Guest Editorial Equalization Techniques for Wireless Communications Theory & Applications

Equalization techniques which can combat and/or exploit the frequency-selectivity of the wireless channel are of enormous importance in the design of high data rate wireless systems. Although such techniques have been studied for over 40 years, wireless systems have evolved rapidly over the last few decades, necessitating a new mindset in the design and analysis of equalization techniques. Current and future generation wireless systems are characterized by their very high spectral efficiency, the use of multiple input multiple output (MIMO) systems, presence of rapidly time varying channels due to high mobility and the availability of partial or no channel state information at the transmitter and/or receiver. These characteristics, along with recent developments in signal processing and coding suggest the need for paradigm shifts in equalization strategies for both single-carrier and multi-carrier based wireless communication systems.

The requirement for high data rates results in significant inter-symbol interference for single carrier based systems, thereby necessitating the use of sophisticated equalization strategies. One of the most promising ways to deal with this problem is through the use of iterative (turbo) techniques which use soft-input soft-output (SISO) signal processing algorithms. Even though turbo equalization is a computationally efficient way to perform nearly optimal joint equalization and decoding, the complexity of the SISO algorithms used in every iteration can become very large when the data rates and the number of transmit antennas increase. Hence, it is critical to devise novel SISO equalization algorithms with low complexity, which can trade off complexity for performance in an efficient way. It is also clearly very important to understand the limitations and capabilities of such turbo equalization schemes through analytical/semi-analytical methods and to consider the design of error correcting codes when turbo receivers are used. Several papers in this issue focus on these problems.

Another important issue to consider is estimation and tracking of time-varying wireless channels. Given the growing trend in designing broadband MIMO systems, this problem becomes more and more important as the channel impulse response is characterized by a large number of parameters. While the estimation problem is important for both single carrier and multicarrier based systems, the time-varying nature of the channel results in significant inter-carrier interference (ICI) which becomes a limiting factor for multi-carrier based systems. Hence, it is crucial to develop appropriate signal processing techniques to combat the effects of ICI at the receiver when multicarrier systems are used. To alleviate this problem along with the problems of high peak-to-average power ratio of multicarrier systems and the exploitation of frequency diversity, several papers in this issue consider single carrier systems with frequency domain equalization and the associated channel estimation problems.

Finally, there is a growing trend toward the use of partial channel state information at the transmitter and jointly optimizing the transmitter/receiver in the presence of such channel state information. Efficient design of precoding techniques at the transmitter and equalization techniques at the receiver can significantly enhance the performance of wireless systems.

The focus of this special issue is on the development of such novel practical, low complexity equalization techniques, channel estimation techniques and precoding techniques and in understanding their potential and limitations when used in wireless communication systems characterized by very high data rates, high mobility and the presence of multiple antennas.

A total of 31 papers were received and after a careful peer-review process, 15 high quality papers have been selected and organized into four different sections.

The first set of five papers deal with low complexity soft-input soft-output equalization/detection algorithms that provide good performance versus complexity trade-offs. In "Monte Carlo Equalization for Nonlinear Dispersive Satellite Channels" , F. Kashif, H. Wymeersch and M. Z. Win describe a novel equalizer based on Markov chain monte carlo methods for channels affected by nonlinear dispersion. The proposed equalizer promises to be a good trade-off between performance and complexity as significant gains over linear equalization are achieved, whereas the complexity is significantly smaller than that of the forward-backward algorithm. In the paper "Reduced-Complexity Equalization Techniques for ISI and MIMO Wireless Channels in Iterative Decoding," K. K. Y. Wong and P. J. McLane describe a low complexity soft output algorithm based on the M-algorithm. The main novelty in their paper is in the use of the terminated paths in the M-algorithm to efficiently generate soft-output. This technique is shown to be very effective for equalization of MIMO frequency selective channels as even trellises with millions of branches per interval can be decoded with modest complexity and good performance. The third in the sequence of five papers in this section is "Graph-Based Detection Algorithms for Layered Space-Time Architecture" by J. Hu and T. Duman. In this paper, the authors consider the use of graph-based iterative algorithms for MIMO detection and equalization in layered space-time architectures. While the use of a graph based detection algorithm for the MIMO detection problem seems natural, so far,

Digital Object Identifier 10.1109/JSAC.2008.080201

there have not been many efficient graph-based iterative algorithms for this problem. The authors propose careful approximations to the optimal graph based algorithm and show that good performance can be obtained at reduced complexity. In "Low Complexity Soft-Input Soft-Output Block Decision-Feedback Equalization," J. Wu and Y. R. Zheng describe a soft-output equalizer based on the block decision-feedback equalizer that processes an entire sequence of symbols at once, as opposed to the usual symbol-by-symbol processing of conventional decision-feedback equalizers. Their approach promises low complexity and fast convergence. In"Soft-Output Sphere Decoding: Algorithms and VLSI Implementation," C. Studer, A. Burg, and H. Bölcskei, use sphere decoding to implement soft-output MIMO detection with flexible trade-offs between computational complexity and performance. Their VLSI implementation results show that a combination of sorting, MMSE processing, LLR clipping, and run-time constraints can provide near-max-log performance with complexity only 58% higher than that of a hard-output decoder in the example considered.

