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Foundations and Trends® in Communications and Information Theory

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USA
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www.nowpublishers.com
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Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is G. Keshet, Y. Steinberg and N. Merhav, Channel Coding in the Presence of Side Information, Foundations and Trends® in Communications and Information Theory, vol 4, no 6, pp 445–586, 2007

ISBN: 978-1-60198-048-9

Foundations and Trends® in Communications and Information Theory

Volume 4 Issue 6, 2007

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Foundations and Trends® in Communications and Information Theory, 2007, Volume 4, 6 issues. ISSN paper version 1567-2190. ISSN online version 1567-2328. Also available as a combined paper and online subscription.

Foundations and Trends® in
Communications and Information Theory
Vol. 4, No. 6 (2007) 445–586

DOI: 10.1561/0100000025

Channel Coding in the Presence of Side Information

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Abstract

In this survey we review the concepts and methods of communication systems equipped with side information. We focus on the channel coding problem, where side information is available to the transmitter in either a causal or non-causal manner, and we also consider the source coding problem with side information at the receiver.

We first summarize the main results for channels with causal/non-causal side information and the associated capacity formulas. Next, we consider specific channel models, such as Costa's dirty-paper model, the AWGN channel model with fading and the modulo additive noise channel. Further, we provide applications to the models considered here, in particular, we present the watermarking problem and the Gaussian MIMO broadcast channel. We also consider algorithms for the calculation of the channel's capacity, and practical coding schemes for the communication systems explored in this survey. Finally, we study several

related information-theoretic problems and present both the Wyner–Ziv and the Slepian–Wolf problems. The source coding problems and the channel coding problems, are presented in a unified version and the duality between the problems is presented. We also present extensions for the MAC and broadcast channel models, to the case where they are controlled by a state process, and consider several hybrid models, e.g., joint source–channel coding for the Wyner–Ziv source and the Gel'fand–Pinsker channel, and the achievable tradeoff between the message and the state information rates.

Contents

1

Introduction

This survey gives an overview of results pertaining to the capacity of a channel whose conditional output probability distribution depends on a state process, and where the channel state information (CSI) signal (also referred to as "side information") is available at the transmitter (CSIT) or at the receiver (CSIR) or at both ends. These channels have been widely studied over the years and can serve for modeling in a wide range of problems, depending on some assumptions regarding the channel state and on the availability and quality (clean or noisy) of the side information at the transmitter and/or the receiver. For CSI available at the transmitter, we will distinguish between channels where the CSIT is causal and channels where it is non-causal. In the causal case, the transmission, at every time instant, depends only on the past and present CSI, whereas in the non-causal case, the transmitter knows in advance the realization of the entire state sequence from the beginning to the end of the block. The causal CSIT channel model was introduced in 1958 by Shannon [96], who also found its capacity. The non-causal CSIT channel model was introduced in 1974 by Kusnetsov and Tysbakov [73], and its capacity was found in 1980 by Gel'fand and Pinsker [54]. Regarding CSIR, we will not distinguish between causal and non-causal CSI at the receiver, since the receiver waits until the end of the block anyway, before decoding. Channels with CSIR are studied in [12, 60, 93].

One interesting example which can be modeled as a channel with non-causal transmitter CSI, is a computer memory with defective cells [59, 60, 71, 72, 73, 112, 113]. In this example, the process of storing to this memory suffers from random errors caused by noise. A computer memory may also have some cells which are defected, e.g., a memory cell whose stored value seems to be fixed regardless of the input, e.g., the cell is "stuck at one" or "stuck at zero." The location and values (defect information) of the defective cells may be found by storing the all-one bit pattern (or the all-zero bit pattern) in the memory, reading the contents of the memory and comparing it with the stored pattern. This process may be repeated several times in order to exclude the effect of random errors. If this process is not repeated, we can refer to the defect information received from this process as a noisy version of the defect information. By knowing in advance the defect information, we can design codes that are more efficient than the usual error correcting codes. In this example, the defect information plays the role of the channel states and transmitter's CSI.

Another important example for a channel model with transmitter CSI, is the power constrained Gaussian additive noise channel model with additive interference which is known non-causally to the transmitter as side information and is statistically independent of the noise. In this example, the channel output is given by

$$Y_i = X_i + S_i + Z_i, \quad i = 1,2,\dots,N, \tag{1.1}$$

where $S^N = (S_1,\dots,S_N)$ is the i.i.d. side information sequence (the interference) distributed as $S^N \sim \mathcal{N}(0,QI)$ (I being the identity matrix), Q is the side information variance, and $Z^N = (Z_1,\dots,Z_N)$ is the i.i.d. noise sequence distributed as $Z^N \sim \mathcal{N}(0,BI)$, B being the noise variance. Based on the message to be sent and on the interference samples $S_1,\dots,S_N$, the encoder sends a codeword $X^N = (X_1,\dots,X_N)$, which must satisfy the power constraint

