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978-1-107-01883-9 - Compressive Sensing for Wireless Networks
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1 Introduction

Sampling is not only a beautiful research topic with an interesting history, but also a subject with high practical impact, at the heart of signal processing and communications and their applications. Conventional approaches to sample signals or images follow Shannon's celebrated theorem: the sampling rate must be at least twice the maximum frequency present in the signal (the so-called Nyquist rate) has been to some extent accepted and widely used ever since the sampling theorem was implied by the work of Harry Nyquist in 1928 ("Certain topics in telegraph transmission theory") and was proved by Claude E. Shannon in 1949 ("Communication in the presence of noise"). However, with the increasing demand for higher resolutions and an increasing number of modalities, the traditional signal-processing hardware and software are facing significant challenges. This is especially true for wireless communications.

The compressive sensing (CS) theory is a new technology emerging in the interdisciplinary area of signal processing, statistics, optimization, as well as many application areas including wireless communications. By utilizing the fact that a signal is sparse or compressible in some transform domain, CS can acquire a signal from a small set of incoherent measurements with a sampling rate much lower than the Nyquist rate. As more and more experimental evidence suggests that many kinds of signals in wireless applications are sparse, CS has become an important component in the design of next-generation wireless networks.

This book aims at developing a unified view on how to efficiently incorporate the idea of CS over assorted wireless network scenarios. This book is interdisciplinary in that it covers materials in signal processing, optimization, information theory, communications, and networking to address the issues in question. The primary goal of this book is to enable engineers and researchers to understand the fundamentals of CS theory and tools and to apply them in wireless networking and other areas. Additional important goals are to review some up-to-date and state-of-the-art techniques for CS, as well as for industrial engineers to obtain new perspectives on wireless communications.

1.1 Motivation and objectives

CS is a new signal-processing paradigm and aims to encode sparse signals by using far fewer measurements than those in the Nyquist setup. It has attracted a great amount of attention from researchers and engineers because of its potential to revolutionize many sensing modalities. For example, in a cognitive radio system, to increase the efficiency of the utility of spectrum, it is necessary to separate occupied spectrum and unoccupied spectrum first, which becomes a spectrum sensing problem and can leverage CS techniques. However, as with many great techniques, there is a gap between the theoretical breakthrough of CS and its practical applications, in particular the applications in wireless networking. This motivates us to write a book to narrow this gap by presenting the theory, models, algorithms, and applications in one place. The book was written with two main objectives. The first one is to introduce the basic concepts and typical steps of CS. The second one is to demonstrate its effective applications, which will hopefully inspire future applications.

1.2 Outline

In order to achieve the objectives, the book first presents an introduction to the basics of wireless networks. The book is written in two parts as follows: the first part studies the CS framework, and the second part discusses its applications in wireless networks by presenting several existing implementations. Let us summarize the remaining chapters of this book as follows:

Chapter 2 Overview of wireless networks
: Different wireless network technologies such as, cellular wireless, WLAN, WMAN, WPAN, WRAN technologies, and the related standards are reviewed. The review includes the basic components, features, and potential applications. Furthermore, advanced wireless technologies such as cooperative communications, network coding, and cognitive radio are discussed. Some typical wireless networks such as ad hoc/sensor networks, mesh networks, and vehicular networks are also studied. The research challenges related to the practical implementations at the different layers of the protocol stack are discussed.

Part I: Compressive sensing framework

Before we discuss how to employ CS in different wireless network problems, the choice of a design technique is crucial and must be studied. In this context, this part presents different CS techniques, which are applied to the design, analysis, and optimization of wireless networks. We introduce the basic concepts, theorems, and applications of CS schemes. Both theoretical analysis and numerical algorithms are discussed and CS examples are given. Finally, we discuss the current state-of-the-art for CS-based analog-to-digital converters.

Chapter 3 Compressive sensing framework
: This chapter overviews the basic concepts, steps, and theoretical results of CS. It is a methodology using incoherent linear measurements to recover sparse signals. The preliminaries and notation are set up for further usage. This chapter also

presents the elements of a typical CS process. The conditions that guarantee successful CS encoding and decoding are presented.

Chapter 4 Sparse optimization algorithms

There are a collection of various algorithms for recovering sparse solutions, as well as low-rank matrices, from their linear measurements. Generally, they can be classified into optimization models and algorithms and non-optimization ones. The chapter gives more emphasis on the first class and briefly discusses the second one. When presenting algorithms, the big picture is focused, and some detailed analyses are omitted and referred to related papers. The advantages and disadvantages of presented algorithms are discussed to help the reader pick appropriate ones to solve their own problems.