The next set of three papers deal with analytical and semi-analytical tools for understanding the performance of iterative equalization and decoding, and novel interpretations of such algorithms. In "Evolution Analysis of Low-Cost Iterative Equalization in Coded Linear Systems with Cyclic Prefixes," X. Yuan, Q. Guo, X. Wang, and L. Ping develop an SNR-variance evolution technique as an alternative to the Extrinisic Information Transfer (EXIT) chart for efficiently and accurately evaluating the performance of turbo frequency-domain equalization over time-varying channels. In their approach, the transfer function of the equalizer/detector is generated analytically on-the-fly (rather than pre-simulated) in a low-complexity way for each channel realization during the evolution process. In the next paper titled "LMMSE Turbo Equalization Based on Factor Graphs," Q. Guo and L. Ping propose a novel turbo equalization approach based on factor graphs. The main novelty is that the factor graphs presented are cycle-free and, hence, message passing can be used for equalization. They show that their approach is an efficient realization of the linear MMSE equalizer based on the entire observation. In "Joint Iterative Decoding of LDPC Codes for Channels with Memory and Erasure Noise," H. D. Pfister and P. H. Siegel present sequences of irregular LDPC codes that together with iterative decoding achieve the symmetric information rate of a class of channels with memory and erasures. They thus prove for the first-time that iterative decoding can be information-rate lossless with respect to maximum-likelihood decoding for some channels with memory.

The next set of five papers address the issue of communicating through time varying channels and channel estimation techniques, which are particularly important for broadband MIMO communications where several parameters in the channel impulse response need to be estimated and tracked. In "Communications through Time-Varying Subspace Channels," B. Friedlander describes several detection schemes for communication through a time-varying channel whose impulse response parameters are unknown, but have known statistics. The performance of the detection schemes is evaluated as a function of the rank of the channel covariance matrix. In "Iterative Frequency Domain Channel Estimation for DFT-Precoded OFDM Systems using In-Band Pilots," C. T. Tam, D. Falconer and F. Danilo-Lemoine consider two techniques of in-band frequency domain multiplexed (FDM) pilots using interleaved frequency domain multiple access signal with a Chu sequence for DFT-precoded OFDM or single-carrier (SC) systems. They show that using FDM pilots in SC systems facilitates flexible and efficient assignment of signals to available spectrum. Iterative interference cancellation and channel estimation techniques are also presented. In the next paper, "Subblock Processing in MMSE-FDE Under Fast Fading Environments," K. Kambara, H. Nishimoto, T. Nishimura, T. Ohgane, and Y. Ogawa propose sub-block based processing techniques for frequency domain equalization to combat intersymbol interference caused by frequency-selective fading in single carrier systems. By reducing the processed data block lengths and introducing a pseudo cyclic prefix technique, they show that the proposed method effectively decreases the error floor in fast fading environments. In the paper, "A Novel Receiver Architecture for Single-Carrier Transmission over Time-Varying Channels," Z. Tang and G. Leus propose frequency-domain equalization schemes for a single-carrier communication system transmitting through a fast fading channel with severe inter-block interference. The proposed techniques are shown to be effective and numerical results are presented on the error rate performance of these schemes. Since the overhead in estimating the channel impulse response can be quite significant, blind channel estimation is considered in the last paper in this section "Robust Subspace Blind Channel Estimation for Cyclic Prefixed MIMO OFDM Systems: Algorithm, Identifiability and Performance Analysis" by F. Gao, Y. Zeng, A. Nallanathan and T.-S. Ng. Traditional blind channel estimation methods, especially those based on the popular subspace techniques that are consistent in SNR, suffer from drawbacks including sensitivity to proper channel delay spread knowledge and breakdown for certain channel realizations, especially in the MIMO case. To alleviate this problem, a judicious twist to the problem formulation of blind channel estimation for MIMO standard OFDM systems is proposed in this paper. This formulation allows blind MIMO channel identification without channel delay spread knowledge and without any restriction on the channel realization.

