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Compressive sensing with a microwave photonic filter

Ying Chen [a,b], Xianbin Yu [b], Hao Chi [a,*], Shilie Zheng [a], Xianmin Zhang [a], Xiaofeng Jin [a], Michael Galili [b]

[a] Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China
[b] Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark

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ABSTRACT

In this letter, we present a novel approach to realizing photonics-assisted compressive sensing (CS) with the technique of microwave photonic filtering. In the proposed system, an input spectrally sparse signal to be captured and a random sequence are modulated on an optical carrier via two Mach–Zehnder modulators (MZMs). Therefore, the mixing process (the signal to be captured mixing with the random sequence) is realized in the optical domain. The mixed optical signal then propagates through a length of dispersive fiber. As the double-sideband modulation in a dispersive optical link leads to a frequency-dependent power fading, low-pass filtering required in the CS is then realized. A proof-of-concept experiment for compressive sampling and recovery of a signal containing three tones at 310 MHz, 1 GHz and 2 GHz with a compression factor up to 10 is successfully demonstrated. More simulation results are also presented to recover signals within wider bandwidth and with more frequency components.

1. Introduction

Analog-to-digital converters (ADCs) play an important role in modern communication and information systems bridging the analog and the digital worlds. However, the improvement of the speed of ADCs largely lags behind that of the digital signal processing, which is mainly owing to the lack of high speed clock source with ultra-low time jitter. In the past decade, the technique of compressive sensing (CS) has been proposed to acquire a signal with samples much less than that required by Nyquist–Shannon sampling theorem given that the signal is sparse in a domain [1,2]. For many applications, the concerned signal is usually spectrally sparse; or in other words, although the available frequency spectrum is very broad, only a small portion of the spectrum is occupied at a given time. CS for sparse signal acquisition contains a linear projection process and a nonlinear reconstruction process. In the linear projection, an incoming signal with N pieces of information is 'compressed' to M samples (M≤¡N) with a measurement process, which can be mathematically modeled as $\mathbf{y} = \Phi\mathbf{x}$, where $\mathbf{x}$ is the discrete representation of the sparse signal at or above Nyquist rate of dimension N, Φ is an $M \times N$ pseudo-random matrix denoting the measurement process, and $\mathbf{y}$ ($M \times 1$) is the measured values at sub-Nyquist rate. In the random demodulator (RD)-based CS, the measurement process includes mixing of the sparse signal with a random sequence at/above Nyquist rate, low-pass filtering or integration and sub-Nyquist sampling. The signal $\mathbf{x}$, if it is spectrally sparse, can be expressed as $\mathbf{x} = \mathrm{W}\theta$ where W is an $N \times N$ Fourier basis and θ is an $N \times 1$ vector representing its spectrum. If the measurement matrix Φ consists of random entries from a suitable probability distribution and Wis a standard orthogonal basis, it is proved that the matrix product ΦW satisfies the restricted isometry property. In this case, the spectrum vector θ can be fully recovered from the measurement result $\mathbf{y}$ in the nonlinear reconstruction process by solving a minimization problem [1,2].

Recently, there have been increasing interests in the photonics-assisted CS since photonic links provide extremely high bandwidth with mature technologies of stable laser sources, high-speed electro-optic modulators (EOMs), and large-bandwidth photodetctors (PDs) [3–15]. In addition, the mixing of the sparse signal with the random sequence is realized in the optical domain in the photonics-assisted CS, which avoids the difficulties of high-speed mixers in the conventional CS [3–6]. The concept of photonics-assisted CS was initially proposed by Valley et al. in [3,4]. In their approach, the input sparse signal is firstly modulated on a chirped optical pulse; then the optical pulse is spectrally modulated in a spatial light modulator (SLM)-based pulse shaper to implement random mixing in which the random sequence is recorded on the SLM. The approaches of CS with optical random mixing based on EOMs have also been demonstrated [5,6]. To further decrease the sampling rate of the digitizer, the scheme combining the techniques of CS and photonic time stretch has been proposed [7,8]. The

* Corresponding author.
E-mail address: chihao@zju.edu.cn (H. Chi).

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integration function in the CS can also be realized in the optical domain [9,10]. In [9], chirped optical pulses are modulated by a sparse signal and then a random sequence; the optical mixed pulses are compressed by using a dispersion medium to implement the integration operation. In [10], the optical integration was realized in a way as delay-and-sum by using multi-wavelength source and dispersive fiber.

In this letter, we propose a novel realization of photonics-assisted CS with optical signal processing technique to realize low-pass filtering. The low-pass filter presented here can replace the aforementioned integrator while its implementation is quite simple. In the system, a continuous-wave (CW) light source with single wavelength and two conventional EOMs for signal modulation and random mixing are employed. A dispersive element is added before the PD to achieve frequency-dependent RF power fading which acts as the required low-pass filtering. Compared with our previous work in [10], which implements a multi-tap microwave photonic filter with a multi-wavelength optical source, the low pass filtering in this paper is realized with a single CW light source. In addition, the frequency response of the photonic filter given here can be adjusted by using a tunable dispersion element in the photonic link.