$$\frac{1}{N}\sum_{n=1}^{N} E(X_n^2) \le \Gamma, \tag{1.2}$$

where $\Gamma > 0$ is a given constant. This channel with non-causal CSIT, is known as Costa's channel [30], which has recently received much attention, as it has been proven useful for modeling in various communication problems, among them precoding for intersymbol interference (ISI) channel, digital watermarking, and various broadcasting schemes. Again, this problem can be divided to the causal and non-causal CSIT scenarios. When the CSIT is non-causal, this problem is known as writing on dirty paper (WDP), or the dirty-paper problem. When the CSIT is causal, the problem is known as writing on dirty tape (WDT), or the dirty-tape problem [14]. The dirty-tape setting is often used to describe cases where we restrict the encoder to be causal in order to reduce the implementation complexity compared to dirty-paper implementation.

Costa showed, for the dirty-paper setting, that the capacity of this channel is the same as if the interference was not present or, equivalently, if it was also known at the decoder and could be subtracted off, i.e., the capacity is given by

$$C = \frac{1}{2}\log\left(1 + \frac{\Gamma}{B}\right). \tag{1.3}$$

This surprising result is another reason why this problem has received so much attention.

Yet another interesting example for a channel model with transmitter CSI, is digital watermarking [19, 21, 20, 22, 23, 28, 36, 43, 44, 45, 75, 76, 78, 83, 86, 100, 99]. Digital watermarking is the process of embedding a message within a host signal to form a composite (watermarked) signal. The embedding must not cause a noticeable distortion relative to the host signal. On the other hand, the embedding should be robust to attacks on the watermarked signal. In some applications, these attacks are the result of standard signal processing operations. In other cases they are malicious. The digital watermarking problem can be modeled as a channel whose conditional output probability depends on a state process, and where the transmitter has channel state information. Here the input power constraint is replaced by a constraint on the distortion between the channel input and the host signal. This expresses the requirement that the embedding does not cause a noticeable distortion to the host signal. The dirty-paper problem may be used to model watermarking in a Gaussian environment. We can model watermarking as a communication system in which the transmitter, which must satisfy a distortion constraint with regard to the host signal, sends a watermark message through a noisy channel with the host signal playing the role of state. The state (the host signal), is available to the transmitter, and therefore it can be used by the transmitter as side information, just like in the dirty-paper problem.

The purpose of this survey is to give an overview of the subject of coding for channels with side information, both from the theoretical point of view (capacity, fundamental limits, duality with source coding), and the practical point of view, including coding and decoding techniques, structures of classes of codes, application aspects, etc. A fundamental ingredient in the solutions of the channel coding problems presented in this survey, and the dual source coding problems (e.g., the Slepian–Wolf and the Wyner–Ziv problems [98, 124]), is the "binning" concept. In the context of channel coding with side information, a binning scheme divides a set of codewords into subsets or "bins," such that the codewords in each bin are as far apart as possible. These bins are constructed at random and each bin is assigned to a different message index. When given with a message to be transmitted in a channel coding scenario, we use only the codewords from the bin with the same index as our message, and we choose a codeword which is the closest to (or jointly typical with) the side information vector. Since the messages to be transmitted over the channel are presented by bin indices, it is desired that codewords in each bin are as far apart as possible, to cause minimal rate loss, but not too far, so that every realization of the side information will have a "matching" codeword in the bin. Therefore, in channel coding applications, the codewords in each bin should constitute a good source code, where here the "source" is the channel state. In source coding problems, a codeword that is jointly typical with the source sequence is found, among all the codewords, and the bin index in which it resides is sent to the decoder. The decoder looks in this particular bin for a codeword that is jointly typical with the side information. The codewords in each bin should be close to each other — to reduce the overall rate — but not too close, so that only one codeword in the particular bin will be jointly typical with the side information. Therefore, in the context of source coding, the codewords in each bin should constitute a good channel code.

The outline of this survey is as follows. In Section 2, we specify the notation conventions that will be used and we formalize the model of a channel with CSIT. Section 3 describes the main theoretical results pertaining to the capacity of channels with side information. In Section 4, we describe some specific channel models for various problems. In Section 5, we present several applications for the models which were presented in the preceding sections. Section 6 presents related problems which are linked to the problem of coding for a channel with side information. These problems include source coding dual, which is the Wyner–Ziv problem, the Gaussian vector broadcast channel and multiuser channels. In Section 7, we describe algorithms for computation of the capacity of channels that were presented in the previous sections, as well as several coding techniques for these channels. Section 8 concludes the survey.

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