Chapter 5 CS Analog-to-digital converter

Wideband analog signals push contemporary analog-to-digital conversion systems to their performance limits. In many applications, however, sampling at the Nyquist rate is inefficient because the signals of interest contain only a small number of significant frequencies relative to the limited band, though the locations of the frequencies may not be known a priori. In this chapter, we discuss several possible strategies in the literature. First, we study the CS-based ADC and its applications to 60 GHz communication. Then we describe the random demodulator, which demodulates the signal by multiplying it with a high-rate pseudonoise sequence and smears the tones across the entire spectrum. Next, we study the modulated wideband converter, which first multiplies the analog signal by a bank of periodic waveforms. The product is then low-pass filtered and sampled uniformly at a low rate, which is orders of magnitude smaller than Nyquist. Perfect recovery from the proposed samples is achieved under certain necessary and sufficient conditions. Finally, we study Xampling, a design methodology for analog CS in which analog band-limited signals are sampled at rates far lower than Nyquist without loss of information.

Part II: Compressive Sensing Applications in Wireless Networks

To exploit CS in wireless communication, many applications using CS are given in detail. However, CS has more places to be adopted and emphasized. Because of the authors' limited time and effort, we have only contributed those listed related to wireless networking in the book, but hope this can motivate the readers to discover more in the future. The process of designing a suitable model for CS and problem formulation is also described to help engineers who are also interested in using the new technology – CS – in their research.

Chapter 6 Compressed channel estimation

In communications, CS is largely accepted for sparse channel estimation and its variants. In this chapter, we highlight the fundamental concepts of CS channel estimation with the fact that multipath channels are sparse in their equivalent baseband representation. Popular channels such as OFDM and MIMO are investigated by use of CS. Then, a belief-propagation-based channel estimation scheme is used with a standard bit-interleaved coded OFDM transmitter, which performs joint sparse-channel estimation and data decoding. Next, blind channel estimation is studied to show how to use the CS and matrix completion. Finally, a special channel, the underwater acoustic channel, is investigated from the aspect of CS channel estimation.

Chapter 7 Ultra-wideband systems

Ultra-wideband (UWB) has been heavily studied due to its wide applications like short-range communications and localizing. However, it suffers from the extremely narrow impulse width that makes the design of the receiver difficult. Meanwhile, the narrow impulse width and low duty cycle also provides the sparsity in the time domain that facilitates the application of CS. In this chapter, we will provide a brief model of UWB signals. Then, we will review different approaches of applying CS to enhance the reception of UWB signals for general purposes. The waveform template-based approach and Bayesian CS method will be explained as two case studies.

Chapter 8 Positioning

Precise positioning (e.g., of the order of centimeters or millimeters) is useful in many applications like robot surgery. Usually it is achieved by analyzing the narrow pulses sent from the object and received at multiple base stations. The precision requirement places a pressing demand on the timing acquisition of the received pulses. In this chapter, we discuss the precision positioning using UWB impulses. In contrast to the previous chapter, this chapter is focused on the CS with the correlated signals received at the base stations. We will first introduce the general models and approaches of positioning. Then, we will introduce the framework of Bayesian CS and explain the principle of using the a priori distribution to convey the correlated information. Moreover, we will introduce the general principle of how to integrate CS with the subsequent positioning algorithm like the Time Difference Arrival (TDOA) approach, which can further improve the precision of positioning.

Chapter 9 Multiple access

In wireless communications, an important task is the multiple access that resolves the collision of the signals sent from multiple users. Traditional studies assume that all users are active and thus the technique of multiuser detection can be applied. However, in many practical systems like wireless sensor networks, only a random and small fraction of users send signals simultaneously. In this chapter, we study the multiple access with sparse data traffic, in which the task is to recover the data packets and the identities of active users. We will formulate the general problem as a CS one due to the sparsity of active users. The algorithm of reconstructing the above information will be described. In particular, the feature of discrete unknowns will be incorporated into the reconstruction algorithm. The CS-based multiple access scheme will further be integrated with the channel coding. Finally, we will describe the application in the advanced metering infrastructure (AMI) in a smart grid using real measurement data.

