Compressive Sensing for Wireless Networks

Zhu Han
Husheng Li
Wotao Yin

CAMBRIDGE

Compressive Sensing for Wireless Networks

ZHU HAN
University of Houston, USA

HUSHENG LI
University of Tennessee, USA

WOTAO YIN
Rice University, USA

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Mexico City

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9781107018839

First published 2013

Printed and bound by CPI Group (UK) Ltd, Croydon CR0 4YY

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Han, Zhu, 1974–
Compressive sensing for wireless networks / Zhu Han, University of Houston, USA, Husheng Li, University of Tennessee, USA, Wotao Yin, Rice University, USA.
pages cm
Includes bibliographical references and index.
ISBN 978-1-107-01883-9 (hardback)
1. Coding theory. 2. Data compression (Telecommunication) 3. Signal processing – Digital techniques. 4. Sampling (Statistics) I. Li, Husheng, 1975– II. Yin, Wotao. III. Title.
TK5102.92.H355 2013
621.39′81 – dc23 2013000272

ISBN 978-1-107-01883-9 Hardback

Compressive Sensing for Wireless Networks

Compressive sensing is a new signal-processing paradigm that aims to encode sparse signals by using far lower sampling rates than those in the traditional Nyquist approach. It helps acquire, store, fuse and process large data sets efficiently and accurately. This method, which links data acquisition, compression, dimensionality reduction, and optimization, has attracted significant attention from researchers and engineers in various areas. This comprehensive reference develops a unified view on how to incorporate efficiently the idea of compressive sensing over assorted wireless network scenarios, interweaving concepts from signal processing, optimization, information theory, communications, and networking to address the issues in question from an engineering perspective. It enables students, researchers, and communications engineers to develop a working knowledge of compressive sensing, including background on the basics of compressive sensing theory, an understanding of its benefits and limitations, and the skills needed to take advantage of compressive sensing in wireless networks.

Zhu Han is an Associate Professor in the Electrical and Computer Engineering Department at the University of Houston, Texas. He received an NSF CAREER award in 2010 and the IEEE Fred W. Ellersick Prize in 2011. He has co-authored papers that won the best paper award at the IEEE International Conference on Communications 2009, the 7th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt09), the IEEE Wireless Communication and Networking Conference, 2012 and IEEE Smartgridcomm Conference, 2012.

Husheng Li is an Assistant Professor in the Electrical and Computer Engineering Department at the University of Tennessee. He received the Best Paper Award of the EURASIP Journal on Wireless Communications and Networking in 2005 (together with his PhD advisor, Professor H. V. Poor), the Best Demo Award of IEEE Globecom in 2010, and the Best Paper Award at IEEE ICC in 2011.

Wotao Yin is an Associate Professor at the Department of Computational and Applied Mathematics at Rice University. He won an NSF CAREER award in 2008 and an Alfred P. Sloan Research Fellowship in 2009.

For the people I met in the Barneo ice camp, North Pole, who showed me the bravery to conquer any difficulty, which encouraged me to finish this challenging book

Zhu Han

To my wife, Min Duan, and my son, Siyi Li

Husheng Li

To those who advocate for intellectual honesty and defend academic integrity

Wotao Yin

Preface

Over the past few decades, wireless communications and networking have witnessed an unprecedented growth, and have become pervasive much sooner than anyone could have predicted. For example, cellular wireless networks are expected to become the dominant and ubiquitous telecommunication means in the next few decades. The widespread success of cellular and WLAN systems prompts the development of advanced wireless systems to provide access to information services beyond voice such as telecommuting, video conferencing, interactive media, real-time internet gaming, and so on, anytime and anywhere. The enormous potential demands for these wireless services require a careful design of the future networks. Many technical challenges remain to be addressed such as limited resources, adverse natures of wireless channels, interference, etc.

Today, with the increasing demand of higher resolution and increasing number of modalities, the traditional wireless signal processing hardware and software are facing significant challenges since the Nyquist rate, which is part of the dogma for signal acquisition and processing, has become too high in many wireless applications. How to acquire, store, fuse, and process these data efficiently becomes a critical problem. The most current solution to this problem is to compress after sensing densely. However, this oversampling-then-discarding procedure wastes time, energy, and/or other precious resources.

A new paradigm of signal acquisition and processing, named compressive sensing (CS), has emerged since 2004. Starting with the publication of "Compressed sensing" by D. Donoho, and a few seminal works by E. J. Candès, J. Romberg, and T. Tao, the CS theory, which integrates data acquisition, compression, dimensionality reduction, and optimization, has attracted lots of research attention. The CS theory consists of three key components: signal sparsity, incoherent sensing, and signal recovery. It claims that, as long as the signal to be measured is sparse or can become sparse under a certain transform or dictionary, the information in the signal can be encoded in a small number of incoherent measurements, and the signal can be faithfully recovered by tractable computation.

Since CS is so new a tool bearing a large number of potential applications in engineering, there is not yet a published book for the engineers. However, the applications of CS in wireless communication are very important and have the potential to revolutionize certain traditional design concepts. This produces the foremost motivation of this book: to equip engineers with the fundamental knowledge of CS and demonstrate its strong potential in wireless networking fields. Secondly, understanding a large portion of the existing CS results in the literature requires a good mathematical background, but this book is written at a level for the engineers. Most parts of this book are suitable for readers who want to broaden their views, and it is also very useful for engineers and researchers in applied fields who deal with sampling problems in their work.

We would like to thank Drs. Richard Baraniuk, Stephen Boyd, Rick Chartrand, Ekram Hossain, Kevin Kelly, Yingying Li, Lanchao Liu, Jia Meng, Lijun Qian, Stanley Osher, Zaiwen Wen, Zhiqiang Wu, Ming Yan, and Yin Zhang for their support and encouragement. We also would like to thank Lanchao Liu, Nam Nguyen, Ming Yan, and Hui Zhang for their assistance and Mr. Ray Hardesty for text editing. Finally, we would like to acknowledge NSF support (ECCS-1028782), ARL and ARO grant W911NF-09-1-0383 and NSF grant DMS-0748839.

ZHU HAN
HUSHENG LI
WOTAO YIN

Contents

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.