
Bit-Interleaved Coded Modulation

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Foundations and Trends[®] in Communications and Information Theory

Published, sold and distributed by:

now Publishers Inc.
PO Box 1024
Hanover, MA 02339
USA
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

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 A. Guillén i Fàbregas, A. Martinez and G. Caire, Bit-Interleaved Coded Modulation, Foundations and Trends[®] in Communications and Information Theory, vol 5, nos 1-2, pp 1-153, 2008

ISBN: 978-1-60198-190-5

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Communications and Information Theory**
Volume 5 Issue 1–2, 2008
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Foundations and Trends[®] in Communications and Information Theory, 2008, Volume 5, 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. 5, Nos. 1–2 (2008) 1–153
© 2008 A. Guillén i Fàbregas, A. Martinez and G. Caire
DOI: 10.1561/01000000019



Bit-Interleaved Coded Modulation

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Abstract

The principle of coding in the signal space follows directly from Shannon's analysis of waveform Gaussian channels subject to an input constraint. The early design of communication systems focused separately on *modulation*, namely signal design and detection, and *error correcting codes*, which deal with errors introduced at the demodulator of the underlying waveform channel. The correct perspective of signal-space coding, although never out of sight of information theorists, was brought back into the focus of coding theorists and system designers by Imai's and Ungerböck's pioneering works on coded modulation. More recently, powerful families of binary codes with a good tradeoff between performance and decoding complexity have been (re-)discovered. Bit-Interleaved Coded Modulation (BICM) is a pragmatic approach combining the best out of both worlds: it takes advantage of the signal-space coding perspective, whilst allowing for the use

of powerful families of binary codes with virtually any modulation format. BICM avoids the need for the complicated and somewhat less flexible design typical of coded modulation. As a matter of fact, most of today's systems that achieve high spectral efficiency such as DSL, Wireless LANs, WiMax and evolutions thereof, as well as systems based on low spectral efficiency orthogonal modulation, feature BICM, making BICM the *de-facto* general coding technique for waveform channels.

The theoretical characterization of BICM is at the basis of efficient coding design techniques and also of improved BICM decoders, e.g., those based on the belief propagation iterative algorithm and approximations thereof. In this text, we review the theoretical foundations of BICM under the unified framework of error exponents for mismatched decoding. This framework allows an accurate analysis without any particular assumptions on the length of the interleaver or independence between the multiple bits in a symbol. We further consider the sensitivity of the BICM capacity with respect to the signal-to-noise ratio (SNR), and obtain a wideband regime (or low-SNR regime) characterization. We review efficient tools for the error probability analysis of BICM that go beyond the standard approach of considering infinite interleaving and take into consideration the dependency of the coded bit observations introduced by the modulation. We also present bounds that improve upon the union bound in the region beyond the cutoff rate, and are essential to characterize the performance of modern randomlike codes used in concatenation with BICM. Finally, we turn our attention to BICM with iterative decoding, we review extrinsic information transfer charts, the area theorem and code design via curve fitting. We conclude with an overview of some applications of BICM beyond the classical coherent Gaussian channel.

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List of Abbreviations, Acronyms, and Symbols

APP	A posteriori probability
AWGN	Additive white Gaussian noise
BEC	Binary erasure channel
BICM	Bit-interleaved coded modulation
BICM-ID	Bit-interleaved coded modulation with iterative decoding
BIOS	Binary-input output-symmetric (channel)
BP	Belief propagation
CM	Coded modulation
EXIT	Extrinsic information transfer
FG	Factor graph
GMI	Generalized mutual information
ISI	Inter-symbol interference
LDPC	Low-density parity-check (code)
MAP	Maximum a posteriori
MIMO	Multiple-input multiple-output
MLC	Multi-level coding
MMSE	Minimum mean-squared error
MSD	Multi-stage decoding

