Simultaneous Distributed Acoustic Sensing and Communication in Digital Subcarrier Multiplexing Systems

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Abstract *By leveraging the flexibility of DSCM in allocating spectrum, we multiplex a FrFT-DC signal with digital subcarriers to achieve simultaneous DAS and communication. Through a shared transmitter, 200-Gb/s DP-16QAM transmission with DAS sensitivity of 88* $\mathrm{p\varepsilon}/\sqrt{\mathrm{Hz}}$ *at 4-m spatial resolution has been demonstrated.*

Introduction

The integration of distributed sensing and optical communication has garnered significant interest lately due to its potential of endowing intelligent functionalities to ubiquitous optical fibre networks. The communication networks equipped with high-performance sensing possess the capability to detect and localize vibrations, enabling the physical environment and human activity monitoring. For widely-deployed short-reach communication systems, fibre sensing can be employed as an effective tool for network diagnostic and environment monitoring. However, corresponding solutions must be compatible with the as-deployed network architecture, to promise cost-effectiveness [1].

In the aspect of the system architecture, particularly methods of signal modulation and detection, the distributed acoustic sensing (DAS) system exhibits strong similarities to a conventional optical communication system. This similarity enables DAS a good option for integrating sensing capability into communication system in an optical fibre, by means of wavelength division multiplexing (WDM), frequency division multiplexing (FDM) [2] and mode division multiplexing (MDM) techniques [3]. However, these reported works simply share the fibre and there still exists two individual systems [2]. Recently, the digital subcarrier multiplexing (DSCM) technology, based on the traditional coherent network architecture, has attracted considerate attentions for short-reach transmission [4-6] .Moreover, the DSCM system is hailed as “engine” of next-generation flexible, adaptable, and scalable software-configurable optical networks [6]. Owing to the inherent flexibility in the spectrum allocation, the DSCM system offers a cost-effective way for digitally spectrally-multiplexing DAS probe and subcarrier signals in the same wavelength channel.

In this paper, we propose a scheme of integrating DAS and DSCM system to achieve low-cost sensing and communication. The p-order fractional Fourier transform (FrFT) of a direct current (DC) signal (hereinafter referred to as the FrFT-DC signal) is dedicated for high-performance vibration sensing [7]. We localize the digital FrFT-DC sensing signal in the central portion of the DSCM spectrum, resulting in the achievement of the simultaneous sensing and communication through the shared transmitter. We demonstrate a 200-Gb/s DP-16QAM transmission, while simultaneously achieving high performance DAS over 10-km fibre with a sensitivity of 88 $\mathrm{p\varepsilon}/\sqrt{\mathrm{Hz}}$ at 4-m spatial resolution.

Principles of Operation

The principle of the DAS-compatible DSCM system and experimental setup is illustrated in Fig. 1 (a). At the transmitter-side (Tx), the light of laser is split into two tributaries by a 50:50 polarization maintaining coupler. One tributary serves as the local oscillator (LO) for the sensing receiver. The other tributary is sent to a single polarization in-phase and quadrature (IQ) modulator for signal modulation. As shown in Fig. 1(b), in the Tx digital signal processing (DSP), the integrated digital signals comprise DSCM signals with 2 subcarriers by root-raised-cosine (RRC) filters, and a sensing FrFT-DC signal inserted between 2 subcarriers by spectrally multiplexing. The digital spectrum of the integrated signals is shown in the inset of Fig. 1(a). Then the modulated optical integrated signals are sent into the fibre.

At the communication receiver (Rx), the integrated signal is detected using an integrated coherent receiver (ICR). The received analogue signal is digitized by a digital storage oscilloscope (DSO), and the following DSP flow for communication is conducted after down-sampling the signal to twice the baud rate, as shown in Fig. 1(c). When demultiplexing, the digital RRC filters are used to extract the communication signal with 2 subcarriers and remove the sensing probe FrFT-DC signal.

