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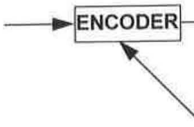

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Editorial Preface

It is with great pleasure that I intro
Research Studies Press on C
Applications. The aim of the seri
featuring subjects in Communicati
have interacted beneficially. The
Most chapters in the three secti
Communications Techniques, and
bands, are concerned with topics v
of the beneficial and close synergy

This third book in the Series is a
emerged from the International
Applications, held regularly at A
Symposium held in July 1999 achi
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material which will inform an
community. On behalf of Researc
possible to include this outstanding

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Gallager Codes –

David J. C. MacKay (m
Cavendish Laboratory, Cambri

Abs

In 1948, Claude Shannon posed
problems of information theory. Th
to communicate reliably over noisy
He defined a theoretical limit, no
to which communication is possible
is not possible. Since 1948, coding
error-correcting codes capable of g

In the last decade remarkable p
that are defined in terms of sparse
coded by a simple probability-base

This paper reviews low-density
repeat-accumulate codes, and turb
Some previously unpublished resul
experiments on Gallager codes wit
rule for decoding of repeat-accum
time and allows block decoding er
(c) the empirical power-laws obeye
codes.

1 Introduction

The central problem of communicatio
a decoding system that make it possib
channel. The encoding system uses
from a set of codewords. The decod
output of the channel, which codewor
been transmitted; for an appropriate d
codeword to the received signal. A go
are well spaced apart, so that codewo

Designing a good and practical e
(a) it is hard to find an explicit set o
generic code, decoding, *i.e.*, finding th
is intractable.

However, a simple method for desi
(1962), has recently been rediscovere

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fined in terms of sparse random graphs. Because the graphs are constructed randomly, the codes are likely to have well-spaced codewords. And because the codes' constraints are defined by a sparse graph, the decoding problem can be solved — almost optimally — by message-passing on the graph. The practical performance of Gallager's codes and their modern cousins is vastly better than the performance of the codes with which textbooks have been filled in the intervening years.

2 Sparse Graph Codes

In a **sparse graph code**, the nodes in the graph represent the transmitted bits and the constraints they satisfy. For a linear code with a codeword length N and rate $R = K/N$, the number of constraints is of order $M = N - K$. [There could be more constraints, if they happen to be redundant.] Any linear code can be described by a graph, but what makes a sparse graph code special is that each constraint involves only a small number of variables in the graph: the number of edges in the graph scales roughly linearly with N, rather than as N^2.

The graph defining a **low-density parity-check code**, or Gallager code (Gallager 1962; Gallager 1963; MacKay 1999), contains two types of node: codeword bits, and parity constraints. In a regular (j, k) Gallager code (figure 1a), each codeword bit is connected to j parity constraints and each constraint is connected to k bits. The connections in the graph are made at random.

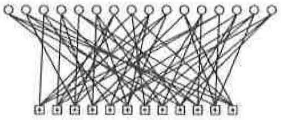
Repeat-accumulate codes (Divsalar *et al.* 1998) can be represented by a graph with four types of node (figure 1b): equality constraints $\boxed{=}$, intermediate binary variables (black circles), parity constraints $\boxed{+}$, and the transmitted bits (white circles). The encoder sets each group of intermediate bits to values read from the source. These bits are put through a fixed random permutation. The transmitted stream is the accumulated sum (modulo 2) of the permuted intermediate bits.

In a **turbo code** (Berrou and Glavieux 1996), the K source bits drive two linear feedback shift registers, which emit parity bits (figure 1c).

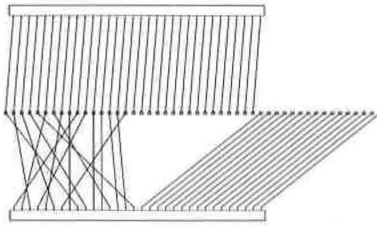
All these codes can be decoded by a local message-passing algorithm on the graph, the sum-product algorithm (MacKay and Neal 1996; McEliece *et al.* 1998), and, while this algorithm is not the optimal decoder, the empirical results are record-breaking. Figure 2 shows the performance of various sparse graph codes on a Gaussian channel. In figure 2(a) turbo codes with rate 1/4 are compared with regular and irregular Gallager codes over GF(2), GF(8) and GF(16). In figure 2(b) the performance of repeat-accumulate codes of various blocklengths and rate 1/3 is shown.

THE BEST SPARSE GRAPH CODES

Which of the three types of sparse graph code is 'best' depends on the chosen rate and blocklength, the permitted encoding and decoding complexity, and



(a) Gallager code



(c1) Turbo code

Figure 1. Graphs of three sparse graph c
(a) A rate 1/4 low-density
blocklength $N = 16$, and M
resents a transmitted bit. Ea
represented by $\boxed{+}$ squares. E
$k = 4$ bits to which it is conne
(b) A repeat-accumulate c
resents a transmitted bit. Eac
binary variable. Each $\boxed{=}$ con
connected to be equal.
(c) A turbo code with rate
word bits. The two rectangle
(c2), with the systematic bits
angle and the parity bits $\{t^{(b)}$

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