PSK	Phase-shift keying
QAM	Quadrature-amplitude modulation
RA	Repeat-accumulate (code)
SNR	Signal-to-noise ratio
TCM	Trellis-coded modulation
TSB	Tangential sphere bound
A_d	Weight enumerator at Hamming distance d
A_{d,ρ_N}	Weight enumerator at Hamming distance d and pattern ρ_N
A'_d	Bit weight enumerator at Hamming distance d
b	Bit in codeword
$\bar{b}$	Binary complement of bit b
$b_j(x)$	Inverse labeling (mapping) function
C	Channel capacity
$C_{\mathcal{X}}^{\text{bicm}}$	BICM capacity over set $\mathcal{X}$
C_{bpsk}	BPSK capacity
$C_{\mathcal{X}}^{\text{cm}}$	Coded modulation capacity over set $\mathcal{X}$
$\mathcal{C}$	Binary code
c_1	First-order Taylor capacity series coefficient
c_2	Second-order Taylor capacity series coefficient
d	Hamming distance
$\mathbf{d}$	Scrambling (randomization) sequence
$\bar{d}_v$	Average variable degree (LDPC code)
$\bar{d}_c$	Average check node degree (LDPC code)
ΔP	Power expansion ratio
ΔW	Bandwidth expansion ratio
$\mathbb{E}[U]$	Expectation (of a random variable U)
E_b	Average bit energy
$\frac{E_b}{N_0}$	Ratio between average bit energy and noise spectral density
$\frac{E_b}{N_0} \lim$	$\frac{E_b}{N_0}$ at vanishing SNR
E_s	Average signal energy
$E(R)$	Reliability function at rate R
$E_0^{\text{bicm}}(\rho, s)$	BICM random coding exponent
$E_0^{\text{cm}}(\rho)$	CM random coding exponent

$E_0^q(\rho, s)$	Generalized Gallager function
$E_r^q(R)$	Random coding exponent with mismatched decoding
$\text{exit}_{\text{dec}}(y)$	Extrinsic information at decoder
$\text{exit}_{\text{dem}}(x)$	Extrinsic information at demapper
h_k	Fading realization at time k
$I(X; Y)$	Mutual information between variables X and Y
$I^{\text{cm}}(X; Y)$	Coded modulation capacity ($C_{\mathcal{X}}^{\text{cm}}$)
$I^{\text{gmi}}(X; Y)$	Generalized mutual information
$I_s^{\text{gmi}}(X; Y)$	Generalized mutual information (function of s)
$I^{\text{ind}}(X; Y)$	BICM capacity with independent-channel model
K	Number of bits per codeword $\log_2 \mathcal{M} $
$\kappa(s)$	Cumulant transform
$\kappa''(s)$	Second derivative of cumulant transform
$\kappa_1(s)$	Cumulant transform of bit score
$\kappa_v(s)$	Cumulant transform of symbol score with weight v
$\kappa_{\text{pw}}(s)$	Cumulant transform of pairwise score
$\kappa_{\text{pw}}(s, \rho_N)$	Cumulant transform of pairwise score for pattern ρ_N
M	Input set (constellation) $\mathcal{X}$ cardinality
m	Number of bits per modulation symbol
m_f	Nakagami fading parameter
μ	Labeling (mapping) rule
$\mathcal{M}$	Message set
$\mathbf{m}$	Message
$\hat{\mathbf{m}}$	Message estimate
$\text{mmse}(\text{snr})$	MMSE of estimating input X (Gaussian channel)
N	Number of channel uses
N_0	Noise spectral density (one-sided)
$\mathcal{N}(\cdot)$	Neighborhood around a node (in factor graph)
$\nu^{f \rightarrow \vartheta}$	Function-to-variable message
$\nu^{\vartheta \rightarrow f}$	Variable-to-function message
$\mathcal{O}(f(x))$	Term vanishing as least as fast as $af(x)$, for $a > 0$
$\mathcal{o}(f(x))$	Term vanishing faster than $af(x)$, for $a > 0$
P	Signal power
P_b	Average probability of bit error
P_e	Average probability of message error

