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Error Control Coding

FOR B3G/4G WIRELESS SYSTEMS

Paving the Way to IMT-Advanced Standards

Editors
Thierry Lestable and Moshe Ran

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ERROR CONTROL CODING FOR B3G/4G WIRELESS SYSTEMS

PAVING THE WAY TO IMT-ADVANCED STANDARDS

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The *Wiley-WWRF Series* is a series of comprehensive and timely books based on the work of the WWRF (Wireless World Research Forum). This Forum is a global organization with over 130 members from five continents, representing all sectors of the mobile communications industry and the research community, with the mission to shape the wireless future. The authors are all active members of the WWRF. The series is focused on wireless communications, embracing all aspects from spectrum strategies, the physical layer and networking protocols, up to applications and services. Each volume of the series is a development of the white papers produced by the working groups of WWRF, based on contributions from members, and each describes the current research in the subject, together with an identification of future research requirements.

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To my amazing wife Cynthia, the love of my life, our two outstanding sons, Quentin and Florian, my mother Elisabeth, my sister Nathalie, and my brother Christian.
In beloved memory of my father Michel, my grandmother Noëline, and my nephew Benoit who left us too soon.

Thierry Lestable

"*A vaincre sans péril, on triomphe sans gloire.*"
"Triumph without peril brings no glory"
Le Cid (1636), by Pierre Corneille

To my wife Zvia, my son Omer, and our daughters Idit and Einat who are the most precious people in my life, for their love and support during the preparation of this book.
Special thanks to all the contributors of this book for their hard teamwork and dedication.

Moshe Ran

About the Editors

Thierry Lestable

Thierry Lestable received his Engineering degree and PhD from the Ecole Supérieure d'Electricité (Supelec) in 1997 and 2003 respectively. He has been involved with cutting-edge wireless telecommunications since 1998 and is the author of over 40 international publications, including two Wiley books and over 25 patents. Since 2008, Dr Lestable has been Technology and Innovation Manager at SAGEMCOM (Paris, France), in charge of technology strategy and the roadmap within the CTO office.

Dr Lestable is an expert in his field for the European Commission (FP7), and Eureka Cluster CELTIC, whilst chairing the Machine-to-Machine (M2M) group in the eMobility European Technology Platform Expert Group. He is the manager of FP7-BeFEMTO project targeting next-generation LTE-based Femtocells, and he initiated the FP7-EXALTED project dedicated to LTE-based M2M communications. Since 2010, he has been a member of the Telecom Steering Board from the System@-tic Competitiveness Cluster in France.

At Alcatel Labs (1998–2003), he investigated multicarrier wireless systems paving the way for 4G Chinese systems with FuTURE 863 projects. From 2004, Dr Lestable was with Samsung Electronics Research Institute (SERI) in the UK, heading the Advanced Technology Group and focusing on advanced channel coding (LDPC), iterative processing and the cross-layer approach for MIMO-OFDM based systems. He contributed actively to IEEE 802.16m, and 802.20 standards while participating in European research projects (FP6-WINNER), and creating the FP7-DAVINCI Consortium.

Moshe Ran

Moshe Ran holds a PhD from Tel Aviv University, and has been the head of research and development at Holon Institute of Technology (HIT) since 2009. He has 25 years' experience in state-of-the-art communications systems and has led R&D groups in several communication topics including: broadband access technologies, 3G and 4G systems, and short-range communications, with a focus on ultra-wideband (UWB) technologies, error correction codes.

Dr Ran formerly held prominent management and technical positions including CEO of MostlyTek Ltd. He has been an active member in standards bodies and technology-related partnerships including IEEE802.16, ETSI/BRAN and WWRF. He was the project manager and coordinator of the IST-FP6 STREP project named UROOF, targeting UWB over optical fiber for next-generation broadband communications. He is a senior member of the IEEE and has published more than 60 technical international publications and papers in the areas of error control coding and broadband wireless/wireline integration.

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Preface

The outstanding near-capacity performances of advanced channel coding schemes have attracted for more than 15 years the interest of the overall information theory community and their industry partners. The maturity of both the theoretical framework and the technology has given birth to many different designs and analysis tools, together with outperforming applications and new business opportunities (e.g. Flarion, Digital Fountain), especially driven by the fast growth of wireless telecom systems.

After some years of an unshared reign from the technology supporting the turbo codes (PCCC, SCCC and TPC), we have entered an era of fierce competition where many different iterative decoding solutions are available, with their respective performance and complexity.

