Channel Coding

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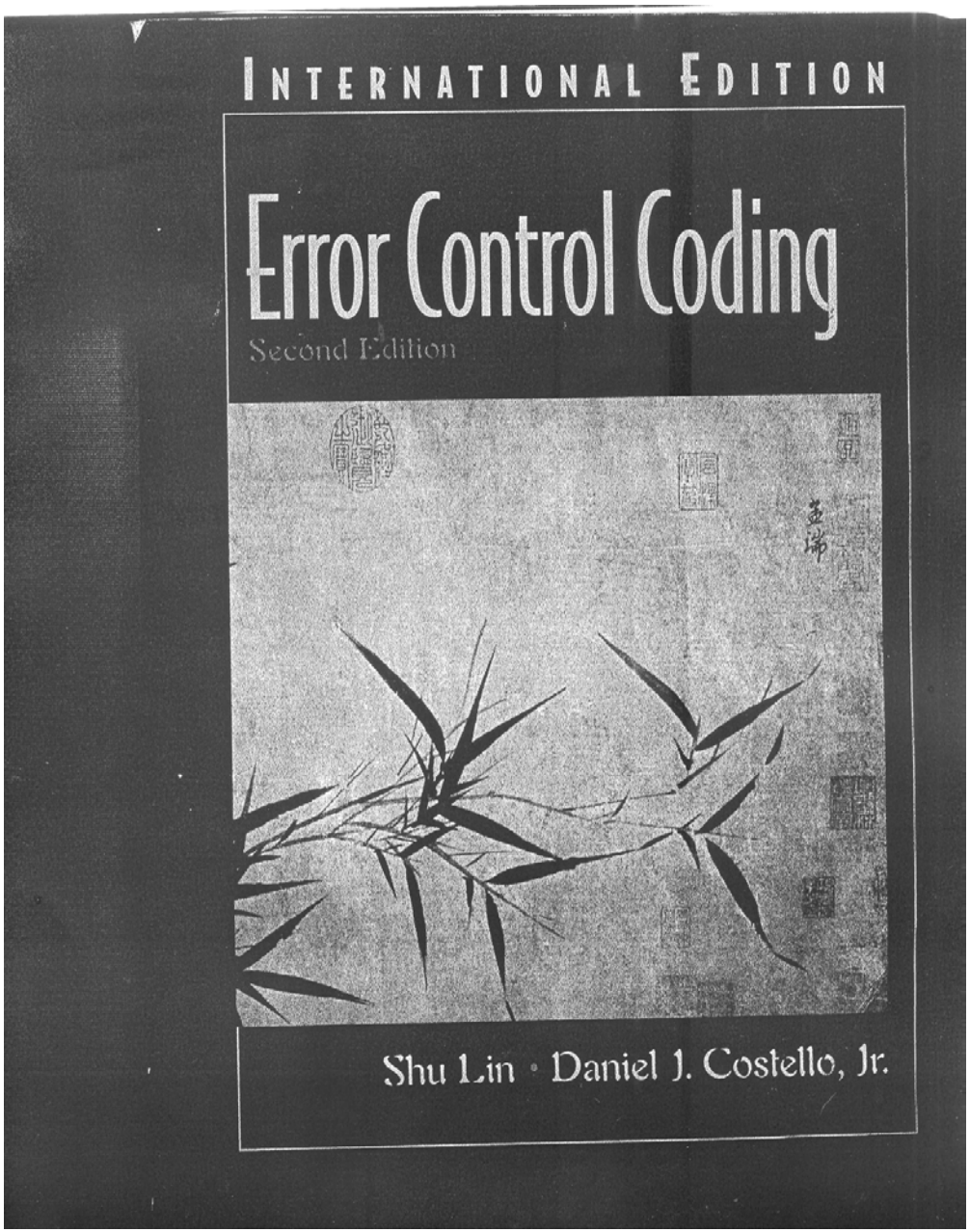
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Channel Coding: The Road to Channel Capacity

Fifty years of effort and invention have finally produced coding schemes that closely approach Shannon's channel capacity limit on memoryless communication channels.

By Daniel J. Costello, Jr., *Fellow IEEE*, and G. David Forney, Jr., *Life Fellow IEEE*

ABSTRACT | Starting from Shannon's celebrated 1948 channel coding theorem, we trace the evolution of channel coding from Hamming codes to capacity-approaching codes. We focus on the contributions that have led to the most significant improvements in performance versus complexity for practical applications, particularly on the additive white Gaussian noise channel. We discuss algebraic block codes, and why they did not prove to be the way to get to the Shannon limit. We trace the antecedents of today's capacity-approaching codes: convolutional codes, concatenated codes, and other probabilistic coding schemes. Finally, we sketch some of the practical applications of these codes.

KEYWORDS | Algebraic block codes; channel coding; codes on graphs; concatenated codes; convolutional codes; low-density parity-check codes; turbo codes

I. INTRODUCTION

The field of channel coding started with Claude Shannon's 1948 landmark paper [1]. For the next half century, its central objective was to find practical coding schemes that could approach channel capacity (hereafter called "the Shannon limit") on well-understood channels such as the additive white Gaussian noise (AWGN) channel. This goal proved to be challenging, but not impossible. In the past decade, with the advent of turbo codes and the rebirth of low-density parity-check (LDPC) codes, it has finally been achieved, at least in many cases of practical interest.

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As Bob McEliece observed in his 2004 Shannon Lecture [2], the extraordinary efforts that were required to achieve this objective may not be fully appreciated by future historians. McEliece imagined a biographical note in the 166th edition of the *Encyclopedia Galactica* along the following lines.

> **Claude Shannon**: Born on the planet Earth (Sol III) in the year 1916 A.D. Generally regarded as the father of the Information Age, he formulated the notion of channel capacity in 1948 A.D. Within several decades, mathematicians and engineers had devised practical ways to communicate reliably at data rates within 1% of the Shannon limit . . .

The purpose of this paper is to tell the story of how Shannon's challenge was met, at least as it appeared to us, before the details of this story are lost to memory.

We focus on the AWGN channel, which was the target for many of these efforts. In Section II, we review various definitions of the Shannon limit for this channel.

In Section III, we discuss the subfield of algebraic coding, which dominated the field of channel coding for its first couple of decades. We will discuss both the achievements of algebraic coding, and also the reasons why it did not prove to be the way to approach the Shannon limit.

In Section IV, we discuss the alternative line of development that was inspired more directly by Shannon's random coding approach, which is sometimes called "probabilistic coding." This line of development includes convolutional codes, product codes, concatenated codes, trellis decoding of block codes, and ultimately modern capacity-approaching codes.

In Section V, we discuss codes for bandwidth-limited channels, namely lattice codes and trellis-coded modulation.