Guest Editorial
Network Coding for Wireless Communication Networks

In wireless communication networks, network performance is largely affected by various network characteristics, such as limited channel bandwidth, unstable signal transmission, severe power constraint, high node unreliability, and easy interception of wireless signals. Network coding has recently emerged as a new coding paradigm that has demonstrated a wide range of potential applications for improving network performance in wireless communication networks. The core notion of network coding is to allow the information (or data) received from multiple links to be mixed at intermediate network nodes for subsequent transmissions so that the amount of data transmitted in the network is reduced and the network performance in terms of network throughput is improved. This notion can also be applied to the data received on a single link within a single stream or across different streams, and even to the physical layer, where different signals can be combined for further transmission. In contrast to traditional network operations that try to avoid collisions of data streams through resource management, this elegant principle not only provides a new way to improve network throughput but also brings a plethora of other surprising benefits, such as energy efficiency, network robustness, and network security. Owing to its wide range of potential applications, network coding has recently received increasing attention from the research community. To better exploit this promising coding paradigm in wireless communication networks, many technical issues remain to be studied, which has invigorated a considerable amount of research activities in the area.

This special issue includes a collection of 19 outstanding research papers which cover a diversity of topics on the application of network coding in wireless communication networks.

The first eight papers are on the performance analysis of network coding in different types of wireless networks. In the paper "Bounds on the Throughput Gain of Network Coding in Unicast and Multicast Wireless Networks," Liu et al. studied bounds on the throughput gain of network coding in unicast and multicast wireless networks. For random networks of any dimension under either the protocol or physical communication model that was introduced by Gupta and Kumar, they showed that network coding and broadcasting lead to at most a constant factor improvement in per node throughput. For the protocol model, they provided bounds on this factor. They also established bounds on the throughput benefit of network coding and broadcasting for multiple source multicast in random networks. For an arbitrary network deployment, they showed that the coding benefit ratio is at most O(logn) for both the protocol and physical models. These results provide guidance on the application of network coding, and more generally indicate the difficulty in improving the scaling behavior of wireless networks without modification of the physical layer.

In "Modeling Throughput Gain of Network Coding in Multi-Channel Multi-Radio Wireless Ad Hoc Networks," Su and Zhang modeled the network throughput gains of two types of network coding (NC) schemes, including the conventional NC and analog NC schemes, over the traditional non-NC transmission scheduling schemes in multi-hop, multi-channel, and multi-radio wireless ad hoc networks. They first showed the network throughput gains of the conventional NC and analog NC, and then proposed an analytical framework for deriving the network throughput gain of the NC schemes over general network topologies. By solving the problem of maximizing the network throughput subject to the fairness requirements under the proposed analytical framework, they quantitatively analyzed the network throughput gains of these two types of NC schemes for a variety of network topologies with different routing strategies. In addition, they also developed a heuristic joint link scheduling, channel assignment, and routing algorithm that aims at approaching the optimal solution to the optimization problem under the proposed framework.

In "Cross-Layer Optimization for Wireless Multihop Networks with Pairwise Intersession Network Coding," Khreishah et al. showed that with a new flow-based characterization of pairwise intersession network coding, an optimal joint coding, scheduling, and rate-control scheme can be devised and implemented using only the binary XOR operation. The new scheduling or rate-control scheme demonstrates provably graceful throughput degradation with imperfect scheduling, which facilitates the design tradeoff between the throughput optimality and computational complexity of different scheduling schemes. The results show that pairwise intersession network coding improves the throughput of non-coding solutions regardless of whether perfect or imperfect scheduling is used. This work shows a striking resemblance between pairwise intersession network coding and non-coded solutions, and thus advocates extensions of non-coding wisdoms to their network coding counterpart.

In "Optimized Multipath Network Coding in Lossy Wireless Networks," Zhang and Li considered maximizing the benefits of network coding for unicast sessions in lossy wireless environments, and proposed Optimized Multipath Network Coding (OMNC), a rate control protocol that dramatically improves the throughput of lossy wireless networks. OMNC employs multiple paths to push coded packets to the destination, and uses the broadcast MAC to deliver packets between neighboring nodes. The coding and broadcast rate is allocated to transmitters by a distributed optimization algorithm that maximizes the advantage of network coding while avoiding congestion.

In "Is Rate Adaptation Beneficial for Inter-Session Network Coding?" Kim and Veciana considered the interplay between rate adaptation and inter-session network coding gains in wireless mesh or ad hoc networks. They considered inter-session coding, restricted to a single relay (bottleneck) node, or star network

Digital Object Identifier 10.1109/JSAC.2009.090601

topology, and provided heuristics to find a suboptimal solution to the joint optimal rate vector selection and optimal network coding problem. Additionally, a linear programming formulation is provided for network coding when only pairwise inter-session coding is allowed. The averaged throughput is evaluated in two different scenarios, where relays have different access opportunities.

