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**Proceedings**

**THIRTY-SEVENTH ANNUAL ALLERTON CONFERENCE  
ON COMMUNICATION, CONTROL AND COMPUTING**

**September 22 - 24, 1999**

**Allerton House, Monticello, Illinois**

**Sponsored by the  
Coordinated Science Laboratory and the  
Department of Electrical and Computer Engineering of the  
University of Illinois at Urbana-Champaign**

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**PROCEEDINGS**

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**Bruce Hajek  
R.S. Sreenivas  
Conference Co-Chairs**



**Conference held  
September 22, September 23, and September 24, 1999  
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and  
The Department of Electrical and Computer Engineering  
of the  
UNIVERSITY OF ILLINOIS  
at  
Urbana-Champaign**

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## TABLE OF CONTENTS

<b>FORWORD.....</b>	<b>i</b>
 <b>I-A: STOCHASTIC NETWORKS I</b>	
Organizers: S.P. Meyn and R. Srikant (University of Illinois at Urbana-Champaign)	
Chair: S.P. Meyn (University of Illinois at Urbana-Champaign)	
REPRESENTATION AND EXPANSION OF (MAX, PLUS) LYAPUNOV EXPONENTS .....	1
F. Baccelli, S. Gaubert, and D. Hong	
MARTINGALE PROBLEMS AND LINEAR PROGRAMS FOR SINGULAR CONTROL .....	11
T.G. Kurtz and R.H. Stockbridge	
STATIONARY REFLECTED LÉVY PROCESSES IN STOCHASTIC NETWORKS .....	21
T. Konstantopoulos and G. Last	
ON THE IMPACT OF VARIABILITY ON THE BUFFER DYNAMICS IN IP NETWORKS .....	30
Y. Joo, V. Ribeiro, A. Feldmann, A.C. Gilbert, and W. Willinger	
QUEUEING NETWORKS WITH INTERACTING SERVICE RESOURCES .....	42
M. Armony and N. Bambos	
 <b>I-B: CODING THEORY I: DECODING AND CHANNELS</b>	
Organizers: R. Koetter and R.E. Blahut (University of Illinois at Urbana-Champaign)	
Chair: A. Vardy (University of California, San Diego)	
A NEW UPPER BOUND ON THE RELIABILITY FUNCTION OF THE GAUSSIAN CHANNEL .....	52
A. Ashikhmin, A. Barg, and S. Litsyn	
RECURSIVE DECODING OF REED-MULLER CODES.....	61
I. Dumer	
LOSSLESS COMPRESSION IN CONSTRAINED CODING.....	70
J.L. Fan, B. Marcus, and R. Roth	
 <b>I-C: HYBRID/DISCRETE-EVENT-DYNAMIC SYSTEMS</b>	
Chair: R.S. Sreenivas (University of Illinois at Urbana-Champaign)	
MODELLING OF TIMED DISCRETE EVENT SYSTEMS .....	75
R.S. Minhas and W.M. Wonham	
INTERACTING DISCRETE EVENT SYSTEMS .....	85
S. Abdelwahed and W.M. Wonham	
STABILITY ANALYSIS FOR INTERCONNECTED HYBRID SYSTEMS.....	93
S. Yamamoto and T. Ushio	



DECENTRALIZED SUPERVISORY CONTROL OF CONCURRENT DISCRETE EVENT SYSTEMS WITH PARTIAL OBSERVATIONS .....	103
S. Jiang and R. Kumar	
A NEW PROBABILISTIC APPROACH TO CONGESTION CONTROL IN COMMUNICATION NETWORKS....	113
H. Mortazavian and J. Mirkovic	
A BIGRAPH MATCHING THEOREM.....	124
S. Ayyorgun and R.L. Cruz	
<b>I-D: ACTIVE NETWORKS</b>	
Organizer/Chair: Y. Shavitt (Bell Labs, Lucent Technologies)	
CHUNKS IN PLAN: LANGUAGE SUPPORT FOR PROGRAMS AS PACKETS.....	127
J.T. Moore, M. Hicks, and S. Nettles	
ON THE INTERFACE OF PROGRAMMABLE NETWORK ELEMENTS .....	137
G. Hjálmtýsson	
BOWMAN AND CANES: IMPLEMENTATION OF AN ACTIVE NETWORK .....	147
S. Merugu, S. Bhattacharjee, Y. Chae, M. Sanders, K. Calvert, and E. Zegura	
DESIGN OF A FLEXIBLE OPEN PLATFORM FOR HIGH PERFORMANCE ACTIVE NETWORKS .....	157
S. Choi, D. Decasper, J. Dehart, R. Keller, J. Lockwood, J. Turner, and T. Wolf	
IMPLEMENTING A CONCAST SERVICE .....	166
K. Calvert, J. Griffioen, B. Mullins, A. Sehgal, and S. Wen	
ACTIVE DISTRIBUTED MANAGEMENT FOR IP NETWORKS.....	176
R. Kawamura and R. Stadler	
<b>I-F: SPACE-TIME METHODS FOR COMMUNICATION</b>	
Chair: D. Sarwate (University of Illinois at Urbana-Champaign)	
NEW APPROACH FOR SPACE-TIME TRANSMITTER/RECEIVER DESIGN .....	186
H. El Gamal and A.R. Hammons, Jr.	
INTERFERENCE SUPPRESSION FOR CDMA VIA A SPACE-TIME POWER MINIMIZATION BASED PREPROCESSOR WITH APPLICATIONS TO GPS.....	196
W.L. Myrick, M.D. Zoltowski, and J.S. Goldstein	
SOFT-WEIGHTED TRANSMIT DIVERSITY FOR WCDMA.....	204
A. Hottinen, R. Wichman, and D. Rajan	
MULTIUSER DETECTION TECHNIQUES FOR COMBINED ARRAY PROCESSING AND SPACE-TIME BLOCK CODING.....	214
B. Lu and X. Wang	
A TRANSMIT ADAPTIVE ANTENNA SCHEME WITH FEEDBACK FOR WIRELESS COMMUNICATIONS.....	216
Y. Le Pézennec, F. Boixadera, Y. Farminé, and N. Whinnett	



## II-A: CODING THEORY II: ITERATIVE DECODING AND TURBO CODES

Organizers: R. Koetter and R.E. Blahut  
(University of Illinois at Urbana-Champaign)  
Chair: R. Koetter  
(University of Illinois at Urbana-Champaign)