The last two papers in this issue consider joint optimization of the transmitter and receiver in the presence of channel state information at the transmitter. In the first paper "Frequency Domain Pre-Equalization with Transmit Precoding for MIMO Broadcast Wireless Channels," K. B. Letaief and Y. Zhu propose two novel frequency domain transmitter-based equalization schemes employing parallel and successive Tomlinson-Harashima precoding for broadcast frequency-selective MIMO channels. The performance of these transmitter-based equalization schemes is illustrated via analysis and computer simulation. The joint transceiver optimization of a linear precoder at the transmitter and a linear receiver for point-to-point MIMO communications using various Mean Squared Error (MSE) based criteria has been considered before in the literature. In the paper entitled "A Framework for Designing MIMO

Systems with Decision Feedback Equalization (DFE) or Tomlinson-Harashima (TH) Precoding" M.B. Shenouda and T. N. Davidson extend such joint transceiver optimization to the cases of (causal) interference cancellation in either a linear precoder plus DFE receiver or TH precoder plus linear receiver (including modulo operations). Within this unified framework, optimal designs for two broad classes of communication objectives are proposed, namely those that are Schur-convex and those that are Schur-concave functions of the logarithms of the MSEs of the data streams. These optimal designs allow the solution of several open problems that are detailed in the paper, and are shown to perform better than their linear transceiver counterparts.

Acknowledgments

We have very much enjoyed putting this special issue together and this would not have been possible without the help of many individuals. We would like to express our thanks to the reviewers who provided high quality reviews in a timely manner and to the authors who submitted their work to this special issue. Thanks to Larry Milstein at UCSD for suggesting this special issue and to Martha Steenstrup for help during the early stages of planning of this special issue. Ms. Paula Evans at Texas A&M University provided much need administrative help during the review process and we very much appreciate her help. Thanks also to Ms. Sue Lange from IEEE Communications Society for coordinating the publication process and keeping us on schedule.

JOHN R. BARRY, *Guest Editor*
Georgia Insitute of Technology,
Atlanta, USA

FUYUN LING, *Guest Editor*
Qualcomm Research & Development,
San Diego, USA

KRISHNA NARAYANAN, *Guest Editor*
Texas A&M University,
College Station, USA

JOHN PROAKIS, *Guest Editor*
The University of California at San Diego,
La Jolla, USA

DIRK T. M. SLOCK, *Guest Editor*
Institut Eurecom,
Sophia Antipolis, France

L. Milstein, *J-SAC Board Representative*

John R. Barry (Senior Member) received the B.S. degree in electrical engineering from the State University of New York, Buffalo, in 1986 and the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1987 and 1992, respectively. Since 1992, he has been with the Georgia Institute of Technology, Atlanta, where he is Professor with the School of Electrical and Computer Engineering. His research interests include wireless communications, equalization, and multiuser communications. He is a coauthor with E. A. Lee and D. G. Messerschmitt of Digital Communication (Norwell, MA: Kluwer, 2004, Third ed.) and the author of Wireless Infrared Communications (Norwell, MA: Kluwer, 1994)

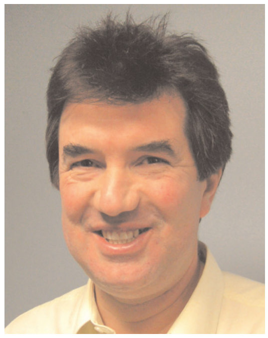
Fuyun Ling (S'81-M'84-SM'87-F'97) received his B. S. degree from Tsinghua University, Beijing, China, in 1968, and his MS and Ph. D. degrees from Northeastern University, Boston, Mass., USA, in 1981 and 1984 respectively. From 1984 to 1998, he was with Motorola Inc. working on research and development of various wireline and wireless communication technologies and products. In 1998, he joined Qualcomm Incorporated, San Diego, California, as a Vice President of Technology and worked on research and development of new wireless communication technologies. Since 2003, he has been working on MediaFLO project and is currently responsible for FLO PHY Layer specification and development.

Throughout his career, Dr. Ling has been working on digital communications and digital signal processing and their application to wireless and wireline communications. He holds 70 US Patents with a number of other patent applications pending. He has also published over 80 papers and two books all in his technical areas. He is an Adjunct Professor of Tsinghua University and a Fellow of IEEE.