Chapter 10 Cognitive radio networks

In wideband cognitive radio (CR) networks, spectrum sensing is an essential task for enabling dynamic spectrum sharing. For sensor networks, the event detection is critical for the whole network performance. But it entails several major technical challenges: very high sampling rates required for wideband processing, limited power and computing resources per CR or sensor, frequency-selective wireless fading, possible failure of reporting to the fusion center, and interference due to signal leakage from other coexisting CRs or sensor transmitters. The algorithms in the literature using CS, joint sparsity recovery, and matrix completion are reviewed. The dynamic for such a system is also investigated. Then the distributed solution is studied based on decentralized consensus optimization algorithms. Next, by utilizing a Bayesian CS framework, the sampling reduction advantage of CS can be achieved with significantly less computational complexity. Moreover, the CR or sensor does not have to reconstruct the entire signal because it is only interested in detecting the presence of Primary Users, which can also reduce the complexity. Finally, the joint spectrum sensing and localization problem is introduced.

In conclusion, this book focuses on teaching engineers to use CS and connecting engineer research and CS. On the other hand, it helps mathematicians to obtain feedback from engineers in their design and problem solving. This connection will help fill the gap and benefit both sides. This book will serve this purpose by explaining CS in engineering language and concentrating on the applications in wireless communication.

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2 Overview of wireless networks

A wireless network refers to a telecommunications network that interconnects between nodes that are implemented without the use of wires. Wireless networks have experienced unprecedented growth over the past few decades, and they are expected to continue to evolve in the future. Seamless mobility and coverage ensure that various types of wireless connections can be made anytime, anywhere. In this chapter, we introduce some basic types of wireless networks and provide the reader with some necessary background on the state-of-the-art developments.

Wireless networks use electromagnetic waves, such as radio waves, for carrying the information. Therefore, their performance is greatly affected by the randomly fluctuating wireless channels. To develop an understanding of channels, in Section 2.1 we will study the radio frequency band first, then the existing wireless channel models used for different network scenarios, and finally the interference channel.

There exist many wireless standards, and we describe them according to the order of coverage area, starting with cellular wireless networks. In Section 2.2.1, we provide an overview of the key elements and technologies of the third-generation (3G) wireless cellular network standards. WiMax, based on the IEEE 802.16 standard for the wireless metropolitan area network, is discussed in Section 2.2.2. In Section 2.2.3, we study a wireless local area network (WLAN or WiFi), which is a network in which a mobile user can connect to a local area network through a wireless connection. A wireless personal area network (WPAN) is a personal area network for wireless interconnecting devices centered around an individual person's workspace. IEEE 802.15 standards specify some technologies used in Bluetooth, ZigBee, and ultra-wideband, and these are investigated in Section 2.2.4. Networks without any infrastructure, such as ad hoc and sensor networks, are also discussed in Sections 2.2.5 and 2.2.6, respectively.

Finally, we briefly discuss various advanced wireless technologies in Section 2.3, such as OFDM, MIMO (space-time coding, beamforming, etc.), cognitive radios, localization, scheduling, and multiple access. The motivations for deploying such techniques, the design challenges to maintain basic functionality, and recent developments in real implementation are explained in detail.

2.1 Wireless channel models

2.1.1 Radio propagation

Unlike wired channels, which are stationary and predictable, wireless channels are extremely random and hard to analyze. Modeling wireless channels is one of the most

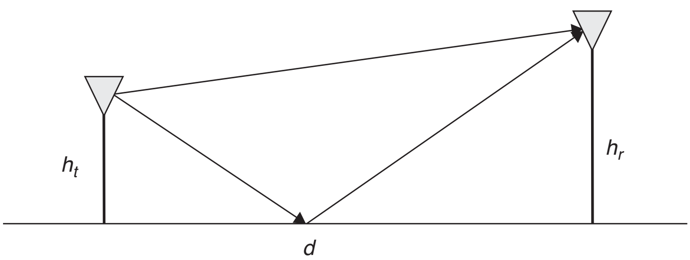

Figure 2.1 Reflection and two-ray model.

challenging tasks encountered in wireless network design. Wireless channel models can be classified as large-scale propagation models and small-scale propagation models relative to the wavelength.

