fiber jumpers. The standard deviation is 22.86 m, indicating good localization precision. We also study the influence of the Rayleigh backscattering of 16-QAM signal on $\phi_C(t)$ and the measured spectra of $\phi_C(t)$ is shown in Fig. 3(d) with and without the 16-QAM signal. It can be seen that the 16-QAM signal will slightly worsen the SNR of the $\phi_C(t)$ at some high frequency band, e.g. from 5 kHz to 10 kHz and from 12.5 kHz to 16.8 kHz. Fortunately, the SNR decrease occur at frequency ranges whose original noise levels are relatively low. Therefore, the influence of communication on vibration sensing performance is negligible as long as the vibration amplitudes are above the noise level.

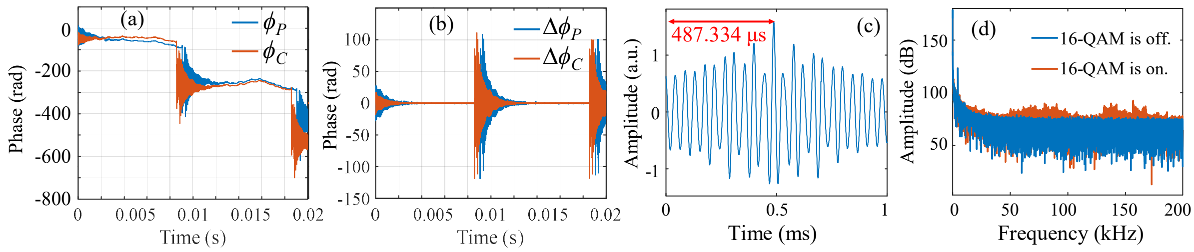

Fig. 3(a) Extracted phase profiles of CW tone $\phi_C(t)$ and pilot tone $\phi_P(t)$; (b) phase profiles $\Delta\phi_C(t)$ and $\Delta\phi_P(t)$ after high-pass filtering; (c) cross-correlation between $\Delta\phi_C(t)$ and $\Delta\phi_P(t)$ and (d) effect of the 16-QAM communication signal on the spectra of $\phi_C(t)$.

4. Conclusions

We demonstrated for the first time the coexistence of vibration sensing and unidirectional communication signals over a single 100-km deployed fiber link with simple fiber interferometry through an in-band pilot tone travelling with the communication signal and a counter-propagating continuous wave tone. We verify that communications performance will not be affected as long as the power of the CW signal remains low. The proposed scheme is also applicable to short or medium-distance optical networks and is an alternative way to add sensing capabilities to deployed fiber networks.

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