Enabling Endogenous DAS in P2MP Digital Subcarrier Coherent Transmission System with Enhanced Frequency Response

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Abstract: We propose an endogenous DAS in P2MP digital subcarrier coherent transmission systems. By redesigning and reusing FrFT-based synchronization pilots, vibrations up to 12 kHz are successfully detected over 10-km-long fiber, along with 100-Gb/s 16QAM transmission. © 2024 The Author(s)

1. Introduction

Most recently, the coherent digital subcarrier multiplexing (DSCM) system is widely considered to be a promising candidate solution in next generation point-to-multipoint (P2MP) optical networks [1-3]. With the fast development towards B5G/6G era, there has been an increasing interest in this solution because of its high spectral efficiency and spectral flexibility. As coherent P2MP has the ambition to rule the access/metro networks [3], these densely populated areas are currently also the focus of monitoring the ambient environmental data [4].

In DSCM-based P2MP networks, the data exchange occurs between several geographically distributed leaf nodes and a central hub node. While the individual leaf nodes only modulate and demodulate a subset of digital subcarriers on their respective sub-band, the hub transmits and receives all of them [1]. In the downstream direction, all the aggregated subcarriers transmitted from the hub are broadcast to different-frequency leaf nodes. Thus, the aggregated subcarriers, consisting of signals on different sub-bands, must possess multi-frequency pilots to achieve timing synchronization of multiple users. [5]. To solve the timing synchronization issue, the narrow-bandwidth fractional Fourier transform (FrFT)-based pilot has been proposed to enable robust timing/frequency synchronization in DSCM communication systems [6]. Intriguingly, the FrFT-based linear frequency modulated (LFM) signal has also been demonstrated to realize high-performance distributed acoustic sensing (DAS) [7]. However, it remains challenging to codesign communication and sensing functions to synergize for mutual benefits.

In this work, we strategically redesign the multi-frequency FrFT-based synchronization pilots in P2MP networks. Besides addressing the timing/frequency offset problems, the high-performance vibration sensing can also be achieved by rearranging the pilots as multi-tone sensing probes. With equal time intervals, the multi-tone sensing probes furtherly remove restriction imposed by the round-trip time along the sensing fiber, thus enhancing the vibration frequency response range [8]. We demonstrate our scheme for 100-Gb/s 16QAM DSCM-based P2MP transmission while simultaneously achieving DAS over 10-km fiber with the vibration frequency up to 12 kHz.

2. Principle of Operations

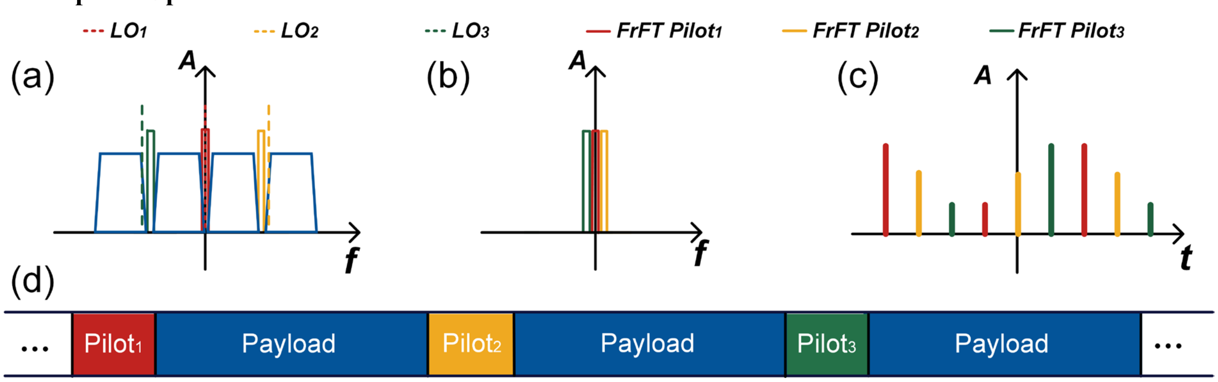

Fig. 1. (a) The spectrum of the transmitted signals with sensing LOs (b) The spectrum of the pilots at the sensing receiver (c) The temporal vibration waveform after synthesization at the sensing receiver (d) The frame structure of the transmitted signals