Large-scale models predict behavior averaged over distances much longer than the wavelength. The models are usually functions of distance and significant environmental features and are roughly frequency independent. The large-scale models are useful for modeling the range of a radio system and rough capacity planning. Some large-scale theoretical models (e.g., first four) and large-scale experimental models (the rest) are listed as follows:

- Free space model
  Path loss is a measure of attenuation based only on the distance from the transmitter to the receiver. The free space model is only valid in the far-field and only if there is no interference and obstruction. The received power $P_r(d)$ of the free space model as a function of distance d can be written as

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}, \tag{2.1}$$

  where P_t is the transmit power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain, λ is the wavelength, and L is the system loss factor not related to propagation. Path loss models typically define a "close-in" point d_0 and reference other points from that point. The received power in dB form can be written as

$$P_d(d) \text{ dBm} = 10\log_{10}\left[\frac{P_r(d_0)}{0.001W}\right] + 20\log_{10}\left(\frac{d_0}{d}\right). \tag{2.2}$$

- Reflection model
  Reflection is the change in the direction of a wave front at an interface between two different media so that the wave front returns to the medium from which it originated. A radio propagation wave impinges on an object that is large compared with the wavelength, e.g., the surface of the Earth, buildings, or walls.

  A two-ray model is one of the most important reflection models for wireless channels. An example of a reflection and the two-ray model is shown in Figure 2.1. The two-ray model considers a model in which the receiving antenna sees a direct path signal as well as a signal reflected off the ground. Specular reflection, much

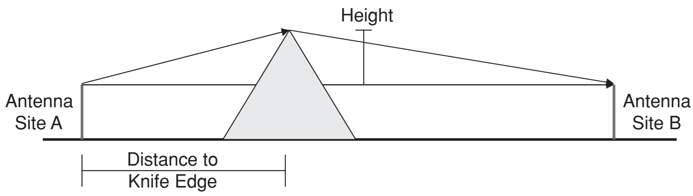

Figure 2.2 Diffraction and knife edge model.

like light off a mirror, is assumed and to a very close approximation. The specular reflection arrives with strength equal to that of the direct path signal (i.e., without loss in strength by reflection). The reflected signal shows up with a delay relative to the direct path signal and as a consequence, may add constructively (in phase) or destructively (out of phase). The received power of the two-ray model can be written as

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}, \tag{2.3}$$

where h_t and h_r are the transmitter height and receiver height, respectively, and d is the distance between the two antennas.

- Diffraction model
  Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface with sharp, irregular edges. Radio waves bend around the obstacle even when a line of sight (LOS) does not exist. In Figure 2.2, we show a knife edge diffraction model in which the radio wave of the diffraction path from the knife edge and the radio wave of LOS are combined at the receiver. Similar to the reflection, the radio waves might add constructively or destructively.
- Scattering model
  Scattering is a general physical process whereby the radio waves are forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass. In conventional use, this also includes deviation of reflected radiation from the angle predicted by the law of reflection. The obstructing objects are smaller than the wavelength of the propagation wave, e.g., foliage, street signs, and lampposts. One scattering example is shown in Figure 2.3.
- Log scale propagation model and log-normal shadowing model
  From the experimental measurement, the received signal power decreases logarithmically with distance. However, because of the variety of factors, the decreasing speed is very random. To characterize the mean and variance of this randomness, the log scale propagation model and log-normal shadowing model are used, respectively.

  The log scale propagation model generalizes path loss to account for other environmental factors. The model chooses a distance d_0 in the far-field and measures the path loss $PL(d_0)$. The propagation path loss factor α indicates the rate at which the path loss increases with distance. The path loss of the log scale propagation model is given

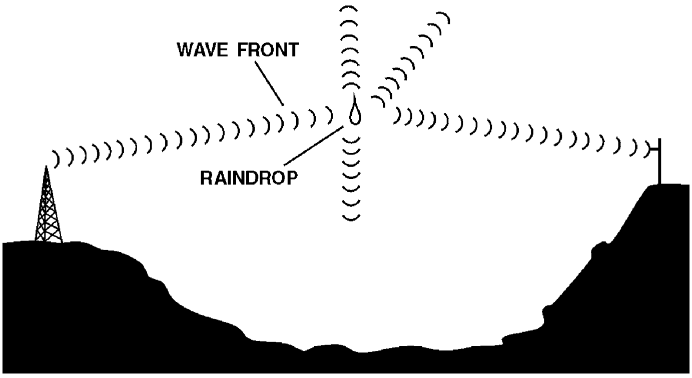

Figure 2.3 Scattering.

by

$$PL(d)\,(\text{dB}) = PL(d_0) + 10\alpha \log_{10}\left(\frac{d}{d_0}\right). \tag{2.4}$$

In the free space propagation model, the path loss factor α equals 2.