It thus becomes crucial to give a fair state-of-the-art of such leading-edge solutions, and then to sketch their pros and cons, in terms of both theoretical advances and implementations aspects.

The primary intention of this book is thus to give an opportunity to present clearly both the latest findings and implementation solutions in this fast-evolving area of advanced coding targeting IMT-Advanced systems.

The book is structured as follows. Chapter 1 gives an insight overview of major advanced codes (Turbo-PCCC, SCCC, binary and nonbinary LDPC, 3D Turbo), their design and optimization techniques (EXIT charts, PEG), whilst Chapter 2 describes their advanced decoding techniques (BCJR, BP). Special attention is given to incremental redundancy techniques in Chapter 3, since they are a key feature of wireless systems. Chapter 4 describes real-world implementation aspects of coding and decoding techniques by examining hardware and architecture solutions (VLSI complexity, FPGA, ASIC). Turbo-processing techniques are described thoroughly in Chapter 5, thanks to key applications such as turbo-MIMO, turbo-equalization and turbo-interleaving techniques.

Finally, Chapter 6 concludes the book by both identifying trends and giving the latest status of major standardization activities implementing such advanced coding

techniques, with special interest in 3GPP UMTS, LTE, WiMAX, IEEE 802.11n, DVB-RCS, DVB-S2, and IEEE 802.22.

As a result, *Error Control Coding for B3G/4G Wireless Systems* provides a unique compromise whilst understanding leading-edge coding techniques, by bringing together in a coherent manner academic and industry standpoint and vision.

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Acknowledgments

This book originates from initial and fruitful discussions among coding experts within the *Wireless World Research Forum* (WWRF) that led quickly first to the release of a comprehensive White Paper on Coding, then to a section within the third volume of WWRF's *Technologies for the Wireless Future*.

Besides the WWRF framework, many contributors cooperated together during the years 2004–2007 within the WINNER project (Phase I and II), partly funded by the European Commission. We would thus like to acknowledge here this successful venture.

Then, the editors would like to express their full gratitude to all the contributing authors, since we do believe this was a unique opportunity to bring together those talented and distinguished researchers and engineers from both academics (*Holon Institute of Technology, Universität der Bundeswehr Munich, ETIS ENSEA, INSA-IETR, University of Cambridge, Technical University of Dresden – Vodafone Chair, Telecom Bretagne, Technical University of Kaiserslautern*) and industry (*Samsung Electronics, Orange Labs, ST-Ericsson*): Claude Berrou, Gerhard Bauch, David Declercq, Charly Poulliat, Ming Jiang, Omer Ran, Stefania Sesia, Jossy Sayir, Marcos B.S. Tavares, Marie-Hélène Hamon, Isabelle Siaud, Anne-Marie Ulmer-Moll, Maryline Hélard, Carlos De Ségovia, Frank Kienle, Alexandre Graell I Amat, Yannick Saouter, and Youssouf Ould-Cheikh-Mouhamedou.

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Finally, last but not least, the editors would like to extend their warmest thanks to their families, since this book would not have been possible without their continuous support, understanding and patience.

Abbreviations

3G	Third Generation (cellular system)
3GPP	3G Partnership Project
3GPP2	3G Partnership Project 2
3GPP-LTE	3GPP long-term evolution
ACS	add–compare–select
AMC	adaptive modulation and coding
AMD	acknowledged mode
APP	a posteriori probability
ARQ	automatic retransmission request
ASD	algebraic soft decision
AWGN	additive white Gaussian noise
BCH	Bose Chaudhuri Hocquenghem (code)
BCJR	Bahl Cocke Jelinek Raviv
BEC	binary erasure channel
BER	bit error rate
BPSK	binary phase shift keying
BICM	bit interleaved coded modulation
BLER	block error rate
BMU	branch metric unit
BP	belief propagation
BS	base station
CB	circular buffer
CCSDS	consultative committee for space data systems
CDMA	code division multiple access
CFU	check nodes functional unit
CIR	channel impulse response
CN	check node
CNB	check node block
CNP	check node processor
CRC	cyclic redundancy check