The FrFT of a direct current (DC) signal (hereinafter referred to as the FrFT-DC signal) is used to generate LFM signals. Each FrFT pilot sequence consists of two FrFT-DC signals, with opposite orders p and -p, for communication timing/frequency synchronization [6]. Here, the frequency domain multiplexing (FDM) and time domain multiplexing (TDM) are both strategically deployed to enable the endogenous frequency-response-enhanced

DAS in P2MP digital subcarrier coherent transmission systems. As shown in Fig.1(a), three pilots, also deemed as multi-tone sensing signals, are located in the spectral dips of the DSCM signal. The three-tone optical comb is used as the local oscillators at the sensing receiver for respective pilots. The frequency spacing of the comb is slightly greater than that of the pilots, thus yielding multi-path interferences. It leads to an efficient down conversion of the optical frequencies of pilots onto the radio frequency domain. As shown in Fig.1(b), the bandwidth of the pilots at the sensing receiver can be down to the summed bandwidth of the narrow pilots. The backscattering sensing signals can be separated and demodulated individually by different matched filters. On the other hand, utilizing TDM method, the pilots, also serving as multi-tone sensing probes, are inserted in the communication DSCM signal. The time interval of the pilots is set as one-third of the frame length, as depicted in Fig.1(d). The vibration waveforms demodulated from these backscattering signals are synthesized chronologically to enhance the vibration response bandwidth, as depicted in Fig.1(c) [8]. Consequently, the vibration response bandwidth is increased threefold.

3. Experimental setup and results

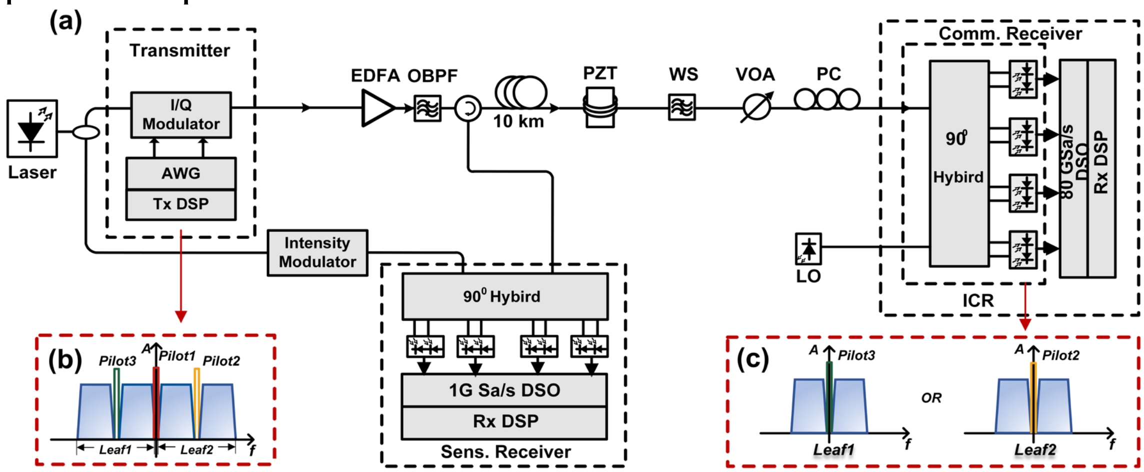

Fig. 2. (a) Experimental setup; (b) Spectrum of the transmitted signals; (c) Spectrum of the received communication signals of Leaf1 or Leaf2.