CONCENTRATE .....	221
T. Richardson and R. Urbanke	
EFFICIENT ENCODING OF LOW-DENSITY PARITY-CHECK CODES.....	231
T. Richardson and R. Urbanke	
IRREGULAR TURBOCODES.....	241
B.J. Frey and D.J.C. MacKay	
ON QUASI-CYCLIC REPEAT-ACCUMULATE CODES.....	249
R.M. Tanner	
THE SERIAL CONCATENATION OF RATE-1 CODES THROUGH UNIFORM RANDOM INTERLEAVERS ....	260
H.D. Pfister and P.H. Siegel	

## II-B: STOCHASTIC NETWORKS II

Organizers: S.P. Meyn and R. Srikant  
(University of Illinois at Urbana-Champaign)  
Chair: R. Srikant  
(University of Illinois at Urbana-Champaign)

QUEUE LENGTH ASYMPTOTICS FOR MARKOVIAN SERVICE NETWORKS .....	270
A. Mandelbaum, W.A. Massey, and M.I. Reiman	
EXACT ASYMPTOTICS FOR 1-LIMITED EXPONENTIAL POLLING MODELS .....	280
W. Chang, D.G. Down, and R.D. Foley	
INVARIANT RATE FUNCTIONS FOR DISCRETE TIME QUEUES .....	288
A.J. Ganesh, N. O'Connell, and B. Prabhakar	
LARGE DEVIATIONS AND OPTIMALITY OF THE LARGEST WEIGHTED DELAY FIRST DISCIPLINE.....	297
A.L. Stolyar and K. Ramanan	
ON ESTIMATING BUFFER OVERFLOW PROBABILITIES UNDER MARKOV-MODULATED INPUTS.....	306
I.Ch. Paschalidis and S. Vassilaras	
INDUCED BURSTINESS IN GENERALIZED PROCESSOR SHARING QUEUES WITH LONG-TAILED TRAFFIC FLOWS.....	316
S. Borst, O. Boxma, and P. Jelenković	
THE ASYMPTOTICS OF SELECTING THE SHORTEST OF TWO, IMPROVED.....	326
M. Mitzenmacher and B. Vöcking	

## II-C: LEARNING ALGORITHMS IN SIGNAL PROCESSING

Organizers: A. Singer and M. Feder  
(University of Illinois at Urbana-Champaign and Tel Aviv University)

Chair: M. Feder  
(Tel Aviv University)

UNIVERSAL FILTERING AND PREDICTION OF INDIVIDUAL SEQUENCES CORRUPTED BY NOISE .....	328
A. Baruch and N. Merhav	
FAST RLS LAGUERRE ADAPTIVE FILTERING .....	338
R. Merched and A.H. Sayed	
MACHINE LEARNING APPLICATIONS IN GRID COMPUTING .....	348
G. Cybenko, G. Jiang, and D. Bilar	
REDUNDANCY OF THE LEMPEL-ZIV CODES .....	358
S.A. Savari	
THE INFORMATION BOTTLENECK METHOD .....	368
N. Tishby, F.C. Pereira, and W. Bialek	
THEORY MEETS PRACTICE: UNIVERSAL SOURCE CODING WITH THE BURROWS WHEELER TRANSFORM .....	378
M. Effros	

## II-D: OPTICAL NETWORKS I

Organizers: M. Médard and E. Modiano  
(University of Illinois at Urbana-Champaign  
and Massachusetts Institute of Technology)

Chair: E. Modiano  
(Massachusetts Institute of Technology)

OPTICAL SPACE COMMUNICATIONS AND NETWORKING.....	388
V.W.S. Chan	
ON THE BENEFITS OF CONFIGURABILITY IN WDM NETWORKS .....	390
E. Modiano and A. Narula-Tam	
NONBLOCKING WDM NETWORKS WITH FIXED-TUNED TRANSMITTERS AND TUNABLE RECEIVERS .....	400
T. Lin and G. Sasaki	
ON NEW ARCHITECTURES FOR WDM NETWORKS .....	402
A. Sen, T. Shah, and B.P. Sinha	
ALL-OPTICAL LABEL SWAPPING WITH WAVELENGTH CONVERSION FOR WDM-IP NETWORKS WITH SUBCARRIER MULTIPLEXED ADDRESSING .....	414
D.J. Blumenthal	

## **II-E: COMMUNICATION SYSTEMS AND SERVICES**

Chair: S. Lin  
(University of Hawaii)

ON DISCRETE SUFFICIENT STATISTICS FOR ACQUISITION IN ASYNCHRONOUS BAND-LIMITED CDMA SYSTEMS.....	424
A. Mantravadi and V.V. Veeravalli	
FREQUENCY SYNCHRONIZATION ALGORITHM FOR FREQUENCY HOPPING SYSTEM BASED ON SINGULAR VALUE DECOMPOSITION.....	434
A. Pouttu	
A SOFTWARE-ORIENTED STREAM CIPHER FOR CELLULAR AND PERSONAL COMMUNICATIONS SERVICES.....	443
M. Zhang, A. Chan, and C. Carroll	
BINARY RANK CRITERIA FOR PSK MODULATED SPACE-TIME CODES.....	445
H. El Gamal and A.R. Hammons, Jr.	
TURBO CODES WITH ORTHOGONAL MODULATION IN DS-CDMA MOBILE RADIO SYSTEM WITH SHORT FRAME TRANSMISSION.....	451
G. Li and Y.L. Guan	
AN INTERACTIVE CONCATENATED TURBO CODING SYSTEM.....	461
Y. Liu, H. Tang, S. Lin, and M.P.C. Fossorier	
BI-DIRECTIONAL SOVA DECODING FOR TURBO-CODES.....	471
J. Chen, M.P.C. Fossorier, S. Lin, and C. Xu	

## **II-F: FADING CHANNELS AND POWER CONTROL**

Chair: D. Sarwate  
(University of Illinois at Urbana-Champaign)

ANALYSIS OF AN UP/DOWN POWER CONTROL ALGORITHM IN CDMA REVERSE LINK UNDER FADING CONDITION.....	475
L. Song, N. Mandayam, and Z. Gajic	
A CLASS OF DISTRIBUTED ASYNCHRONOUS POWER CONTROL ALGORITHMS FOR CELLULAR WIRELESS SYSTEMS.....	485
J.D. Herdtner and E.K.P. Chong	
DISTRIBUTED CONNECTION ADMISSION CONTROL FOR POWER-CONTROLLED CELLULAR WIRELESS SYSTEMS.....	495
M. Xiao, N.B. Shroff, and E.K.P. Chong	
INTERFERENCE AVOIDANCE AND DISPERSIVE CHANNELS: A NEW LOOK AT MULTICARRIER MODULATION.....	505
D.C. Popescu and C. Rose	
PERFORMANCE OF OPTIMAL CODES ON GAUSSIAN AND RAYLEIGH FADING CHANNELS: A GEOMETRICAL APPROACH.....	515
S. Vialle and J. Boutros	
IMPROVED MARKOV MODELS FOR FADING CHANNELS: ANALYSIS AND DESIGN.....	525
D.L. Goeckel, M.J. Chu, and W.E. Stark	