$P_j(y b)$	Transition probability of output y for j th bit
$P_{\mathbf{j}}(y \mathbf{b})$	Output transition probability for bits $\mathbf{b}$ at $\mathbf{j}$ positions
$P_{B_j Y}(b y)$	j th a posteriori marginal
$P_{\cdot}$	Probability distribution
$P_{Y X}(y x)$	Channel transition probability (symbol)
$P_{\mathbf{Y} \mathbf{X}}(\mathbf{y} \mathbf{x})$	Channel transition probability (sequence)
$\text{PEP}(d)$	Pairwise error probability
$\text{PEP}_1(d)$	Pairwise error probability (infinite interleaving)
$\text{PEP}(\mathbf{x}_{\text{m}'}, \mathbf{x}_{\text{m}})$	Pairwise error probability
π_n	Interleaver of size n
$\text{Pr}^{\text{dec} \rightarrow \text{dem}}(b)$	Bit probability (from the decoder)
$\text{Pr}^{\text{dem} \rightarrow \text{dec}}(b)$	Bit probability (from the demapper)
$Q(\cdot)$	Gaussian tail function
$q(x, y)$	Symbol decoding metric
$q(\mathbf{x}, \mathbf{y})$	Codeword decoding metric
$q_j(b, y)$	Bit decoding metric of j th bit
R	Code rate, $R = \log_2 \mathcal{M} /N$
r	Binary code rate, $r = \log_2 \mathcal{C} /n = R/m$
R_0	Cutoff rate
R_0^{av}	Cutoff rate for average-channel model
R_0^{ind}	Cutoff rate for independent-channel model
R_0^q	Generalized cutoff rate (mismatched decoding)
ρ_N	Bit distribution pattern over codeword
$\sum_{\sim x}$	Summary operator — excluding x —
$\hat{s}$	Saddlepoint value
σ_X^2	Variance
$\hat{\sigma}_X^2$	Pseudo-variance, $\sigma_X^2 \triangleq \mathbb{E}[X ^2] - \mathbb{E}[X] ^2$
ζ_0	Wideband slope
snr	Signal-to-noise ratio
W	Signal bandwidth
$\mathcal{X}$	Input signal set (constellation)
$\mathcal{X}_b^j$	Set of symbols with bit b at j th label
$\mathcal{X}_{b_{i_1}, \dots, b_{i_v}}^{j_{i_1}, \dots, j_{i_v}}$	Set of symbols with bits $b_{i_1}, \dots, b_{i_v}$ at positions $j_{i_1}, \dots, j_{i_v}$

x_k	Channel input at time k
$\mathbf{x}$	Vector of all channel inputs; input codeword
$\mathbf{x}_m$	Codeword corresponding to message m
$\Xi_{m(k-1)+j}$	Bit log-likelihood of j th bit in k th symbol
y_k	Channel output at time k
$\mathbf{y}$	Vector of all channel outputs
$\mathcal{Y}$	Output signal set
z_k	Noise realization at time k
Ξ^{pw}	Pairwise score
Ξ_k^{s}	Symbol score for k th symbol
$\Xi_{k,j}^{\text{b}}$	Bit score at j th label of k th symbol
Ξ_1^{b}	Symbols score with weight 1 (bit score)
$\Xi_{m(k-1)+j}^{\text{dec} \rightarrow \text{dem}}$	Decoder LLR for j th bit of k th symbol
$\Xi^{\text{dec} \rightarrow \text{dem}}$	Decoder LLR vector
$\Xi_{\sim i}^{\text{dec} \rightarrow \text{dem}}$	Decoder LLR vector, excluding the i th component
$\Xi_{m(k-1)+j}^{\text{dem} \rightarrow \text{dec}}$	Demodulator LLR for j th bit of k th symbol
$\Xi^{\text{dem} \rightarrow \text{dec}}$	Demodulator LLR vector
$\Xi_{\sim i}^{\text{dem} \rightarrow \text{dec}}$	Demodulator LLR vector, excluding the i th component

1

Introduction

Since Shannon's landmark 1948 paper [105], approaching the capacity of the Additive White Gaussian Noise (AWGN) channel has been one of the more relevant topics in information theory and coding theory. Shannon's promise that rates up to the channel capacity can be reliably transmitted over the channel comes together with the design challenge of effectively constructing coding schemes achieving these rates with limited encoding and decoding complexity.

The complex baseband equivalent model of a bandlimited AWGN channel is given by

$$y_k = \sqrt{\text{snr}} x_k + z_k, \quad (1.1)$$

where y_k, x_k, z_k are complex random variables and snr denotes the Signal-to-Noise Ratio (SNR), defined as the signal power over the noise power. The capacity C (in nats per channel use) of the AWGN channel with signal-to-noise ratio snr is given by the well-known

$$C = \log(1 + \text{snr}). \quad (1.2)$$

The coding theorem shows the existence of sufficiently long codes achieving error probability not larger than any $\epsilon > 0$, as long as the

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coding rate is not larger than C . The standard achievability proof of (1.2) considers a random coding ensemble generated with i.i.d. components according to a Gaussian probability distribution.

