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Introduction

Imagine a dense sensor network consisting of many tiny sensors deployed for information gathering. Readings from neighboring sensors will often be highly correlated. This correlation can be exploited to significantly reduce the amount of information that each sensor needs to send to the base station, thus reducing power consumption and prolonging the life of the nodes and the network. The obvious way of exploiting correlation is to enable neighboring sensors to exchange data with one another. However, communication among sensors is usually undesirable as it increases the complexity of the sensors, which in turn leads to additional cost and power consumption. How then is it possible to avoid information exchange among sensors but still be able to exploit the statistical dependency of the readings in different sensor nodes? The solution lies in *distributed source coding*.

Distributed source coding (DSC) enables correlation to be exploited efficiently without the need for communications among sensors. Moreover, in some specific cases it does not incur any loss compared to the case when the sensors communicate.

DSC has been receiving significant attention since the beginning of the 21st century from academics and industrial researchers in different fields of electrical and computer engineering, and mathematical and computer science. Indeed, special sessions and tutorials dedicated to DSC are given at major communications, signal processing, multimedia, and computer engineering conferences. This is no wonder as DSC has potential applications ranging from wireless sensor networks, ad-hoc networks, surveillance networks, to robust low-complexity video coding, stereo/multiview video coding, high-definition television, and hyper-spectral and multi-spectral imaging. This book is intended to act as a guidebook for engineers and researchers to grasp the basic concepts quickly in order to understand and contribute to this exciting field and apply the emerging applications.

Distributed Source Coding: Theory and Practice, First Edition. Shuang Wang, Yong Fang, and Samuel Cheng.

Companion Website: www.wiley.com/go/cheng/dsctheoryandpractice

1.1 What is Distributed Source Coding?

DSC deals with the source coding or compression of correlated sources. The adjective *distributed* stresses that the compression occurs in a distributed or noncentralized fashion. We can, for example, assume that the sources to be compressed are distributed across different nodes in a network. The task is to compress these sources and communicate compressed streams to a decoder for joint decompression. The basis of DSC is that the compressions take place *independently*, that is, the nodes do not exchange their information, whereas decompression is *joint*.

This is illustrated in Figure 1.1 for the simple case of two nodes. Each node has access only to its source, and does not have information about sources present at other nodes. Therefore, "distributed" in this context refers to separate compression at each node. Note that if decompression were also separate for each of the sources, then the problem would boil down to multiple conventional compressions. Throughout the book, distributed compression will always refer to separate encoding and joint decoding, whereas joint compression will refer to joint encoding and joint decoding, if not stated otherwise.

The search of achievable rates of DSC is a major information-theoretical problem and lies in the framework of network information theory, a branch of information theory that tries to find the compression and communication limits of a network of nodes. In the case of discrete sources and perfect reconstruction at the decoder, DSC extends Shannon's Source Coding Theorem, in information theory, from the point-to-point to multipoint scenario. This is referred to as lossless DCS. When we allow for some distortion in reconstruction, the DSC problem becomes a rate-distortion problem and is referred to as lossy DSC.

1.2 Historical Overview and Background

DSC started as an information-theoretical problem in the seminal 1973 paper of Slepian and Wolf [1]. Slepian and Wolf considered lossless separate compression of two discrete sources, and showed that roughly speaking there is no

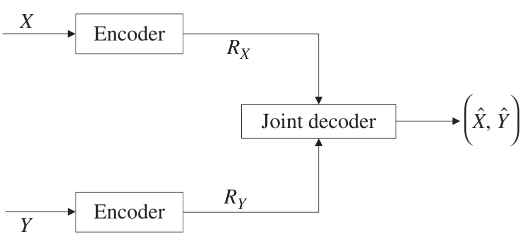

Figure 1.1 DSC concept with two separate encoders who do not talk to each other and one joint decoder. X and Y are discrete, correlated sources; R_X and R_Y are compression rates.

performance loss compared to joint compression as long as joint decompression is performed.

This remarkable result triggered significant information-theoretical research resulting in solutions – in the form of achievable rate regions – for more complicated lossless setups. In 1976, Wyner and Ziv [2] considered a lossy version, with a distortion constraint, of a special case of the Slepian–Wolf (SW) problem, where one source is available at the decoder as side information. Wyner and Ziv showed that for a particular correlation where source and side information are jointly Gaussian, there is no performance loss due to the absence of side information at the encoder. The lossy case of the generalized SW setup, known as multiterminal (MT) source coding, was introduced by Berger and Tung in 1977 [3, 4].

A possible realization of DSC via the use of conventional linear channel codes to approach the SW bound was known as early as 1973, but due to the lack of any potential application of DSC, work on code designs, that is, how to code the sources to approach given bounds, started only at the end of the last century. The first practical design was reported in 1999 [5], followed by many improved solutions. One key insight of these designs is that conventional channel coding can be used for compression. Indeed, correlation between the sources is seen as a virtual communication channel, and as long as this virtual channel can be modeled by some standard communication channel, for example Gaussian, channel codes can be effectively employed. Capacity-approaching designs [6] based on quantization followed by advanced channel coding, for example with turbo codes [7] and low-density parity-check (LDPC) codes [8], come very close to the bounds for two jointly Gaussian sources.