### III-A: CODING THEORY III: ALGEBRAIC AND COMBINATORIAL CODING THEORY

Organizers: R. Koetter and R.E. Blahut  
(University of Illinois at Urbana-Champaign)  
Chair: N. Boston  
(University of Illinois at Urbana-Champaign)

ON THE CLASSIFICATION OF EXTREMAL ADDITIVE CODES OVER $GF(4)$ .....	535
P. Gaborit, W.C. Huffman, J.-L. Kim, and V. Pless	
TWO FAST ALGORITHMS IN THE SUDAN DECODING PROCEDURE .....	545
G.-L. Feng	
FROM WEIGHT ENUMERATORS TO ZETA FUNCTIONS .....	555
I. Duursma	
ALTERNATIVE APPROACHES TO THE COMPUTATION OF ERROR VALUES FOR HERMITIAN CODES .....	557
M.E. O'Sullivan	

### III-B: STOCHASTIC NETWORKS III

Organizers: S.P. Meyn and R. Srikant  
(University of Illinois at Urbana-Champaign)  
Chair: S.P. Meyn  
(University of Illinois at Urbana-Champaign)

BUFFER OVERFLOW ASYMPTOTICS IN HOL SERVICE SYSTEMS WITH HETEROGENEOUS LONG-TAILED INPUTS .....	567
C. Kotopoulos, N. Likhanov and R.R. Mazumdar	
SCHEDULING AND CONTROL OF MANUFACTURING SYSTEMS — A FLUID APPROACH .....	577
G. Weiss	
MULTICLASS NETWORKS IN HEAVY TRAFFIC: ASYMPTOTIC OPTIMALITY OF TRACKING POLICIES .....	587
C. Maglaras	
SCHEDULING OPEN QUEUEING NETWORKS WITH SUFFICIENTLY FLEXIBLE RESOURCES .....	597
S. Kumar	
OPTIMALLY STABILIZING CONTROLS FOR A DETERMINISTIC NETWORK MODEL .....	607
P. Dupuis and R. Atar	

### III-C: ROBUST CONTROL AND DECISION MAKING

Chair: C. Beck  
(University of Illinois at Urbana-Champaign)

EVALUATING CUMULANT CONTROLLERS ON A BENCHMARK STRUCTURE PROTECTION PROBLEM IN THE PRESENCE OF CLASSIC EARTHQUAKES .....	617
K.D. Pham, M.K. Sain, S.R. Liberty, and B.F. Spencer, Jr.	
RISK-SENSITIVE DECISION-THEORETIC TROUBLESHOOTING .....	627
M.A. Shayman and E. Fernández-Gaucherand	

H <sub>∞</sub> CONTROL FOR MIXED DISTURBANCE REJECTION .....	637
J.C. Luo and E.B. Lee	
SOLVING POLYNOMIAL SYSTEMS IN ROBUST STABILITY ANALYSIS .....	641
N.-P. Ke	
ROBUST, NEAR TIME-OPTIMAL CONTROL OF THIRD-ORDER UNCERTAIN SYSTEMS .....	651
K.H. You and E.B. Lee	
A NEW CONVEX RELAXATION FOR ROBUST H <sub>2</sub> PERFORMANCE ANALYSIS OF UNCERTAIN LINEAR SYSTEMS .....	655
L. El Ghaoui and E. Feron	
A NEW RESULT ON THE BELLMAN EQUATION FOR EXIT TIME CONTROL PROBLEMS WITH CRITICAL GROWTH DYNAMICS .....	657
M. Malisoff	

### III-D: OPTICAL NETWORKS II

Organizers: M. Médard and E. Modiano  
(University of Illinois at Urbana-Champaign and  
Massachusetts Institute of Technology)  
Chair: M. Médard  
(University of Illinois at Urbana-Champaign)

FAULT PROTECTION IN WDM MESH NETWORKS .....	659
G. Ellinas	
A COMPARISON OF ALLOCATION POLICIES IN WAVELENGTH ROUTING NETWORKS .....	669
Y. Zhu, G.N. Rouskas, and H.G. Perros	
OPTICAL BUFFERS FOR MULTI-TERABIT IP ROUTERS .....	679
D.K. Hunter, I. Andonovic, and M.C. Chia	
THE $\lambda$ -SCHEDULER: A MULTIWAVELENGTH SCHEDULING SWITCH .....	689
J.P. Lang, E.A. Varvarigos, and D.J. Blumenthal	
ON DIFFERENT ROUTING STRATEGIES IN TRANSPARENT ALL-OPTICAL NETWORKS .....	699
O.K. Tonguz	

### III-E: COMMUNICATION NETWORKS

Chair: R. Cruz  
(University of California, San Diego)

TRANSMISSION POLICIES FOR TIME VARYING CHANNELS WITH AVERAGE DELAY CONSTRAINTS .....	709
B.E. Collins and R.L. Cruz	
FAIR ALLOCATION OF UTILITIES IN MULTIRATE MULTICAST NETWORKS .....	718
S. Sarkar and L. Tassiulas	
ON THE USE OF MULTIPLE WORKING POINTS IN MULTICHANNEL ALOHA WITH DEADLINES .....	728
D. Baron and Y. Birk	

SPECIFICATION AND ANALYSIS OF A RELIABLE BROADCASTING PROTOCOL IN MAUDE .....	738
G. Denker, J.J. Garcia-Luna-Aceves, J. Meseguer, P.C. Ölveczky, J. Raju, B. Smith, and C.L. Talcott	
MODELING AND ANALYSIS OF ACTIVE MESSAGES IN VOLATILE NETWORKS .....	748
C. Okino and G. Cybenko	
IMPLEMENTATION OF AN ACTIVE CONGESTION CONTROL SCHEME IN NARROWBAND ATM NETWORKS .....	758
S. Sheth, J. Evans, A. Kulkarni, and G. Minden	
CPU SCHEDULING FOR ACTIVE PROCESSING USING FEEDBACK DEFICIT ROUND ROBIN .....	768
T. Wolf and D. Decasper	
 <b>III-F: WIRELESS COMMUNICATION I: DETECTION AND ESTIMATION</b>	
Organizers: V.V. Veeravalli and U. Madhow (Cornell University and University of Illinois at Urbana-Champaign)	
Chair: V.V. Veeravalli (Cornell University)	
PRECODING FOR SCATTERING FUNCTION ESTIMATION OF MOBILE CHANNELS USING OUTPUT CORRELATIONS ONLY .....	770
C. Tepedelenlioğlu and G.B. Giannakis	
TWO-STAGE HYBRID ACQUISITION OF MULTICARRIER DIRECT-SEQUENCE SPREAD-SPECTRUM SIGNALS .....	780
F.J. Block and C.W. Baum	
TRAINING SEQUENCE-BASED MULTIUSER CHANNEL ESTIMATION FOR BLOCK-SYNCHRONOUS CDMA .....	790
G. Caire and U. Mitra	
SUPPRESSION OF HIGH-DENSITY, DYNAMIC NARROWBAND INTERFERENCE IN DS/CDMA SPREAD-SPECTRUM SYSTEM .....	800
C. Carlemalm, H.V. Poor, and A. Logothetis	
LARGE SYSTEM PERFORMANCE OF REDUCED-RANK LINEAR FILTERS .....	810
M.L. Honig and W. Xiao	
NONLINEAR MULTIUSER RECEIVERS WITH DISTRIBUTED POWER CONTROL IN CELLULAR RADIO NETWORKS .....	820
M.K. Varanasi	