In "Wireless Network Coding in Slotted ALOHA with Two-Hop Unbalanced Traffic," Umehara et al. analyzed the performance of network coding on a two-hop wireless relay access system employing the slotted ALOHA under balanced bidirectional traffic, and provided closed-form expressions for the throughput and packet delay for two-hop unbalanced bidirectional traffic cases both with and without network coding from a theoretical perspective of the slotted ALOHA. The results show that the transmission probability of the relay node is a design parameter that is crucial to maximizing the achievable throughput of wireless network coding in the slotted ALOHA on two-hop unbalanced traffic cases.

In "On the Improvement of Scaling Laws for Large-Scale MANETs with Network Coding," Zhang et al. characterized the throughput-delay storage tradeoffs in mobile ad hoc networks (MANETs) with network coding, and compared with the scenarios where only replication and forwarding are allowed in each node. The schemes that effectively achieve those tradeoffs in a decentralized manner are proposed and the optimality of those tradeoffs is established. The scenarios in which network coding can provide significant improvement on network performance are identified under different node mobility patterns (fast and slow mobility). The insights on when and how information mixing is beneficial to MANETs with multiple unicast and multicast sessions are provided.

In "Doped Fountain Coding for Minimum Delay Data Collection in Circular Networks," Kokalj-Filipovic et al. studied decentralized, Fountain, and network-coding based strategies for facilitating data collection in circular wireless sensor networks, which rely on the stochastic diversity of data storage. The goal is to allow for a reduced delay collection by a data collector which accesses the network at a random position and at a random time. It is shown that network coding makes data dissemination more efficient at the expense of a larger collection delay.

Then, there are three papers on new network coding schemes and techniques for improving the performance of different types of wireless networks. In the paper "A Hybrid Network Coding Technique for Single-Hop Wireless Networks," Tran et al. investigated a hybrid network coding technique to be used at a wireless base station (BS) or access point to increase the throughput efficiency of single-hop wireless networks. Using the proposed network coding technique, the BS encodes the lost packets possibly from different flows together before broadcasting them to all wireless users, thus allowing multiple wireless receivers to recover their lost packets simultaneously with a single transmission from the BS. It is shown that when used in conjunction with an appropriate channel coding technique under typical channel conditions, this technique can increase the throughput efficiency up to 3.5 times over the Automatic Repeat request (ARQ), and up to 1.5 times over the hybrid-ARQ techniques.

In "Optimal Beamforming for Two-Way Multi-Antenna Relay Channel with Analogue Network Coding," Zhang et al. studied the wireless two-way relay channel (TWRC), where two source nodes exchange information through an assisting relay node. Assuming that the two source nodes are each equipped with a single antenna and the relay node with multi-antennas, they analyzed the capacity region of an analogue network coding (ANC)-based TWRC with linear processing (beamforming) at the relay node, and presented the optimal relay beamforming structure as well as an efficient algorithm to compute the optimal beamforming matrix based on convex optimization techniques. Low-complexity suboptimal relay beamforming schemes are also presented, and their achievable rates are compared against the capacity with the optimal scheme.

In "Video-Aware Opportunistic Network Coding over Wireless Networks," Seferoglu and Markopoulou studied video streaming over wireless networks with network coding capability and proposed video-aware opportunistic network coding schemes that take into account both the decodability of network codes by several receivers, and the importance and deadlines of video packets. They concluded that when the transmitted flows are video streams, network codes should be selected such that not only the network throughput but also the video quality is maximized.

The next three papers are on multicast communication using network coding in different types of wireless networks. In "Training Overhead for Decoding Random Linear Network Codes in Wireless Networks," Riemensberger et al. considered multicast communications from a single source to multiple destinations through a wireless network with unreliable links, and presented a joint coding and training scheme in which training bits are appended to each source packet, and the channel code is applied across both the training and data. This scheme allows each destination to decode jointly the network coding matrix along with the data without knowledge of the network topology. It also balances the reliability of communicating the network coding matrices with the reliability of data detection. The throughput for this scheme, accounting for overhead, is characterized as a function of the packet size, channel properties (error and erasure statistics), number of independent messages, and field size.

In "Binary Linear Multicast Network Coding on Acyclic Networks: Principles and Applications in Wireless Communication Networks," Li et al. first discussed the reciprocal theorem of the conventional linear multicast and then designed a linear multicast on any given acyclic network with constant finite field by extending the multicast dimension and relaxing the constraint on the information storage. In particular, they proposed a binary linear multicast network coding and a linear multicast with binary coefficients. With the proposed coding and multicast method, the computational complexity for network coding at the intermediate nodes can be significantly reduced.

In "Reliable Relay Assisted Wireless Multicast Using Network Coding," Fan et al. discussed and analyzed the network coding based cooperative multicast scheme systematically and compare its performance in terms of throughput, delay, and queue length with two other multicast protocols. Based on the analysis, an optimal multicast scheme is proposed to maximize the throughput subject delay and queue length constraints.