Using a Gaussian code is impractical, as decoding would require an exhaustive search over the whole codebook for the most likely candidate. Instead, typical signaling constellations like Phase-Shift Keying (PSK) or Quadrature-Amplitude Modulation (QAM) are formed by a finite number of points in the complex plane. In order to keep the modulator simple, the set of elementary waveforms that the modulator can generate is a finite set, preferably with small cardinality. A practical way of constructing codes for the Gaussian channel consists of fixing the modulator signal set, and then considering codewords obtained as sequences over the fixed modulator signal set, or *alphabet*. These *coded modulation* schemes are designed for the equivalent channel resulting from the concatenation of the modulator with the underlying waveform channel. The design aims at endowing the coding scheme with just enough structure such that efficient encoding and decoding is possible while, at the same time, having a sufficiently large space of possible codes so that good codes can be found.

Driven by Massey's consideration on coding and modulation as a single entity [79], Ungerböck in 1982 proposed Trellis-Coded Modulation (TCM), based on the combination of trellis codes and discrete signal constellations through set partitioning [130] (see also [17]). TCM enables the use of the efficient Viterbi algorithm for optimal decoding [138] (see also [35]). An alternative scheme is multilevel coded modulation (MLC), proposed by Imai and Hirakawa in 1977 [56] (see also [140]). MLC uses several binary codes, each protecting a single bit of the binary label of modulation symbols. At the receiver, instead of optimal joint decoding of all the component binary codes, a suboptimal multi-stage decoding, alternatively termed successive interference cancellation, achieves good performance with limited complexity. Although not necessarily optimal in terms of minimizing the error probability, the multi-stage decoder achieves the channel capacity [140].

The discovery of turbo codes [11] and the re-discovery of low-density parity-check (LDPC) codes [38, 69] with their corresponding iterative

decoding algorithms marked a new era in coding theory. These *modern codes* [97] approach the capacity of binary-input channels with low complexity. The analysis of iterative decoding also led to new methods for their efficient design [97]. At this point, a natural development of coded modulation would have been the extension of these powerful codes to nonbinary alphabets. However, iterative decoding of binary codes is by far simpler.

In contrast to Ungerböck's findings, Zehavi proposed bit-interleaved coded modulation (BICM) as a pragmatic approach to coded modulation. BICM separates the actual coding from the modulation through an interleaving permutation [142]. In order to limit the loss of information arising in this separated approach, soft information about the coded bits is propagated from the demodulator to the decoder in the form of bit-wise *a posteriori* probabilities or log-likelihood ratios. Zehavi illustrated the performance advantages of separating coding and modulation. Later, Caire *et al.* provided in [29] a comprehensive analysis of BICM in terms of information rates and error probability, showing that in fact the loss incurred by the BICM interface may be very small. Furthermore, this loss can essentially be recovered by using iterative decoding. Building upon this principle, Li and Ritcey [65] and ten Brink [122] proposed iterative demodulation for BICM, and illustrated significant performance gains with respect to classical noniterative BICM decoding [29, 142] when certain binary mappings and convolutional codes are employed. However, BICM designs based on convolutional codes and iterative decoding cannot approach the coded modulation capacity, unless the number of states grows large [139]. Improved constructions based on iterative decoding and on the use of powerful families of modern codes can, however, approach the channel capacity for a particular signal constellation [120, 121, 127].

Since its introduction, BICM has been regarded as a pragmatic yet powerful scheme to achieve high data rates with general signal constellations. Nowadays, BICM is employed in a wide range of practical communication systems, such as DVB-S2, Wireless LANs, DSL, WiMax, the future generation of high data rate cellular systems (the so-called 4th generation). BICM has become the *de-facto* standard for coding over the Gaussian channel in modern systems.

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In this text, we provide a comprehensive study of BICM. In particular, we review its information-theoretic foundations, and review its capacity, cutoff rate and error exponents. Our treatment also covers the wideband regime. We further examine the error probability of BICM, and we focus on the union bound and improved bounds to the error probability. We then turn our attention to iterative decoding of BICM; we also review the underlying design techniques and introduce improved BICM schemes in a unified framework. Finally, we describe a number of applications of BICM not explicitly covered in our treatment. In particular, we consider the application of BICM to orthogonal modulation with noncoherent detection, to the block-fading channel, to the multiple-antenna channel as well as to less common channels such as the exponential-noise or discrete-time Poisson channels.

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