

# Analog-to-Information Conversion via Random Demodulation

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*Abstract*— Many problems in radar and communication signal processing involve radio frequency (RF) signals of very high bandwidth. This presents a serious challenge to systems that might attempt to use a high-rate analog-to-digital converter (ADC) to sample these signals, as prescribed by the Shannon/Nyquist sampling theorem. In these situations, however, the information level of the signal is often far lower than the actual bandwidth, which prompts the question of whether more efficient schemes can be developed for measuring such signals. In this paper we propose a system that uses modulation, filtering, and sampling to produce a low-rate set of digital measurements. Our “analog-to-information converter” (AIC) is inspired by the recent theory of Compressive Sensing (CS), which states that a discrete signal having a sparse representation in some dictionary can be recovered from a small number of linear projections of that signal. We generalize the CS theory to continuous-time sparse signals, explain our proposed AIC system in the CS context, and discuss practical issues regarding implementation.

## I. INTRODUCTION

The power, stability, and low cost of digital signal processing (DSP) have pushed the *analog-to-digital converter* (ADC) increasingly close to the front-end of many important sensing, imaging, and communication systems. Unfortunately, many systems, especially those operating in the radio frequency (RF) bands, severely stress current ADC technologies. For example, some important radar and communications applications would be best served by an ADC sampling over 5 GSamples and resolution of over 20 bits, a combination that greatly exceeds current capabilities.

It could be decades before ADCs based on current technology will be fast and precise enough for these applications. And even after better ADCs become available, the deluge of data will swamp back-end DSP algorithms. For example, sampling a 1GHz band using 2 GSamples at 16 bits-per-sample generates data at a rate of 4GB/s, enough to fill a modern hard disk in roughly one minute. In a typical application, only a tiny fraction of this information is actually relevant; the wideband signals in many RF applications often have a large bandwidth but a small “information rate” [1].

Fortunately, recent developments in mathematics and signal processing have uncovered a promising approach to the ADC bottleneck that enables sensing at a rate comparable to the signal’s information rate. A new field, known as *Compressive*

*Sensing* (CS) [2], [3], establishes mathematically that a relatively small number of non-adaptive, linear measurements can harvest all of the information necessary to faithfully reconstruct sparse or compressible signals. An intriguing aspect of the theory is the central role played by randomization.

CS suggests a new framework for *analog-to-information conversion* (AIC) as an alternative to conventional ADC. A typical system is illustrated in Figure 1. The information extraction denoted by the operation  $\Phi$  replaces conventional sampling. Back-end DSP reconstructs the signal, approximates the signal, computes key statistics, or produces other information. For sparse input signals, AIC promises greatly reduced digital data rates (matching the information rate of the signal), and it offers the ability to focus only on the relevant information.

In this paper, we develop a practical AIC architecture based on a wideband pseudorandom demodulator and a low-rate sampler that can efficiently acquire a large class of compressible signals. The remainder of the paper is organized as follows. In Section II, we explain the traditional discrete-time CS problem, discuss methods for extending the basic theory to continuous-time signals, and present a system-level AIC design for low-rate sampling of continuous-time signals having a low information rate. In Section III, we discuss practical issues surrounding the implementation of such a system. Section IV conducts a series of simulation experiments to validate the design. We conclude in Section V.

## II. COMPRESSIVE SENSING FOR ANALOG SYSTEMS

### A. Compressive sensing background

CS deals with the problem of acquiring an  $N \times 1$  discrete-time signal vector  $x$  that is  $K$ -sparse or compressible in some sparsity basis matrix  $\Psi$  (where each column is a basis vector  $\psi_i$ ). By  $K$ -sparse we mean that only  $K \ll N$  of the expansion coefficients  $\alpha$  representing  $x = \Psi\alpha$  are nonzero. By compressible we mean that the entries of  $\alpha$ , when sorted from largest to smallest, decay rapidly to zero; such a signal is well approximated using a  $K$ -term representation.

The theory of CS as introduced by Candès, Romberg, and Tao [2] and Donoho [3] demonstrates that a signal that is  $K$ -sparse or compressible in one basis  $\Psi$  can be recovered

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