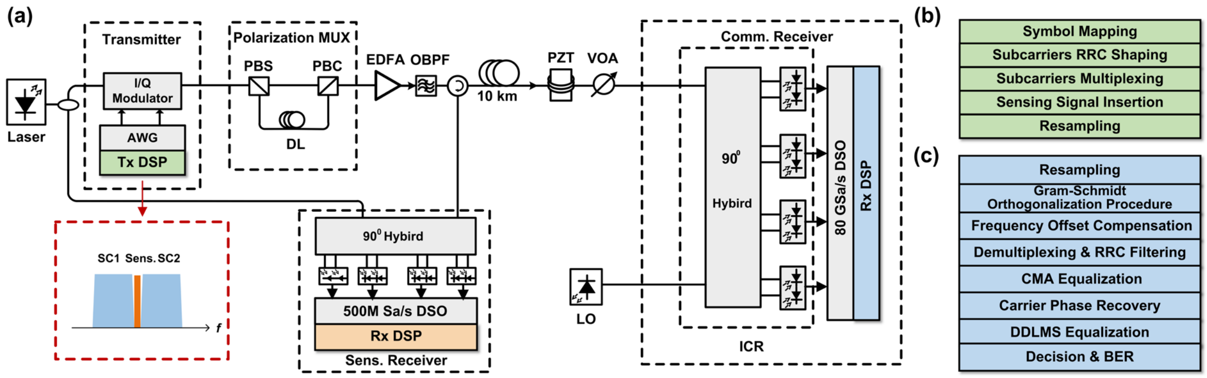

Fig. 1: (a) Experimental setup; (b) block diagram of Tx Integrated DSP; (c) block diagram of Rx Communication DSP.

At the sensing receiver, the Rayleigh backscattering (RBS) light is combined with the transmitter laser and detected by another ICR. Note that polarization diversity detection of ICR can cope with polarization-division-multiplexing (PDM) signals for DAS, thereby eliminating polarization fading in DAS. In the Rx. DSP for sensing, the received digital complex sensing signals, corresponding to X and Y polarizations, are processed using 1-p order FrFT. The length of FrFT window is set to be the same as that of the transmitted FrFT-DC probe signal for sensing. Finally, to suppress signal fading, moving rotated-vector-average (MRVA) method is used to combine the complex signals [8].

Experimental Setup and Results

At the Tx, the DSCM signals with 2 subcarriers of aggregate 25.6-Gbaud dual-polarization 16-ary quadrature amplitude modulation (DP-16QAM) is offline generated, aimed at 200G transmission. The roll-off factor of the digital subcarriers is 0.05. A guard band of 500 MHz between adjacent two subcarriers is reserved for sensing data. The 500-Mbaud FrFT-DC sensing signal is generated using 0.4-order FrFT and inserted in the center of the DSCM spectrum. The period of the FrFT-DC signal is about 125 μs to ensure a coverage of the whole 10-km sensing fibre. Then the digital signal is loaded into an arbitrary waveform generator (AWG, Keysight M8195A) with a sampling rate of 32 GSa/s. The continuous wave (CW), generated by the fibre laser (FL), is used as the Tx light source. The operation wavelength and the linewidth of the FL (NKT E15) are 1550.12 nm and ~100 Hz, respectively. The generated signal from two channels of the AWG is modulated onto the single polarization IQ modulator. Then, PDM is emulated by a pair of polarization maintaining polarization-beam splitter (PBS) and polarization-beam combiner (PBC), with a 15-ns optical delay line (DL, 3m polarization maintaining fibre) to decorrelate transmitted signals in two orthogonal polarizations. The modulated signals are pre-amplified by an erbium doped fibre amplifier (EDFA, Amonics AEFA-PA-35) before propagating over the transmission link through an optical circulator. The noise figure of the EDFA is 4.2 dB. An optical bandpass filter (OBPF) with a bandwidth of 0.8 nm is used to filter the amplified spontaneous emission. After 10-km fibre transmission, a 15-m fibre is wrapped around a piezoelectric transducer (PZT) to imitate external vibrations at the end of the fibre and then a variable optical attenuator (VOA) is used to adjust the received optical power (ROP). At the communication Rx, an external cavity laser (ECL) with a linewidth of 100 kHz is used as the local oscillator. The communication signal is sampled by a DSO with the sampling rate of 80 GSa/s. And the RBS signal is sampled by a DSO at 500 MSa/s, with the analogue bandwidth of 200 MHz to extract the DAS signal.

The signals for communication and sensing are simultaneously generated by a transmitter, hence sharing the same DAC channels. The involvement of the sensing signal inevitably reduces the effective number of bits (ENOB) of DAC and ADC for communication signals, causing a degradation in back-to-back signal-to-noise ratio (SNR). However, inadequate power allocation to the sensing signal may induce a degradation of SNR for sensing signals [1]. Fig. 2(a) shows the relationship between bit error rate (BER) and sensing-to-communication power ratio (SCPR) at ROP of -28dBm. The results suggest that a SCPR value of lower than -10 dB is necessary to ensure optimal communication performance.

Correspondingly, the impact of SCPR on the sensing performance is also investigated. The increase in SCPR improves power of the sensing signal and the ENOB for the sensing signal. As shown in Fig. 2(b), the average phase standard deviation (STD) generally shows a downtrend as the SCPR increases. However, for higher SCPR, the improvement of demodulated phase STD is significantly restricted by the laser phase noise.

