Photonic technologies for undersampling and compressive sensing of high-speed RF signals

George C. Valley, George A. Sefler, T. Justin Shaw
The Aerospace Corporation, Los Angeles, CA, USA 90009-2957
george.valley@aero.org

Abstract: We review photonic subsystems for undersampling and compressive sensing of GHz-band RF signals. We focus on methods for performing the compressive measurement and on the properties of RF signals amenable to such sampling.

OCIS codes: (320.7085) Ultrafast information processing; Data processing by optical means; (060.2360) Fiber optics links and subsystems; (250.4743) Optical processing devices.

1. Introduction

After almost 4 decades of work on photonic analog-to-digital converters (ADCs) [1] and intensive on-going work on electronic ADCs, ADCs are not available that can digitize an input bandwidth of more than 10 GHz with a resolution greater than 10 effective number of bits (ENOB). Even if such ADCs existed, however, they might not be useful for many applications simply because the data rate is so large. For example, an ADC that samples at 25 gigasamples/sec (GSPS) with 12 read-out bits has a data rate of 300 gigabits/sec (Gbps). Direct transmission from the ADC to a remote user probably requires an optical link, which is not possible in many applications. Storing data at this rate fills a 16 TB hard disk in less than 10 minutes. Digital compression to a more manageable rate, such as 1 Gbps, requires both substantial computing resources and a highly compressible RF signal. Compressive sensing (CS) provides an alternative solution for detecting such wide bandwidth, sparse signals [2-4]. In CS, the input RF signal is mixed down in dimension through an analog measurement matrix (MM) and Nyquist rate sampling is replaced by undersampling at a rate on the order of the sparsity of the RF signal. For example, for an input signal consisting of \(K = 50\) sinusoids at random frequencies up to 10 GHz, Nyquist rate sampling at 20 GSPS would generate \(N = 20,000\) samples for a 1 \(\mu\)s time window of interest, while CS would require about \(M \sim 200\) samples \([M \sim K \log(N/K) [2]]\) to recover the signal.

2. Compressive Sensing Measurement Matrix

The critical component in a CS system is the measurement matrix (MM). The function of a MM is equivalent to multiplying the signal by an \(M \times N\) wide matrix with \(M\) uncorrelated rows as illustrated in Fig. 1 (left). Fig. 1 (right) shows an electronic implementation [3,4]. The system makes \(M\) copies of the incoming RF signal, multiplies each copy by a different pseudo-random bit sequence (PRBS), and integrates the mixed signals for the duration of the time window. One of many algorithms now available that can recover sparse signals without ambiguity is used to obtain the input RF from the \(M\) measurements. These algorithms all rely on accurate knowledge of the MM [5], which in this case includes not just the 1’s and 0’s of the PRBSs, but also any amplitude noise and timing jitter of the PRBS bits. Since the bit rate of the PRBSs is the same as the Nyquist sampling rate required for direct digitization of the RF signal, the PRBSs are subject to the same sources of amplitude noise and timing jitter that limit the performance of conventional ADCs at GSPS rates. This has suggested to many authors that the MM might be implemented using photonics with less jitter and noise or with static distortions that can be calibrated.

Fig. 1. Schematic CS system (left) and implementation in the electronic domain that mixes RF with independent pseudo-random bit sequences (right) [3,4].
3. Photonic compressive sensing measurement matrices

Optical implementations of CS systems have been developed that use spatial light modulators (SLM), fiber-coupled intensity modulators, wavelength division multiplexers, and multi-mode waveguide speckle patterns to multiply the input RF signal by pseudo-random patterns [6-16]. Fig. 2 shows our first approach using time-wavelength mapping and an SLM for a MM [6]. This approach was demonstrated using a 1D SLM [7] and synchronized RF signals with the \( M \) measurements taken serially in time. The free-space propagation, however, is bulky and undesirable for applications with vibration. Several researchers proposed and demonstrated systems in which the PRBSs are mixed with the RF signal in the optical domain using cascaded intensity modulators as shown in Fig. 3 [9]. These systems are subject to limitations similar to the purely electronic CS system due to noise and jitter in the electronic PRBS generators. A way around this issue, shown in Fig. 4, is to start with a broadband laser pulse, stretch it in time with a dispersive medium, apply a low rate PRBS sequence, and then compress the pulse/PRBS sequence before mixing with the RF signal [15,16]. Fig. 5 shows a new method for performing the CS with chirped optical pulses and a multimode waveguide. Here the chirped optical pulse is input to a multimode fiber or planar waveguide with length and width chosen so that a detector array at the output plane makes \( M \) measurements of the RF multiplied by independent pseudo-random waveforms [17]. We have shown that the measured speckle patterns as a function of wavelength in the output plane of a 1-m long, 0.22 NA, 105-micron diameter step-index fiber satisfy the criteria for a good CS measurement matrix and simulations show that sparse RF signals consisting of a small number of pulses or sinusoids can be recovered using this system.

![Fig. 2. Photonic CS system using a spatial light modulator to apply independent PRBSs to an RF modulated optical signal [6-8].](image1)

![Fig. 3. Photonic CS system using optical modulators to apply PRBS to multi-wavelength source prior to multiplexing and modulation with an RF signal [9].](image2)
One channel of a photonic CS system that uses time stretching prior to modulation with a PRBS sequence to reduce jitter and compression to decrease sample time of PRBS [15, 16].

Fig. 5. Photonic compressive sensing system using a multi-mode waveguide to apply independent random profiles to multiple locations in the output of a multi-mode optical waveguide.

4. Acknowledgement: This work was supported under The Aerospace Corporation’s Independent Research and Development Program.

5. References