A hardware implementation of random demodulation analog-to-information converter

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Abstract: The analog-to-information converter (AIC) based on compressed sensing samples the analog signals at sub-Nyquist rate. This paper presents a low-cost hardware implementation of AIC based on random demodulation. The realization consists of a sampling part and a transmission part, which are connected by using a FPGA chip. In the former, the input analog signal is modulated with a pseudo-random sequence, and sampled with sub-Nyquist rate to obtain low-dimensional measurements. In the latter, the measurements are transmitted with user datagram protocol to the computer. The experimental results demonstrate the effectiveness of the hardware implementation.

Keywords: compressed sensing, analog-to-information converter, random demodulation, hardware platform

Classification: Electron devices, circuits and modules

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1 Introduction

The theory of compressed sensing (CS) exploits the sparse prior to represent the signals with fewer measurements than the number stated in the Nyquist theorem [1]. According to CS theory, these few measurements are obtained by multiplying signals with a measurement matrix. To obtain compressed measurements directly from an analog signal at sub-Nyquist rate, analog-to-information converter (AIC) has been proposed as a practical technique.

Currently, many AIC architectures have been designed in the literature, such as random demodulation AIC (RD-AIC) [2], modulated wideband converters (MWC) [3], random-modulation pre-integrator (RMPI) [4], partial segmented AIC [5], and so on. Unfortunately, although many works discussed the structures of AIC, only few works discussed the practical hardware implementation, e.g., [4, 6, 7, 8, 9, 10, 11]. [6] proposed the hardware implementation of an AIC scheme based on MWC, and [4, 7] presented the hardware platforms of RMPI. For RD-AIC, [8, 9, 10, 11] described the theory and hardware implementation; however, they only gave the simulated results.

In this paper, we realize a simple and low-cost hardware platform of RD-AIC structure. The platform, controlled by FPGA, consists of a sampling part and a transmission part. The sampling part is used to convert the input analog signal to low-dimensional digital measurements, and the transmission part sends the measurements through the Ethernet to a computer to reconstruct the original signal. We show the performance of our hardware platform for both the single-tone signal and the multi-tone signal. The reconstruction results demonstrate that the input analog sparse signals can be reconstructed reliably with a very low sampling rate, which is 1/10 times of the traditional Nyquist rate. This proportion is superior to the 1/4 in the recent work [10].

2 Backgrounds

Compressed sensing deals with the acquisition and recovery of sparse signals from a small number of random linear measurements. In the acquisition phase, a K -sparse signal $\mathbf{x} \in \mathcal{R}^N$ can be represented by its fewer measurements in the form of

$$\mathbf{y} = \Phi \mathbf{x}, \quad (1)$$

where $\mathbf{y} \in \mathbb{R}^M$ is the measurement vector, and $\Phi \in \mathbb{R}^{M \times N}$ is the measurement matrix ($K < M < N$) [1].

In the recovery phase, the original signal $\mathbf{x}$ is recovered from $\mathbf{y}$ based on the prior information of signal sparsity. [1] showed that the sparse signal can be reliably recovered under some conditions on the measurement matrix Φ by solving an l_1 minimization problem. Many other recovery algorithms are also reported thereafter. Among them, orthogonal matching pursuit (OMP) [12] is a popular greedy algorithm, which has been used widely.

3 Practical implementation

3.1 Hardware architecture

Based on the theoretical structure in [2], we implement RD-AIC hardware architecture as shown in Fig. 1, which obtain digital measurements directly from analog signals. The proposed architecture consists of a sampling part, a transmission part, and a FPGA chip, where the FPGA connects the first two parts.

Fig. 1. RD-AIC architecture

The sampling part includes an inverter, a low-pass filter and an analog-to-digital converter (ADC), where the ADC works with a sub-Nyquist rate and outputs the low-dimensional measurements. The inverter is used to realize the demodulation with a pseudo-random sequence, which spreads the frequency content of the signal. By using an inverter as shown in Fig. 2 rather than a multiplier, the hardware cost is greatly reduced. The inverter is implemented by a pair of controlled switches, where the two switches are controlled synchronously by the pseudo-random sequence that is generated by FPGA, but their states are always opposite. Specifically, when the incoming bit of pseudo-random sequence is positive, the positive switch is on, and the negative switch is connected to the ground. Then signal is input through the upper branch in Fig. 2, and vice versa. The low-pass filter is used to avoid the frequency aliasing phenomenon, and the cut-off frequency is set to be 5 MHz. In this design, we used a 5 order π type LC filter. The filtered results will be

sampled with 10 MHz sampling rate and quantized with 14 bits by ADC to obtain the measurements.