2. Operation principle

The schematic illustration of the proposed photonics-assisted CS is given in Fig. 1. In the system, an incoming spectrally sparse signal $x(t)$ is modulated on a CW light via a Mach–Zehnder modulator (MZM). The modulated optical signal is mixed with a pseudo-random bit sequence (PRBS) $r(t)$ via a second MZM. The bit rate of $r(t)$ should be equal to or above the Nyquist rate of $x(t)$. The mixed optical signal passes through a length of dispersive fiber and is then converted to an electrical signal by a PD. Sub-Nyquist samples obtained by the digitizer are sent to a digital signal processing module for signal reconstruction with a sparse recovery algorithm.

The normalized optical power of the mixed signal at the output of the second MZM can be written as

$$P_{mixed} = [1 + m_1 x(t)][1 + m_2 r(t)] = x'(t)r'(t) \quad (1)$$

where m_1 and m_2 are the modulation depths. A double-sideband modulated optical signal propagating through a dispersive fiber would lead to a frequency-dependent RF power fading. The frequency response can be expressed as [16]

$$H(f) = \cos(\pi D L \lambda^2 f^2 / c) \quad (2)$$

where D is the dispersion coefficient of the fiber in ps/(nm km), L is the fiber length, λ is the wavelength of the optical carrier, f is the modulating frequency and c is the velocity of light in vacuum. The portion between dc and the first dip in the frequency response of (2) can be viewed as the response of a low-pass filter.

Therefore, the measurement matrix Φ of our CS system can be modeled by Φ=DHR, where $R = diag[r'(t)]$ is an $N \times N$ diagonalized matrix denoting the random sequence, H is an $N \times N$ matrix denoting the impulse response of the low-pass filter, and D is an $M \times N$ matrix representing the sub-sampling of the digitizer.

3. Experimental results and discussion

A proof-of-concept experiment with the setup shown in Fig. 1 is implemented to demonstrate the proposed photonics-assisted CS. The wavelength of the applied CW laser is 1550 nm. Two MZMs with bandwidth of 40 GHz are used for signal modulation

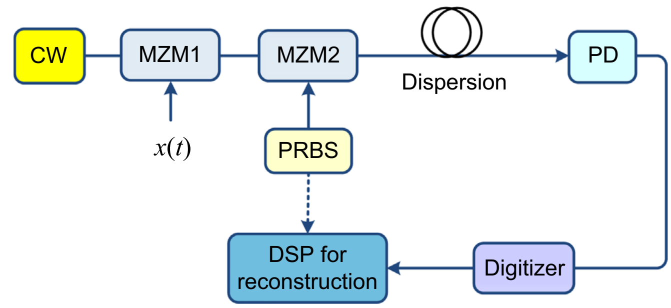

Fig. 1. Schematic illustration of the proposed photonic CS structure (CW: continuous-wave laser, MZM: Mach–Zehnder modulator, PRBS: pseudo-random bit sequence, PD: photodetector, DSP: digital signal processing).

and PRBS modulation. A coil of dispersion compensation fiber (DCF) with total dispersion amount of 4400 ps/nm at 1550 nm is applied as the dispersive element. An erbium-doped fiber amplifier is used to compensate the link loss. The frequency response of the system is measured without applying the unknown sparse signal. The measured and the predicted frequency responses are shown in Fig. 2(a). It is equivalent to a low-pass filter with a 3-dB bandwidth of around 3 GHz. The calculated impulse response based on the measured frequency response is shown in Fig. 2(b), which is used to construct the matrix H.

In the experiment, a three-tone RF signal with frequencies of 310 MHz, 1 GHz and 2 GHz within a bandwidth of 2.5 GHz is employed as the spectrally sparse signal to be measured. We set the length of signal N=10,000. The spectrum of the input signal is shown in Fig. 3(a). The bit rate of the applied PRBS is 5 Gb/s. The electrical signal from the PD is captured by a real time oscilloscope with a sampling rate of 5 GS/s. As the required sampling rate of the digitizer in the CS is much lower than the Nyquist rate, the data captured by the oscilloscope is further down-sampled in a program with a down-sampling rate decided by the required compression factor (N/M). Fig. 3(b) shows a down-sampled signal with a compression factor of 5, which means the equivalent sampling rate of the digitizer is 1 GS/s, i.e., 1/5 of the Nyquist rate of the input signal.

In the signal reconstruction process, the sparse recovery algorithm developed by Figueiredo is applied to reconstruct the original signal from the sub-Nyquist sampled signal [17]. Firstly, the compression factor is set to be 5. Fig. 3(c) and (d) shows the reconstructed signal in the frequency and time domain, respectively. Accurate signal reconstruction is observed from the results in both the time and frequency domain. In order to evaluate the performance of the signal reconstruction, the recovery error estimated by $\|\hat{x} - x\|_2^2 / \|x\|_2^2$ [6] and averaged over 100 times of reconstruction is calculated to be around 0.17. Here, x and $\hat{x}$ denote the input signal and the recovered signal, respectively. Next, the compression factor is increased to be 10. The reconstructed spectrum and time-domain signal are shown in Fig. 3(e) and (f), respectively. In this case, the recovery error averaged over 100 times of reconstruction is calculated to be around 0.25. It is seen the performance of the signal recovery is acceptable even under a compression factor of 10, despite that the noise level and the recovery error increase with the compression factor,

In order to show the potential of the proposed scheme for the sparse sampling and signal recovery within wider bandwidth and with more frequency components, computer simulations are performed. A signal with five tones, 1.0, 3.0, 5.0, 6.0 and 9.5 GHz, within a bandwidth of 10 GHz is to be tested. The signal-to-noise ratio (SNR) of the input signal is set as 25 dB. The bit rate of the