#### IV-A: WIRELESS COMMUNICATIONS II: SYSTEM CONSIDERATIONS IN PHYSICAL LAYER DESIGN

Organizers: V.V. Veeravalli and U. Madhow  
(Cornell University and University of Illinois at Urbana-Champaign)  
Chair: U. Madhow  
(University of Illinois at Urbana-Champaign)

THE CODING-SPREADING TRADEOFF IN CDMA SYSTEMS .....	831
V.V. Veeravalli	
SPECTRAL EFFICIENCY OF RANDOMLY SPREAD DS-CDMA IN A MULTI-CELL MODEL .....	841
B.M. Zaidel, S. Shamai, and S. Verdú	
CDMA DESIGN THROUGH ASYMPTOTIC ANALYSIS: FADING CHANNELS .....	851
E. Biglieri, G. Caire, G. Taricco, and E. Viterbo	
PACKING SPHERES IN THE GRASSMANN MANIFOLD: A GEOMETRIC APPROACH TO THE NON-COHERENT MULTI-ANTENNA CHANNEL.....	861
L. Zheng and D.N.C. Tse	
BLIND ADAPTIVE MULTIUSER DETECTION FOR DS/SSMA COMMUNICATIONS WITH GENERALIZED RANDOM SPREADING IN A FREQUENCY-SELECTIVE FADING CHANNEL .....	871
J.H. Cho and J.S. Lehnert	
TRAFFIC AIDED MULTIUSER DETECTION FOR PACKET SWITCHING RANDOM ACCESS/CDMA NETWORKS.....	881
B. Chen and L. Tong	

#### IV-B: CODING THEORY IV

Chair: R.E. Blahut  
(University of Illinois at Urbana-Champaign)

OPTICAL CHANNELS WITH DEAD TIME .....	891
A. Khandekar and R. McEliece	
AWGN CODING THEOREMS FOR SERIAL TURBO CODES .....	893
H. Jin and R.J. McEliece	
LINEAR CODES OVER $\mathbb{Z}/(2^k)$ OF CONSTANT EUCLIDEAN WEIGHT.....	895
J.A. Wood	
SPACE-TIME TURBO CODES .....	897
Y. Liu and M.P. Fitz	
TURBO DECODING OF CONCATENATED SPACE-TIME CODES .....	899
K.R. Narayanan	
SOFT OUTPUT AND ITERATIVE STACK DECODING .....	901
R. Sivasankaran and S.W. McLaughlin	
ALGEBRAIC GEOMETRIC CODES AND AN IMPROVEMENTS ON THE GILBERT-VARSHAMOV BOUND .....	903
H. Maharaj	

#### **IV-C: STOCHASTIC SYSTEMS AND CONTROL**

Chair: G. Dullerud  
(University of Illinois at Urbana-Champaign)

SINGLE-SAMPLE-PATH-BASED OPTIMIZATION OF MARKOV DECISION PROCESS.....	905
Z. Ren and B.H. Krogh	
TRACKING CAPABILITY ANALYSIS OF THE LMS ALGORITHM FOR FIR SYSTEMS WITH AR COEFFICIENTS .....	915
Y. Wei, S.B. Gelfand, and J.V. Krogmeier	
ADAPTIVE OPTIMAL PREDICTION FOR MIMO STOCHASTIC SYSTEMS USING CANONICAL FORMS .....	925
B. Shahrava and J.D. Aplevich	
SDRE ESTIMATOR PERFORMANCE IN A HARMONIC DISTORTION PROBLEM.....	935
E.E. Yaz, Y. Gao, and K.J. Olejniczak	
STOCHASTIC DIFFERENCE EQUATIONS WITH TIME DELAYS .....	937
A.S.C. Sinha, S.E. Lyshevski, B.R. Pidaparti, and E. Kocaoglan	
CONTROL UNDER COMMUNICATION CONSTRAINTS .....	940
S. Tatikonda and S. Mitter	

#### **IV-D: SPACE-TIME PROCESSING I**

Organizer/Chair: A. Nehorai  
(University of Illinois at Chicago)

SPACE-TIME FADING CHANNEL ESTIMATION IN UNKNOWN SPATIALLY CORRELATED NOISE.....	948
A. Dogandžić and A. Nehorai	
BLAST TRAINING: ESTIMATING CHANNEL CHARACTERISTICS FOR HIGH CAPACITY SPACE-TIME WIRELESS.....	958
T.L. Marzetta	
ANALYSIS OF THE PARALLEL INTERFERENCE CANCELER FOR DS/CDMA SIGNALS .....	967
R. Chandrasekaran and J.J. Shynk	
BEARING ESTIMATION IN A RICEAN CHANNEL .....	977
G. Fuks, J. Goldberg, and H. Messer	
OPTIMAL DOWNLINK BEAMFORMING USING SEMIDEFINITE OPTIMIZATION .....	987
M. Bengtsson and B. Ottersten	
AN OVERVIEW OF A SIMULATION ENVIRONMENT TO STUDY THE IMPACT OF NON-IDEAL HARDWARE ON ARRAY PROCESSING.....	997
J. Yin, C.M.S. See, B.P. Ng, Y.K. Sin, and Y.L. Lu	
SIGNAL REPRESENTATIONS FOR TRANSMIT-RECEIVE ANTENNA ARRAYS .....	1006
J. Zhang, K. Tantinarawat, and A.M. Sayeed	
BLOCK SPACE-TIME ANTENNA PRECODING/DECODING FOR GENERALIZED MULTICARRIER COMMUNICATIONS IN UNKNOWN MULTIPATH.....	1016
Z. Liu, A. Scaglione, S. Barbarossa, and G.B. Giannakis	