The DSCM-based P2MP system is shown in Fig.2 (a). At the transmitter-side (Tx), the light source is the fiber laser (FL) tuned at 1550.02 nm with a linewidth ~100 Hz. The light is split into two tributaries by a 70:30 polarization maintaining coupler. 70% of the optical power is modulated by a Mach-Zehnder intensity modulator. The modulator is driven by a microwave source to generate the multi-tone local oscillators (LO) of the sensing receiver. 30% of the optical power is modulated by a single-polarization (SP) in-phase and quadrature (IQ) modulator driven by 32 GSa/s 8-bit arbitrary waveform generator (AWG, Keysight M8195A). As shown in Fig. 2(b), in the Tx digital signal processing (DSP), 25.6 Gbaud DSCM signals with 4 subcarriers are offline generated. The DSCM signal is filtered by root-raised-cosine (RRC) filters with a roll-off factor of 0.1. Each of the 6.4 Gbaud FrFT-based pilots, with a length of 2048 symbols, is generated using 0.005 and -0.005 order FrFT [6]. The 3 pilots are respectively located between the subcarrier signals. The period of the transmitted signal is 112.8 μs to ensure a coverage of the whole about 10-km fiber. The modulated signals, aimed at the 100G SP-16QAM transmission, are pre-amplified by an Erbium doped fiber amplifier (EDFA, Amonics AEDFA-PA-35). The launch power into the fiber is 6 dBm. At the end of 10-km fiber, the vibration is generated by a piezoelectric transducer (PZT).

At the coherent communication receiver-side (Rx), a waveshaper (WS) with a bandwidth of 15 GHz is used to filter the leaf node with 2 subcarriers to emulate a narrow-band receiver. After filtering, a variable optical attenuator (VOA) is used to adjust the received optical power (ROP). A polarization controller (PC) is used to ensure perfect polarization alignment of the SP optical signals. An external cavity laser (ECL, Coherent solutions MTP1000) with a linewidth of 100 kHz is used as LO. After detected by an integrated coherent receiver (ICR), the received analog signal is digitized by a digital storage oscilloscope (DSO, Teledyne LeCroy 10-36Zi-A) with a sampling rate of 80 GSa/s per channel.At the sensing Rx, the Rayleigh backscattering (RBS) light is detected by another ICR with a 240MHz bandwidth. Then, the electrical signal is sampled by a four-channel DSO (Teledyne LeCroy, WaveRunner 9404) and processed offline. The sampling rate of the DSO is set to 1 GSa/s and the analogue bandwidth is limited to 200 MHz to extract the sensing signals.

Fig.3(a) shows the DSCM communication performance for back-to-back (B2B) and after transmission. The Leaf2 is slightly worse than Leaf1 due to the imperfect state of PC. Compared to B2B, their performance is almost unchanged after transmission. With the low-complexity block localization scheme depicted in [6], the FrFT-based pilots are utilized for timing synchronization. Then, by tuning the wavelength of the Rx laser, we sweep the