Shadowing occurs when objects block the LOS between the transmitter and the receiver. A simple statistical model can account for unpredictable "shadowing" as

$$PL(d)\,(\text{dB}) = PL(d) + X_0, \tag{2.5}$$

where X_0 is a 0-mean Gaussian random variable with variance typically from 3 to 12. The propagation factor and the variance of log-normal shadowing are usually determined by experimental measurement.

- Outdoor propagation models
  In the outdoor models, the terrain profile of a particular area needs to be taken into account for estimating the path loss. Most of the following models are based on a systematic interpretation of measurement data obtained in the service area. Some typical outdoor propagation models are Longley–Rice Model, ITU Terrain Model, Durkins Model, Okumura Model, Hatas Model, PCS Extension of the Hata Model, Walfisch and Bertoni Model, and Wideband PCS Microcell Model [1].
- Indoor propagation models
  For indoor applications, the distances are much shorter than those in the outdoor models. The variability of the environment is much greater, and key variables are layout of the building, construction materials, building type, and antenna location. In general, indoor channels may be classified either as LOS or obstruction with varying degrees of clutter. The losses between floors of a building are determined by the external dimensions and materials of the building, as well as the type of construction used to create the floors and the external surroundings. Some of the available indoor propagation models are Ericsson multiple breakpoint model, ITU model for indoor attenuation, log distance path loss model, attenuation factor model, and Devasirvathams model.

Small-scale (fading) models describe signal variability on a scale of wavelength. In fading, multipath and Doppler effects dominate. Fading is frequency dependent and time variant. The focus is on modeling "fading," which is the rapid change in signal strength over a short distance or length of time.

Multipath fading is caused by interference between two or more versions of the transmitted signal that arrive at slightly different times. The multipath fading causes rapid changes in signal strength over a small travel distance or time interval, random frequency modulation due to varying Doppler shifts on different multipath signals, and time dispersion caused by multipath propagation delays. The response of a multipath fading channel can be written as

$$h(t) = \sum_k a_k \delta(t - \tau_k), \tag{2.6}$$

where τ_k is the delay of the kth multipath and a_k is its corresponding amplitude.

To measure the time dispersion of multiple paths, power delay profile and root mean square (RMS) are the most important parameters. Power delay profiles are generally represented as plots of relative received power as a function of excess delay with respect to a fixed time delay reference. The mean excess delay is the first moment of the power delay profile and is defined as $\bar{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2}$. The RMS is the square root of the second central moment of the power delay profile, defined as $\sigma_\tau = \sqrt{\bar{\tau^2} - (\tau)^2}$, where $\bar{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2}$. Typical values of RMS delay spread are on the order of microseconds in outdoor mobile radio channels and on the order of nanoseconds in indoor radio channels.

Analogous to the delay spread parameters in the time domain, coherent bandwidth is used to characterize the channel in the frequency domain. Coherent bandwidth is the range of frequencies over which two frequency components have a strong potential for amplitude correlation. If the frequency correlation between two multipaths is above 0.9, then the coherent bandwidth is [1] $B_c = \frac{1}{50\sigma}$. If the correlation is above 0.5, this coherent bandwidth is $B_c = \frac{1}{5\sigma}$. Coherent bandwidth is a statistical measure of the range of frequencies over which the channel can be considered flat.

Delay spread and coherent bandwidth describe the time-dispersive nature of the channel in a local area, but they do not offer information about the time-varying nature of the channel caused by the relative motion of the transmitter and the receiver. Next, we define Doppler spread and coherence time, which describe the time-varying nature of the channel in a small-scale region.

Doppler frequency shift is due to the movement of the mobile users. Frequency shift is positive when a mobile moves toward the source; otherwise, the frequency shift is negative. In a multipath environment, the frequency shift for each ray may be different, leading to a spread of received frequencies. Doppler spread is defined as the maximum Doppler shift $f_m = \frac{v}{\lambda}$, where v is the mobile user's speed and λ is the wavelength. If we assume that signals arrive from all angles in the horizontal plane, the Doppler spectrum can be modeled as Clarke's Model [1].

Coherence time is the time duration over which the channel impulse response is essentially invariant. Coherence time is defined as $T_c = \frac{C}{f_m}$, where C is a constant [1]. This definition of a coherence time implies that two signals arriving with a time