LEAST-SQUARES MULTI-USER FREQUENCY-DOMAIN CHANNEL ESTIMATION FOR BROADBAND WIRELESS COMMUNICATION SYSTEMS .....	1026
T.A. Thomas, F.W. Vook, and K.L. Baum	

#### IV-E: MANUFACTURING SYSTEMS

Organizer/Chair: S. Reveliotis  
(Georgia Institute of Technology)

A MARKOV DECISION PROCESS MODELING FOR CONTROL SWITCHING OF DISCRETE EVENT SYSTEMS .....	1036
H. Darabi and M.A. Jafari	

SUPERVISORY CONTROL OF CONTRADICTIONS IN HIERARCHICAL TASK CONTROLLERS .....	1042
X. Guan and L.E. Holloway	

#### IV-F: STOCHASTIC NETWORKS IV

Organizers: S.P. Meyn and R. Srikant  
(University of Illinois at Urbana-Champaign)  
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(University of Illinois at Urbana-Champaign)

MULTIUSER RECEIVERS, RANDOM MATRICES AND FREE PROBABILITY .....	1055
D.N.C. Tse	

STABILITY PROPERTIES OF INCREMENTAL REDUNDANCY IN CDMA PACKET DATA NETWORKS .....	1065
R. Vijayakumar and K.M. Wasserman	

PRICING PRIORITY CLASSES IN A DIFFERENTIATED SERVICES NETWORK .....	1075
P. Marbach	

COMPARING TANDEM QUEUEING SYSTEMS AND THEIR FLUID LIMITS .....	1085
E. Altman, G. Koole, and T. Jiménez	

WAITING TIME ASYMPTOTICS FOR TIME VARYING MULTISERVER QUEUES WITH ABANDONMENT AND RETRIALS .....	1095
A. Mandelbaum, W.A. Massey, M.I. Reiman, and A.L. Stolyar	

LARGE DEVIATIONS FOR SMALL BUFFERS: AN INSENSITIVITY RESULT .....	1105
M. Mandjes and J.H. Kim	

OVERFLOW AND LOSSES IN A NETWORK QUEUE WITH SELF-SIMILAR INPUT .....	1113
B. Tsybakov and N.D. Georganas	

#### V-A: STOCHASTIC NETWORKS V

Organizers: S.P. Meyn and R. Srikant  
(University of Illinois at Urbana-Champaign)  
Chair: S.P. Meyn  
(University of Illinois at Urbana-Champaign)

CHOKER A STATELESS MECHANISM FOR PROVIDING QUALITY OF SERVICE IN THE INTERNET .....	1122
R. Pan and B. Prabhakar	



OPTIMAL ROUTING TO $M$ PARALLEL QUEUES WITH NO BUFFERS .....	1132
E. Altman, S. Bhulai, B. Gaujal, and A. Hordijk	
THE EFFECT OF SCALE ON INTERNET QUALITY .....	1142
M. Siler and J. Walrand	
STABILITY OF MULTILANE INPUT-BUFFERED SWITCHES WITH MARKOV-MODULATED ARRIVAL PROCESSES.....	1152
P. Ho, D. Tse, and J. Walrand	
 <b>V-B: WIRELESS COMMUNICATIONS III: NETWORKING ISSUES</b>	
Organizers: V.V. Veeravalli and U. Madhow (Cornell University and University of Illinois at Urbana-Champaign)	
Chair: V.V. Veeravalli (University of Illinois at Urbana-Champaign)	
ADAPTIVE TRANSMISSION FOR SPREAD-SPECTRUM COMMUNICATIONS OVER MULTIPATH CHANNELS.....	1162
M.B. Pursley and C.S. Wilkins	
ADAPTIVE REDUNDANCY RETRANSMISSION PROTOCOLS FOR WIRELESS NETWORKS.....	1171
T. Ji and W.E. Stark	
RESOURCE POOLING AND EFFECTIVE BANDWIDTHS FOR CDMA ANTENNA ARRAYS .....	1181
S.V. Hanly and D.N.C. Tse	
ROUTING FOR MAXIMUM SYSTEM LIFETIME IN WIRELESS AD-HOC NETWORKS.....	1191
J.-H. Chang and L. Tassiulas	
A SELF ORGANIZING WIRELESS SENSOR NETWORK.....	1201
K. Sohrabi, J. Gao, V. Ailawadhi, and G. Pottie	
 <b>V-C: MULTIUSER DETECTION</b>	
Chair: M.K. Varanasi (University of Colorado at Boulder)	
BLIND ADAPTIVE NONCOHERENT MULTIUSER DETECTION FOR NONLINEAR MODULATION .....	1211
D. Das and M.K. Varanasi	
LOW COMPLEXITY NON-COHERENT NEAR-OPTIMAL MULTIUSER DETECTION FOR OVERSATURATED MA COMMUNICATION.....	1221
R.E. Learned, A.S. Willsky, and D.M. Boroson	
ADAPTIVE MULTIUSER DECISION FEEDBACK FOR ASYNCHRONOUS CELLULAR DS-CDMA .....	1236
R. Ratasuk, G. Woodward, and M.L. Honig	
MULTIUSER EQUALIZATION FOR RANDOM SPREADING: LIMITS OF DECORRELATION WITH AND WITHOUT DECISION-FEEDBACK.....	1246
R.R. Müller	

## **V-D: SPACE-TIME PROCESSING II**

Organizer/Chair: A. Nehorai  
(University of Illinois at Chicago)

SCHEDULING OF SWITCHED MULTIBEAM ANTENNAS IN A MULTIPLE ACCESS ENVIRONMENT..... 1256  
A. Logothetis and H.V. Poor

MULTIPLE ANTENNA DIFFERENTIAL MODULATION..... 1266  
B.M. Hochwald and W. Sweldens

SPACE-TIME ZERO FORCING EQUALIZATION FOR 3G CDMA FORWARD LINK TO RESTORE  
ORTHOGONALITY OF CHANNEL CODES ..... 1274  
M.D. Zoltowski and T.P. Krauss

A NOVEL SPACE-TIME SPREADING SCHEME FOR WIRELESS CDMA SYSTEMS ..... 1284  
B.M. Hochwald, T.L. Marzetta, and C.B. Papadias

## **V-E: CODING FOR MAGNETIC CHANNELS**

Organizer/Chairs: E. Kurtas  
(Quantum Corporation)

2D EQUALIZATION FOR PAGE-ORIENTED DATA STORAGE SYSTEMS..... 1294  
B.V.K.V. Kumar, V. Vadde, and M. Keskinöz