Fig. 2. The implementation of inverter and filter

The FPGA buffers the obtained measurements and divides them into frames. Then, it implements the communication protocol of ethernet and transmits the measurements with user datagram protocol (UDP) frames. The transmission part sends the buffered frames to the computer through the Ethernet, and finally the original signal is reconstructed at the computer with the received measurements.

The parameters of the system are shown in Table I. Note that the sampling rate is only 1/10 times of the Nyquist sampling rate. In addition, Fig. 3 gives the photo of our realized hardware platform.

Table I. Parameters of the system

system clock	125 MHz
bandwidth of input signal	50 MHz
rate of pseudo-random sequence	100 MHz
sub-Nyquist sampling rate	10 MHz
number of quantization bits	14
length of measurements in one frame	$M = 100$
length of reconstructed signal in one frame	$N = 1000$

3.2 System model

Suppose that the input signal $s(t)$ is sparse in continuous fourier basis, which can be expressed as

$$s(t) = \sum_{n=1}^N \alpha_n \Psi_n(t) \quad (2)$$

where $\Psi_n(t)$ represents the continuous fourier basis function and α_n is the sparse coefficient. Let $p_c(t)$ stand for the pseudo-random sequence and $h(t)$ the impulse response of the low-pass filter. Then, for any frame, we can write the m th measurement ($m = 1, \dots, M$) as

$$y_m = \sum_{n=1}^N \alpha_n \int_{-\infty}^{+\infty} \Psi_n(\tau) p_c(\tau) h(Tm - \tau) d\tau \quad (3)$$

Fig. 3. Hardware platform

where T stands for the sampling period in ADC. According to [2], by defining the measurement matrix $\mathbf{V}$ with the entries as $v_{m,n} = \int_{-\infty}^{+\infty} \Psi_n(\tau) p_c(\tau) h(t - \tau) d\tau$, we obtain

$$\mathbf{y} = \mathbf{V}\alpha \quad (4)$$

where $\mathbf{y} = [y_1, y_2, \dots, y_M]^T$ is the measurement vector, and $\alpha = [\alpha_1, \alpha_2 \dots \alpha_n]^T$ is the coefficient vector. Thus, the reconstruction of α , and thus the input signal $s(t)$, from the measurements $\mathbf{y}$ can be achieved by using any CS reconstruction algorithms. In this paper, we use OMP as the reconstruction algorithm.

4 Experimental results

To verify the performance of the implemented hardware platform, we first input a single-tone signal with frequency 42.1 MHz. Fig. 4 shows the reconstructed signal in frequency domain, where the nonzero position is reconstructed successfully, and the spurious free dynamic range is obtained as 10.18 dB. Note that by using other recovery algorithms with higher precision, the reconstruction performance can be further improved.

Fig. 4. Reconstruction result of single-tone signal

Fig. 5 gives the reconstruction results when a multi-tone signal consisting of cosines at 16.3, 21.3, 26.3 and 31.3 MHz with the same amplitude is input into the

Fig. 5. Reconstruction result of multi-tone signal

platform. The nonzero positions are reconstructed successfully, however, the corresponding amplitudes are not equal. We note that such error can also be reduced by using reconstruction algorithms with higher quality.

5 Conclusion

In this paper, we describe a hardware implementation of the RD-AIC scheme, which is simple and low-cost. Using inverter, filters, ADC and FPGA, the implemented RD-AIC hardware architecture enables the sparse analog signal to be sampled at a sub-Nyquist rate directly. Experimental results show that the hardware platform reconstructs the nonzero positions correctly for both the single-tone and multi-tone signals. However, further efforts are needed to perfectly recover the amplitudes. In addition, currently we reconstruct the signals at computer, one future work is to realize the practical hardware platform for reconstruction.

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