CRSC	circular recursive systematic code
CSI	channel state information
CTC	convolutional turbo code
CTF	channel transfer function
CW	codeword
DB TC	duo-binary turbo code
DE	density evolution
DECT	digital cordless telecommunication standard
DEINT	deinterleaver
DIC	dynamic interleaving code
DPREG	dual-ported register
DSP	digital signal processing
DVB-RCS	digital video broadcasting – return channel for satellite distribution systems
DVB-RCT	digital video broadcasting – return channel for terrestrial distribution systems
ECC	error correcting code
ECMA	European Computer Manufacturers Association
EDGE	enhanced data rate for GSM evolution
EIRP	equivalent isotropic radiated power
EMS	extended min-sum
ESA	European Space Agency
ETSI	European Telecommunications Standards Institute
EXIT	EXtrinsic Information Transfer (chart)
FD	frequency domain
FDD	frequency division duplex
FEC	forward error correction
FER	frame error rate
FFT	fast Fourier transform
FIFO	first-in/first-out
FOCTC	frame-oriented convolutional turbo code
FPGA	field programmable gate array
FU	functional units
FWA	fixed wireless access
GA	Gaussian approximation or genetic algorithm
GF	Galois field
GMD	generalized minimum distance
GPRS	general packet radio system
GSM	global system for mobile communications
HARQ	hybrid ARQ
HDR	high data rate
HSDPA	high-speed downlink packet access

HS-DSCH	high-speed downlink shared channel
HSSC	high SNR stopping criterion
IEEE	Institute of Electrical and Electronics Engineers
ICE	iterative channel estimation
IMT	international mobile telecommunications
IN	information nodes
INT	interleaver
IR	incremental redundancy
IRA	irregular repeat accumulate (code)
ISI	inter-symbol interference
ITU-R	International Telecommunication Union – Radiocommunication sector
LDPC	low-density parity-check (code)
LDR	log-density ratio
LFR	linear feedback register
LIFO	last-in/first-out
LLR	log-likelihood ratio
LLRU	LLR unit
LOS	line of sight
LP-OFDM	linear precoded OFDM
LSB	least significant bit
LT	Luby transform
LTE	long-term evolution
LUT	look-up table
MAC	medium access control
MAP	maximum a posteriori
MB	mean bound
MBWA	mobile broadband wireless access
MC-CDMA	multicarrier CDMA
MCF	maximum contention-free
MCS	modulation and coding scheme
MC-SS	multicarrier spread-spectrum
MC-SS-MA	multicarrier spread-spectrum multiple access
MDN	message distribution network
MDS	maximum distance separable
MI	mutual information
MIMO	multiple-input/multiple-output
ML	maximum likelihood
MLD	maximum likelihood decoder
ML-SDD	maximum likelihood soft decision decoding
MLSE	maximum likelihood sequence estimation
MMSE	minimum mean square error

MSA	min-sum algorithm
MSB	most significant bit
MSE	mean square error
MUD	multiuser detection
MUI	multiuser interference
NASA	National American Space Agency
NB-LDPC	nonbinary LDPC (code)
NLOS	non-line of sight
OF	objective function
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
OHRSA	optimized hierarchy reduced search algorithm
OS	objective score
PAN	personal area network
PCCC	parallel concatenated convolutional code
PDU	packet data unit
PEG	progressive edge-growth
PHY	physical layer
PN	parity nodes
PSK	phase shift keying
PUCCH	physical uplink control channel
PUSCH	physical uplink shared channel
QAM	quadrature amplitude modulation
QC	quasicyclic
QoS	quality of service
QPP	quadratic permutation polynomial
QPSK	quaternary phase shift keying
RA	repeat accumulate (code)
RAM	random access memory
RC	rate compatible
RCPC	rate-compatible punctured code
RF	radio frequency
RLC	radio link control
RM	Reed–Muller (code) or rate matching
RS	Reed–Solomon
RSC	recursive systematic code
RTT	round trip time
RU	recursion unit
RV	redundancy version
RX	reception
SAW	stop-and-wait
SCCC	serial concatenation convolutional code

SDD	soft decision decoding
SED	squared Euclidian distance
SISO	soft-in/soft-out
SMM	state metric memory
SNR	signal-to-noise ratio
SOPHIE	soft-output optimized hierarchy
SOVA	soft-output Viterbi algorithm
SP59	sphere-packing bound of Shannon 1959
SPA	sum-product algorithm
SR	selective repeat
STBC	space time block code
TC	turbo code
TD	time domain
TDMA	time division multiple access
TPC	turbo product codes
TSN	transmission sequence number
TTI	transmission time interval
TX	transmission
UMTS	universal mobile telephony system
UT	user terminal
UWB	ultra-wide band
VLSI	very large-scale integration
VFU	variable nodes functional unit
VN	variable node
VNB	variable node block
VNP	variable node processor
VNR	variable node reliability
WCDMA	wideband CDMA
WER	word error rate
WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network
WPAN	wireless personal area network
WWRF	wireless world research forum

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