Krishna Narayanan received his B.E. degree from Coimbatore Institute of Technology, M.S. degree from Iowa State University and Ph.D. degree from Georgia Institute of Technology in 1998. Since then he has been with the Department of Electrical and Computer Engineering at Texas A&M University in College Station, where he is currently an associate professor. His research interests are in coding theory, information theory and receiver signal processing with applications to wireless communications and data storage. During the academic year 2004-2005, he held visiting positions at the University of Illinois at Urbana Champaign, Institut Eurecom in Sophia Antipolis, France and the Indian Institute of Science in Bangalore, India. He currently serves as the area editor for coding theory and applications for the IEEE Transactions on communications. He has served on the editorial board of IEEE Transactions on Wireless Communications and IEEE Communications Letters in the past. He was the recipient of the 2006 best paper award from the IEEE data storage technical committee. He received the CAREER award from the National Science Foundation in 2001 and the outstanding faculty award from the Department of ECE at Texas A&M university in 2002.

John Proakis (S'58-M'62-F'84-LF'99) received the BSEE from the University of Cincinnati in 1959, the MSEE from MIT in 1961 and the Ph.D. from Harvard University in 1967. He is an Adjunct Professor at the University of California at San Diego and a Professor Emeritus at Northeastern University. He was a faculty member at Northeastern University from 1969 through 1998 and held the following academic positions: Associate Professor of Electrical Engineering, 1969-1976; Professor of Electrical Engineering, 1976-1998; Associate Dean of the College of Engineering and Director of the Graduate School of Engineering, 1982-1984; Interim Dean of the College of Engineering, 1992-1993; Chairman of the Department of Electrical and Computer Engineering, 1984-1997. Prior to joining Northeastern University, he worked at GTE Laboratories and the MIT Lincoln Laboratory.

His professional experience and interests are in the general areas of digital communications and digital signal processing. He is the author of the book Digital Communications (New York: McGraw-Hill, 2001, fourth edition), and co-author of the books, Introduction to Digital Signal Processing (Upper Saddle River: Prentice Hall, 2007, fourth edition); Digital Signal Processing Laboratory (Englewood Cliffs: Prentice Hall, 1991); Advanced Digital Signal Processing (New York: Macmillan, 1992); Algorithms for Statistical Signal Processing(Upper Saddle River: Prentice Hall, 2002);Discrete-Time Processing of Speech Signals (New York: Macmillan, 1992, IEEE Press, 2000); Communication Systems Engineering, (Upper Saddle River: Prentice Hall, 2002, second edition); Digital Signal Processing Using MATLAB V.4 (Boston: Brooks/Cole-Thomson Learning, 2007, second edition); Contemporary Communication Systems Using MATLAB (Boston: Brooks/Cole-Thomson Learning, 2004, second edition); Fundamentals of Communication Systems (Upper Saddle River: Prentice Hall , 2005)



Dirk T.M. Slock received an engineering degree from the University of Gent, Belgium in 1982. In 1984 he was awarded a Fulbright scholarship for Stanford University USA, where he received the MS in Electrical Engineering, MS in Statistics, and PhD in Electrical Engineering in 1986,

1989 and 1989 respectively. While at Stanford, he developed new fast recursive least-squares (RLS) algorithms for adaptive filtering. In 1989-91, he was a member of the research staff at the Philips Research Laboratory Belgium. In 1991, he joined the Eurecom Institute where he is now professor. At Eurecom, he teaches statistical signal processing and signal processing techniques for wireless and wireline communications. His research interests include DSP for mobile communications (antenna arrays for (semi-blind) equalization/interference cancellation and spatial division multiple access, space-time processing and coding, channel estimation) and adaptation techniques for audio processing. He has worked in particular on receiver design and downlink antenna array processing for third generation systems, introducing spatial multiplexing (MIMO) in existing wireless systems, fading channel modeling and estimation, and OFDM systems. He invented semi-blind channel estimation, the chip equalizer-correlator receiver used by 3G HSDPA mobile terminals, and his work led to the Single Antenna Interference Cancellation (SAIC) concept used in GSM terminals.

In 2000, he cofounded SigTone, a start-up developing music signal processing products. He has also been active as a consultant on xDSL, DVB-T and 3G systems. He is the (co)author of over 250 technical papers. He received one best journal paper award from the IEEE-SP and one from

EURASIP in 1992. He is the coauthor of two IEEE Globecom98, one IEEE SIU'04 and one IEEE SPAWC'05 best student paper award, and a honorary mention (finalist in best student paper contest) at IEEE SSP'05, IWAENC'06 and IEEE Asilomar'06. He was an associate editor for the IEEE-SP Transactions in 1994-96. He is an editor for the EURASIP Journal on Advances in Signal Processing, for which he also guest edited two special issues. He has also been a guest

editor for IEEE-SP Sig. Proc. Mag. and for IEEE-COM JSAC. He was the General Chair of the IEEE-SP SPAWC'06 workshop. He is a Fellow of the IEEE.