1.3 Potential and Applications

The launch of wireless sensor networks (WSNs) ignited practical DSC considerations in the early years of this century since WSNs naturally call for distributed processing. Closely located sensors are expected to have correlated measurements; thus in theory the DSC setup fulfills the requirement of power-efficient compression for distributed sensor networks. However, many practical problems remain to be solved before DSC is used in mainstream commercial networks. The challenges include the complex correlation structure of real signals, nonGaussian sources, mandatory long codeword lengths, and the complexity of current designs.

Though WSN triggered renewed interest in DSC, another application has emerged: low-complexity video, where the DSC paradigm is used to avoid computationally expensive temporal prediction loop in video encoding. Indeed, loosely speaking, a conventional video encoder needs to find the best matching block to the current one by examining all possible candidates, for example a previous frame. Then, the difference between the two blocks is encoded and motion vectors sent to the decoder. This architecture imposes heavy encoding and light decoding, exactly what is needed for television broadcasting! However, the fact that compression performance is not degraded by the lack of side information at the encoder [2] brings an incredible possibility of avoiding the most resource-consuming motion search at the encoder and shifting it to the decoder side. This idea had remained for more than 20 years in a US Patent [9]. It was only recently with the developed DSC designs that Wyner–Ziv (WZ) or distributed video coding was revisited.

Distributed video coding (DVC) was rediscovered in 2002 [10, 11, 23, 150, 151] and taken forward by many researchers. DVC was proposed as a solution for unconventional setups, such as video surveillance with tiny cameras and cell-to-cell communications, where low encoding complexity is a must. However, other criteria (e.g., the inbuilt robustness of DVC coders to error impairments as there is no error accumulation due to the mismatch of reference frame[1] and a unique opportunity of using a single code for both compression and error protection) have influenced the design philosophy of DVC for broader applications such as robust scalable video transmission over wireless networks and video streaming from multiple sites. Yet another application is multiview and stereo video, where DSC is used to exploit the correlation between different camera views when encodings must be independent.

DVC has also been used to exploit correlation between different bands in multi-spectral and hyper-spectral image coding, then in biometrics, and for compression in microphone array networks. And other applications are emerging, such as spectrum sensing in cognitive radio, compress-and-forward in cooperative communications, and more. These will be discussed in more detail later in the book.

1.4 Outline

While some might prefer to think that DSC is driven by applications, others are fascinated by the information-theoretical challenges it poses. Thus, this book attempts to reconcile both schools of thought by discussing practical code designs and algorithms, together with the theoretical framework for DSC as well as the potential applications various DSC setups have and will impact. The authors attempt to strike a balance between mathematical rigor and intuition. This book is intended to be a guide for both senior/graduate students and engineers who are interested in the field. We have tried our best to ensure the manuscript is self-contained. While we assume no background knowledge in

1 Because the encoder does not use a reference frame.

information and coding theory, we expect the reader to be familiar with calculus, probability theory, and linear algebra as taught in a first- or second-year undergraduate course. The book comprises working examples where possible and includes references to further reading material for more advanced or specialized topics where appropriate.

The book is organized into three parts: Theory, Algorithms, and Applications of DSC.

Part I, Theory, starts with a brief and essential background of information theory and data compression. The background is followed by a comprehensive review of the roots of DSC, namely Slepian and Wolf's theorem and its extension to multiple sources and lossless MT networks. Next, rate-distortion problems will be visited, that is, WZ and lossy MT source coding problems.

Part II, Algorithms, introduces and discusses designs of algorithmic solutions for DSC problems. Most of this part is dedicated to the evolution of code designs for the three most important DSC problems, namely SW, WZ, and MT source coding, introduced in Part I. We start with a background chapter on coding theory, followed by designs for the SW coding problem and elaborate developments from the early work of Wyner in 1974 to the most recent achievements with advanced channel codes, Belief Propagation, and arithmetic codes. Similarly, for the WZ problem we start with the 1999 work of Pradhan and Ramchandran [5] and describe subsequent developments.

Part III is dedicated to potential DSC applications, grouped as multimedia applications and wireless communications applications. We start by providing the necessary background on image/video processing. DVC is discussed first, followed by biometric applications and multi-spectral/hyper-spectral image compression. The two final chapters are dedicated to wireless communications: data gathering in wireless sensor networks, spectrum sensing in cognitive radio, compress-and-forward in cooperative communications scenario, and DSC's relationship to compressive sampling.

Part III will be of great interest to practitioners. Each topic has an educational description and approaches latest developments critically, discussing their strengths and shortcomings, and suggesting possible extensions and future work.