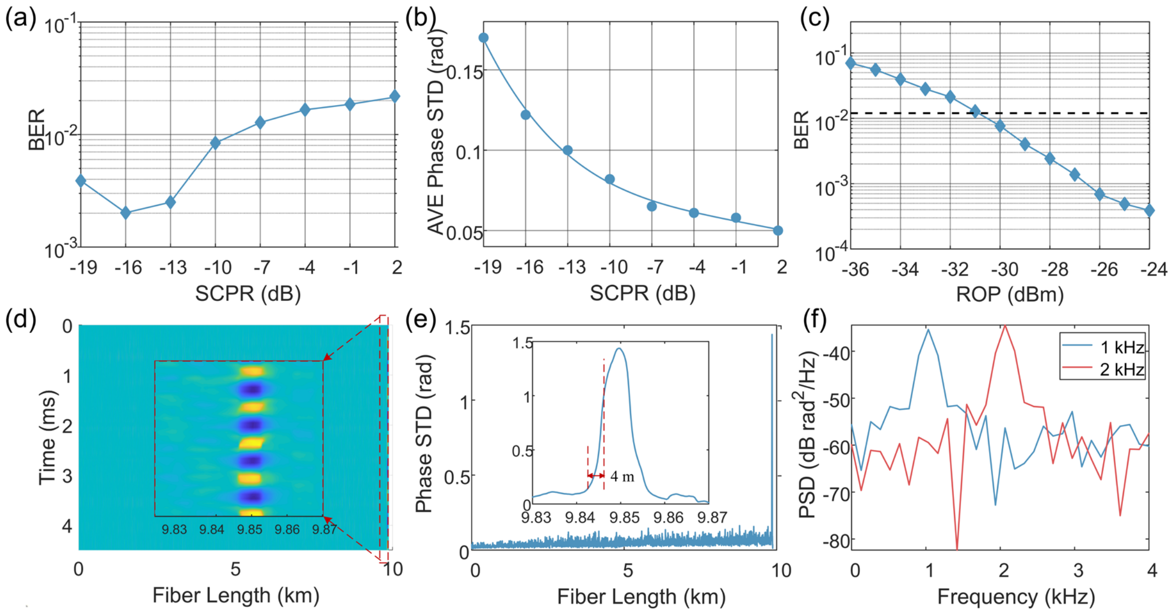

Fig. 2: (a) BER vs SCPR; (b) DAS phase STD vs SCPR; (c) BER vs ROP at SCPR at -13 dB; (d) 3D map of the demodulated phase of DAS; (e) phase STD along the sensing fiber; (f) phase PSD for 1 kHz and 2 kHz vibration.

Considering a balance between the communication and sensing performance above, an optimal SCPR of -13 dB is selected in the following experimental demonstrations.

Next, the BER evolution of the communication with the increment of ROP is investigated on the optimal SCPR of -13 dB. The results indicate that, to achieve line rates of 200 Gb/s with 16QAM, the required ROP is -31 dBm, considering concatenated soft decision (SD) forward error correction (FEC) threshold at BER=1.2E-2, as shown in Fig. 2(c). As the launch power into the fibre is 5 dBm, a power budget of 36 dB is obtained.

Subsequently, the performance of vibration sensing is verified using a PZT. The PZT is driven by a sinusoidal waveform with 1-kHz and 2-kHz frequency, and 0.2-V amplitude. About 40 trace periods are acquired. The vibration phase is retrieved by differentiating the phase traces with a sensing gauge length of 4 m. The demodulated differential phase of different periods is presented in the time-distance domain, whose top view is shown in Fig. 2(d). And the vibration can be clearly discerned as shown in the inset of Fig. 2(d). The STD of the demodulated phase traces is calculated to determine the distributed phase fluctuation and the effective spatial resolution, as shown in Fig. 2(e). A spatial resolution of 4 m is clearly achieved as shown in the inset of Fig. 2(e).

The sensitivity of the DAS system is evaluated by the power spectral density (PSD) of the demodulated vibration phase. As shown in Fig. 2(f), the vibration frequency is correctly restored. The noise floor in the PSD is about -50 dB rad^2/Hz, corresponding to a DAS sensitivity of 88 $\text{p}\varepsilon/\sqrt{\text{Hz}}$.

Conclusions

In this paper, we propose to multiplex a FrFT-DC signal with digital subcarriers to achieve simultaneous DAS and communication. By utilizing the spectrally flexibility of DSCM system, the FrFT-DC sensing signal is digitally inserted in the central spectrum of DSCM communication signal, yielding a cost-effective way for integration of both sensing and communication signals using the shared transmitter. With the optimization of SCPR, we achieve 200-Gb/s DP-16QAM transmission with DAS sensitivity of 88 $\text{p}\varepsilon/\sqrt{\text{Hz}}$ at a spatial resolution of 4 m.

Acknowledgements

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