TOWARDS SOFT OUTPUT APP DECODING FOR NONSYSTEMATIC NONLINEAR BLOCK CODES ..... 1304  
K.D. Anim-Appiah and S.W. McLaughlin

LOW DENSITY PARITY CHECK CODES FOR MAGNETIC RECORDING..... 1314  
J.L. Fan, A. Friedmann, E. Kurtas, and S. McLaughlin

DESIGN CONSIDERATIONS FOR CONCATENATING CONVOLUTIONAL CODES  
WITH PARTIAL RESPONSE CHANNELS ..... 1324  
W.E. Ryan

TURBO CODES FOR TWO-TRACK MAGNETIC RECORDING SYSTEMS ..... 1334  
E. Kurtas and T.M. Duman

LIST OF AUTHORS ..... 1344

# Irregular Turbocodes

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## Abstract

Recently, several groups have increased the coding gain of iteratively decoded Gallager codes (low density parity check codes) by varying the number of parity check equations in which each codeword bit participates. In regular turbocodes, each “systematic bit” participates in exactly 2 trellis sections. We construct irregular turbocodes with systematic bits that participate in varying numbers of trellis sections. These codes can be decoded by the iterative application of the sum-product algorithm (a low-complexity, more general form of the turbo decoding algorithm). By making the original rate 1/2 turbocode of Berrou *et al.* slightly irregular, we obtain a coding gain of 0.15 dB at a block length of  $N = 131,072$ , bringing the irregular turbocode within 0.3 dB of capacity. Just like regular turbocodes, irregular turbocodes are linear-time encodable.

## 1 Introduction

Recent work on irregular Gallager codes (low density parity check codes) has shown that by making the codeword bits participate in varying numbers of parity check equations, significant coding gains can be achieved [1–3]. Although Gallager codes have been shown to perform better than turbocodes at BERs below  $10^{-5}$  [4]<sup>1</sup>, until recently Gallager codes performed over 0.5 dB worse than turbocodes for BERs greater than  $10^{-5}$ . However, in [3], Richardson *et al.* found irregular Gallager codes that perform 0.16 dB *better* than the original turbocode at BERs greater than  $10^{-5}$  [5] for a block length of  $N \approx 131,072$ .

---

<sup>1</sup>Gallager codes do not exhibit decoding errors, only decoding failures, at long block lengths with  $N > 5,000$ .



In this paper, we show that by tweaking a turbocode so that it is irregular, we obtain a coding gain of 0.15 dB for a block length of  $N = 131,072$ . For example, an  $N = 131,072$  irregular turbocode achieves  $E_b/N_0 = 0.48$  dB at  $\text{BER} = 10^{-4}$ , a performance similar to the best irregular Gallager code published to date [3]. By further optimizing the degree profile, the permuter and the trellis polynomials, we expect to find even better irregular turbocodes. Like their regular cousins, irregular turbocodes exhibit a BER flattening due to low-weight codewords.

## 2 Irregular turbocodes

In Fig. 1, we show how to view a turbocode so that it can be made irregular. The first picture shows the set of systematic bits (middle row of discs) being fed directly into one convolutional code (the chain at the top) and being permuted before being fed into another convolutional code (the chain at the bottom). For a rate 1/2 turbocode, each constituent convolutional code should be rate 2/3 (which may, for example, be obtained by puncturing a lower-rate convolutional code).

Since the order of the systematic bits is irrelevant, we may also introduce a permuter before the upper convolutional code, as shown in the second picture. In the third picture, we have simply drawn the two permuters and convolutional codes side by side.

For long turbocodes, the values of the initial state and the final state of the convolutional chains do not significantly influence performance (*e.g.*, see [6]). So, as shown in the fourth picture, we can view a turbocode as a code that copies the systematic bits, permutes both sets of these bits, and then feeds them into a convolutional code. We refer to this turbocode as “regular”, since each systematic bit is copied exactly once.

The final picture illustrates one way the above turbocode can be made irregular. Some of the systematic bits are “tied” together, in effect causing some systematic bits to be replicated more than once. Notice that to keep the rate of the overall code fixed at 1/2, some extra parity bits must be punctured.

More generally, an *irregular turbocode* has the form shown in Fig. 2, which is a type of “trellis-constrained code” as described in [7]. We specify a *degree profile*,  $f_d \in [0, 1]$ ,  $d \in \{1, 2, \dots, D\}$ .  $f_d$  is the fraction of codeword bits that have degree  $d$  and  $D$  is the maximum degree. Each codeword bit with degree  $d$  is repeated  $d$  times before being fed into the permuter. Several classes of permuter lead to linear-time encodable codes. In particular, if the bits in the convolutional code are partitioned into “systematic bits” and “parity bits”, then by connecting each parity bit to a degree 1 codeword bit, we can encode in linear time.

The average codeword bit degree is

$$\bar{d} = \sum_{d=1}^D d \cdot f_d \quad (1)$$

The overall rate  $R$  of an irregular turbocode is related to the rate  $R'$  of the convolutional code and the average degree  $\bar{d}$  by

$$\bar{d}(1 - R') = 1 - R. \quad (2)$$

So, if the average degree is increased, the rate of the convolutional code must also be increased to keep the overall rate constant. This can be done by puncturing the convolutional code or by designing a new, higher rate convolutional code.