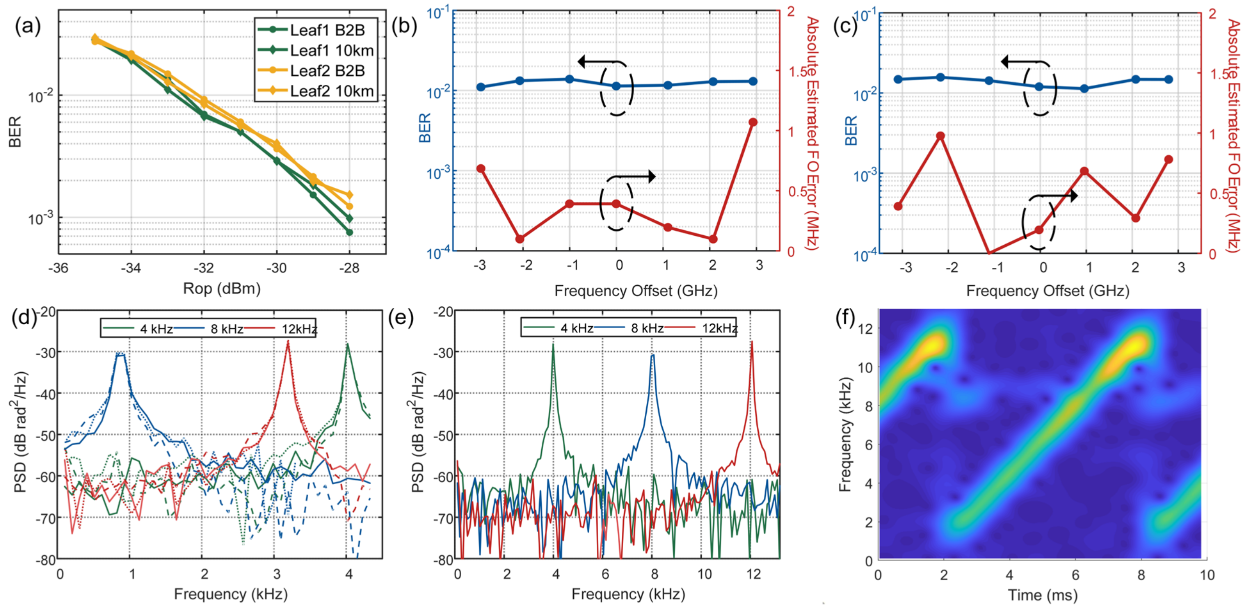

Fig. 3. (a) BER vs received power for B2B and after transmission (b) FOE errors vs BER for Leaf1 (c) FOE errors vs BER for Leaf2 (d) Detected vibration waveform by a single pilot; (e) Detected vibration waveform by 3 pilots; (f) Short time Fourier transform spectrogram of vibrations.

frequency offset (FO) from -3 GHz to 3 GHz to check the FO estimation (FOE) performance. Here, we design a two-stage FOE and compensation scheme, with our FrFT-based pilots for in-advance frequency synchronization before subcarriers de-multiplexing, and traditional fast Fourier transform (FFT) scheme after equalization, to estimate and compensate for the residual tiny FO to calculate the bit error rate (BER). Fig.3(b) and (c) show the FOE errors of the proposed FrFT pilots for Leaf1 and Leaf2 are trivial and below 1.6 MHz [6] at ROP of -33 dBm and FEC threshold of about 1e-2. The corresponding BER results with different FOs are almost the same with negligible performance fluctuation. So, FrFT-based pilots demonstrate its superiority for frequency synchronization.

Subsequently, to verify the effectiveness of the frequency-response-enhanced vibration sensing, we process the pilots as sensing probes with the matched filters. To mitigate the signal fading, moving rotated-vector-average (MRVA) and rotated-vector-sum (RVS) method are adopted [9,10]. The vibration phase generated by PZT is restored by differentiating the demodulated phase traces using a gauge length of 5 m. Three vibrations with the frequencies of 4 kHz, 8 kHz, and 12 kHz are measured, respectively. Fig.3(d) shows the power spectral density (PSD) results of the demodulated vibration using a single pilot. Due to the inadequate sampling rate, only the 4-kHz vibration is are detected successfully. On the contrary, in Fig.3(e), the higher frequency vibrations of 8 kHz and 12 kHz are also clearly recovered by synthesizing the samples from three TDM pilots. The noise floor in the PSD and strain resolution is about -60 dB rad^2/Hz and 22 $p\varepsilon/\sqrt{\mathrm{Hz}}$, respectively. Then, an LFM vibration is applied to the PZT. The frequency is swept from 1 kHz to 12 kHz with a period of about 5 ms. The short time Fourier transform spectrogram of the recovered LFM vibration is shown in Fig. 3(f). It demonstrates the wideband frequency response is achieved by 3 TDM pilots.

4. Conclusions

We propose a novel scheme to enable the endogenous frequency-response-enhanced DAS in P2MP digital subcarrier coherent transmission systems. By strategically redesigning the FrFT-based synchronization pilots, joint timing/frequency synchronization and vibration sensing are simultaneously achieved. Finally, vibrations up to 12 kHz have been successfully detected over 10-km-long fiber, along with 100-Gb/s 16QAM transmission.

Acknowledgement
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