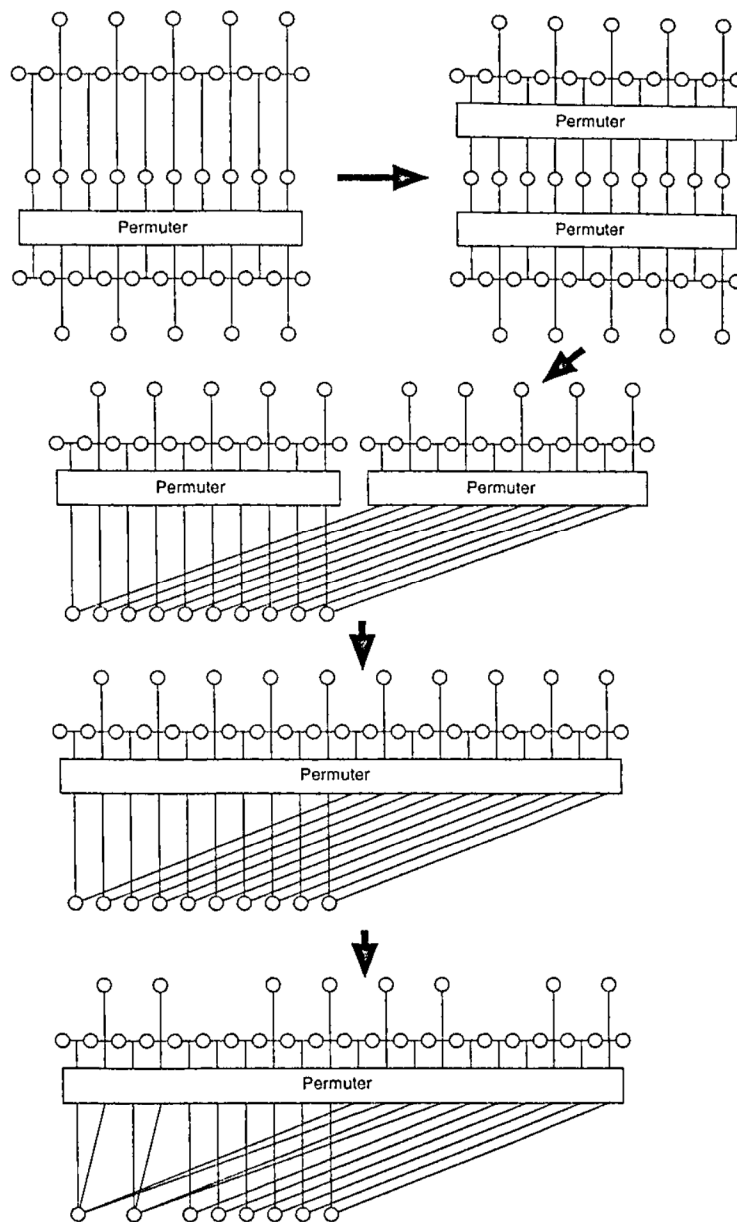


Figure 1: The first 4 pictures show that a turboencoder can be viewed as a code that copies the systematic bits, permutes both sets of these bits and then feeds them into a convolutional code. The 5th picture shows how a turboencoder can be made irregular by "tying" some of the systematic bits together, *i.e.*, by having some systematic bits replicated more than once. To keep the rate fixed, some extra parity bits must be punctured. To keep the block length fixed, we must start with a longer turboencoder.

### 3 Decoding irregular turbocodes

Fig. 2 can be interpreted as the graphical model [6, 8–10] for the irregular turboencoder. Decoding consists of the iterative application of the sum-product algorithm (a low-complexity, more general form of turboencoding) in this graph.

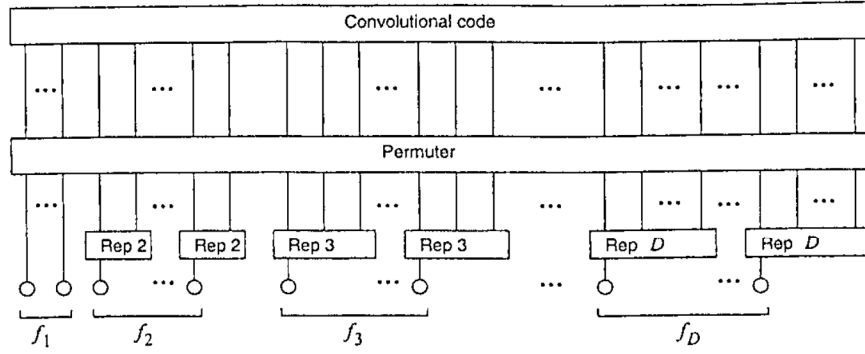


Figure 2: A general *irregular turbocode*. For  $d = 1, \dots, D$ , fraction  $f_d$  of the codeword bits are repeated  $d$  times, permuted and connected to a convolutional code.

After receiving the channel output, the decoder computes the channel output log-likelihood ratios for the  $N$  codeword bits,

$$L_1^0, L_2^0, \dots, L_N^0, \quad (3)$$

and then repeats each log-likelihood ratio appropriately. If codeword bit  $i$  has degree  $d$ , we set

$$L_{i,1} \leftarrow L_i^0, L_{i,2} \leftarrow L_i^0, \dots, L_{i,d} \leftarrow L_i^0. \quad (4)$$

Next, the log-likelihood ratios are permuted and fed into the BCJR algorithm [11] for the convolutional code. The BCJR algorithm assumes the inputs are *a priori* log-probability ratios and uses the forward-backward algorithm [12] to compute a set of *a posteriori* log-probability ratios. If codeword bit  $i$  has degree  $d$ , the algorithm produces  $d$  *a posteriori* log-probability ratios,

$$L'_{i,1}, L'_{i,2}, \dots, L'_{i,d}. \quad (5)$$

For a regular turbocode, there are just two *a posteriori* log-probability ratios,  $L'_{i,1}$  and  $L'_{i,2}$ , for each degree 2 bit and they correspond to the “extrinsic information” produced by each constituent convolutional code.

The current estimate of the log-probability ratio for bit  $i$  given the channel output is

$$\hat{L}_i \leftarrow L_i^0 + \sum_{k=1}^d (L'_{i,k} - L_{i,k}). \quad (6)$$

To compute the inputs to the BCJR algorithm needed for the next iteration, we subtract off the corresponding outputs from the BCJR algorithm produced by the previous iteration:

$$L_{i,k} \leftarrow \hat{L}_i - L'_{i,k}. \quad (7)$$

So, each iteration consists of computing the inputs to the BCJR algorithm, permuting the inputs, applying the BCJR algorithm, permuting the outputs of the BCJR algorithm, and taking the repetitions into account to combine the outputs to form estimates of the log-probability ratios of the codeword bits given the channel output.

In our simulations, after each iteration, we check to see if the current decision gives a codeword. If it does, the iterations terminate and otherwise, the decoder iterates further until some maximum number of iterations is reached and a decoding failure is declared.

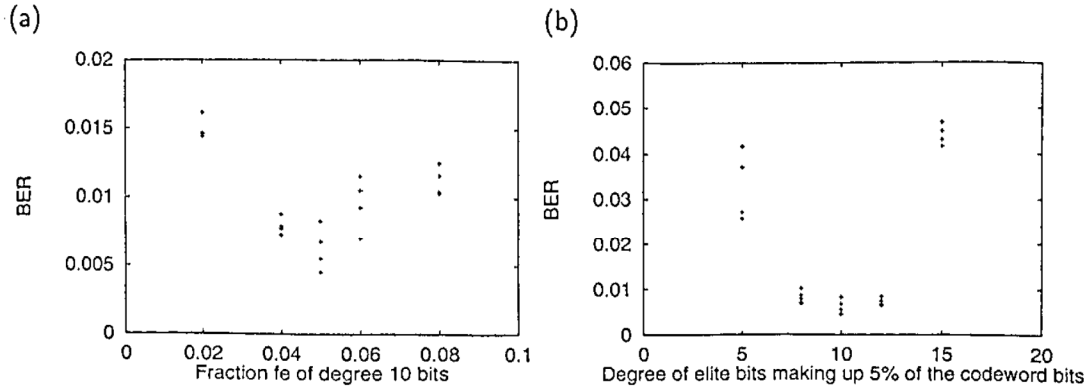


Figure 3: (a) shows the effect of changing the fraction of elite bits on the BER, while keeping the degree of the elite bits fixed at 10. (b) shows the effect of changing the degree of the elite bits on the BER, while keeping the fraction of elite bits fixed at 0.05. For each fraction and degree, the performance of 4 randomly drawn permuters is shown.

## 4 Selecting the profile

Finding a good profile is not trivial, since the best profile will depend on the parameters of the convolutional code, the permuter and the distortion measure (bit error rate, block error rate, decoding failure rate, high-weight decoding failure rate, *etc.*)

The results we report in this paper were obtained by making small changes to a block length  $N = 10,000$  version of the original rate  $R = 1/2$  turbocode proposed by Berrou *et al.*. In this turbocode,  $f_1 = f_2 = 1/2$  (see Fig. 2) and the convolutional code polynomials are 37 and 21 (octal). The taps associated with polynomial 37 are connected to the degree 2 codeword bits, 1/2 of the taps associated with polynomial 21 are connected to the degree 1 bits, and the remaining 1/2 of the taps associated with polynomial 21 are punctured, giving the required convolutional code rate of  $R' = 2/3$ .

To simplify our search, we considered profiles where besides degrees 1 and 2, only one other degree,  $e$  for “elite”, had a nonzero fraction. So, for a code with overall rate  $R$  and fraction  $f_e$  of degree  $e$  elite bits, we have

$$\begin{aligned} f_1 &= 1 - R = 1/2, \\ f_2 &= 1 - f_1 - f_e = 1/2 - f_e. \end{aligned} \quad (8)$$

In this restricted class of codes, irregularity is governed by two parameters,  $e$  and  $f_e$ .

From (2) it is clear that when the average degree is increased, the rate of the convolutional code must also be increased to keep the overall rate at 1/2. We increased the rate of the punctured convolutional code by further puncturing the taps associated with polynomial 21 to obtain a convolutional code with rate

$$R' = 1 - \frac{1 - R}{d} = 1 - \frac{1/2}{1/2 + 2(1/2 - f_e) + ef_e}. \quad (9)$$

So, in the codes we explored, the level of puncturing was quite high and some extra low-weight codewords were introduced.

To begin with, we made an irregular turbocode with  $e = 10$  (chosen using intuition) and varied  $f_e$  from 0.02 to 0.08 while measuring the BER at  $E_b/N_0 = 0.6$  dB. In each

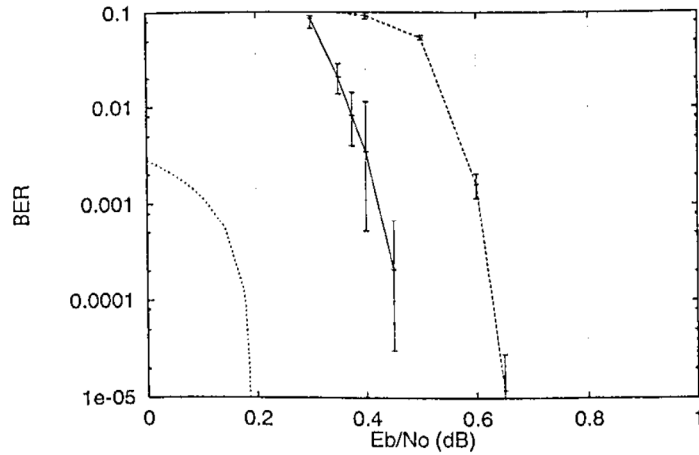


Figure 4: Performance of the original block length  $N = 131,072$  turbocode (dashed line) and one of its irregular cousins (solid line). These results are for irregular turbocodes obtained by tweaking the original turbocode – we are currently searching for optimal degree profiles, permeters and trellis polynomials.

experiment, we simulated enough blocks to obtain a relatively small confidence interval. The results are shown in Fig. 3a, which indicates that for degree 10 elite bits, the best fraction is roughly 0.05. Next, we kept the fraction of elite bits fixed at  $f_e = 0.05$  and we varied the degree of the elite bits. The results are shown in Fig. 3b, which indicates that for a fraction of 0.05, the best degree is roughly 10.

These results show that for  $e = 10$ ,  $f_e = 0.05$  is a good fraction and that for  $f_e = 0.05$ ,  $e = 10$  is a good degree. However, values of  $e$  and  $f_e$  that give good profiles are probably correlated, so we are currently extending our search.

## 5 Results

Fig. 4 shows the simulated BER- $E_b/N_0$  curves for the original block length  $N = 131,072$  regular turbocode (dashed line) and its irregular cousin (solid line), using profile  $e = 10$ ,  $f_e = 0.05$ .

The irregular turbocode clearly performs better than the regular turbocode for BER  $> 10^{-4}$ . At BER  $= 10^{-4}$ , the  $N = 131,072$  irregular turbocode is 0.3 dB from capacity, a 0.15 dB improvement over the regular turbocode.

For high  $E_b/N_0$ , most of the errors for the irregular turbocode were due to low-weight codewords. According to preliminary results, the distribution of error weights appears to indicate that the flattening effect for the particular  $N = 131,072$  irregular turbocode we constructed occurs at a *higher* BER than it does for the regular turbocode. However, the flattening effect is highly sensitive to the technique used to construct the permuter (we drew it at random) and the design of the convolutional code (we just further punctured the convolutional code used in the original turbocode). We are currently experimenting with techniques for lowering the level of the flattening effect (*e.g.*, see [13]).



## 6 Conclusions

We have shown that by making the original, regular turbocode irregular, a coding gain of 0.15 dB is obtained, bringing the irregular turbocode within 0.3 dB of capacity at a BER of  $10^{-4}$ . This irregular turbocode performs in the same regime as the best known irregular Gallager code.

We emphasize that we obtained these results by tweaking the regular turbocode originally introduced by Berrou *et al.*. We believe we will be able to improve these performance curves significantly, both by exploring the polynomials used in the convolutional code and by adjusting the degree profile and the permuter structure. (One way to speed up the search is to extend the method of “density evolution” [3] to models with state.) In particular, we are investigating ways to select the permuter and the polynomials to eliminate low-weight codewords, thus reducing the flattening effect [13–15]. We are also studying ways of constraining the degree 1 “parity” bits (*i.e.*, increasing their degree) to eliminate low-weight codewords.

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