These are followed by the three papers on physical-layer network coding in different types of wireless networks. In the paper "On Capacity of Random Wireless Networks with Physical-Layer Network Coding," Lu et al. studied the theoretical throughput capacity of a random wireless network with three different transmission schemes: traditional flow-based scheme, network coding scheme, and physical-layer network coding scheme. This study reveals that, although physical-layer network coding does not change the scaling law, it can improve throughput capacity by a fixed factor. They observed that for a one-dimensional network, physical-layer network coding can eliminate the effect of interference in some scenarios, and derived a tighter capacity bound for a two-dimensional network. The study also shows achievable lower bounds for random wireless networks with network coding and physical-layer network coding.

In "Optimized Constellations for Two-Way Wireless Relaying with Physical Network Coding," Koike-Akino et al. investigated the modulation schemes optimized for two-way wireless relaying systems, where network coding is employed at the physical layer. The network coding based on denoise-and-forward (DNF) protocol is considered, which consists of two stages: multiple access (MA) stage, where two terminals transmit simultaneously towards a relay, and broadcast (BC) stage, where the relay transmits towards both terminals. For the case of QPSK modulations at the MA stage, it is shown that the QPSK constellation with an XOR network coding does not always offer the best transmission for the BC stage, and that there are several channel conditions in which the unconventional 5-ary constellations lead to a better throughput performance. Through the use of sphere packing, the constellation is optimized for such an irregular network coding. They further discussed the design issue of the modulation in the case when the relay exploits diversity receptions such as multiple-antenna diversity and path diversity in frequency-selective fading.

In "Channel Coding and Decoding in a Relay System Operated with Physical-Layer Network Coding," Zhang and Liew investigated link-by-link channel-coded physical-layer network coding, in which a critical process at the relay is to transform the superimposed channel-coded packets received from the two end nodes (plus noise) to the network-coded combination of the source packets. They showed that if the Repeat Accumulate (RA) channel code is adopted at the two end nodes, there is a compatible decoder at the relay that can perform the transformation efficiently.

The last two papers are on other aspects in the application of network coding in wireless communication networks. In the paper "Network Coding-Based Protection of Many-to-One Wireless Flows," Al-Kofahi and Kamal studied the problem of survivability of many-to-one flows in wireless networks, and presented a network coding-based protection scheme, which overcomes the deficiencies of traditional schemes, such as the (1+1) protection scheme and the (1: N) protection scheme, and provided protection at the speed of proactive protection but at the cost of reactive protection.

In the paper "Improving the Multicommodity Flow Rates with Network Codes for Two Sources," Erez and Feder proposed a code construction scheme for constructing network codes for two sources based on the multi-commodity flow solution, and found a network code that improves the rate region of multi-commodity flows. It is shown that the construction algorithm can be combined with distributed back-pressure routing algorithm for wireless ad-hoc networks. For both the non-distributed case and the distributed case, the computational complexity of the code construction algorithm is comparable to that of the parallel multi-commodity flow problem. They also provided non-trivial upper and lower bounds on the performance of the proposed code construction scheme using random coding techniques.

We thank all the authors who submitted their papers to this special issue. We received a total of fifty-eight submissions in response to our Call for Papers. Owing to the limitation of space, only nineteen papers are included in the issue. We are so grateful to all the reviewers for carefully reviewing all the articles and providing valuable review comments. We appreciate the support and guidance of the Editor-in-Chief, Pamela Cosman, and the Executive Editor, Laurel Greenidge, throughout the process of bringing this special issue to fruition. We also thank the liaison editor, Alberto Leon-Garcia, for providing valuable comments in making the final decisions. In addition, we are thankful to Sue Lange, the Digital Production Manager, and all other publication staff for their support and help during the publication process.

It is our hope that the papers included in this special issue present a good snapshot of the latest research advances in network coding for wireless communication networks and become an important reference for researchers and practitioners in the area. Finally, we hope that the readers of IEEE J-SAC will find this special issue timely, informative, and stimulating.

Jun Zheng, *Lead Guest Editor*
School of Information Science and Engineering
Southeast University
Nanjing, China
jzheng@ieee.org

Nirwan Ansari, *Guest Editor*
Department of Electrical and Computer Engineering
New Jersey Institute of Technology
Newark, USA
nirwan.ansari@njit.edu

Victor O.K. Li, *Guest Editor*
Department of Electrical and Electronic Engineering
The University of Hong Kong
Hong Kong, China
vli@eee.hku.hk

Xuemin (Sherman) Shen, *Guest Editor*
Department of Electrical and Computer Engineering
University of Waterloo
Waterloo, Canada
xshen@bbcr.uwaterloo.ca

Hossam S. Hassanein, *Guest Editor*
Department of Electrical and Computer Engineering
Queen's University
Kingston, Canada
hossam@cs.queensu.ca

Baoxian Zhang, *Guest Editor*
Graduate University
Chinese Academy of Sciences
Beijing, China
bxzhang@gucas.ac.cn

Alberto Leon-Garcia, *J-SAC Board Representative*

Jun Zheng is a Professor with the School of Information Science and Engineering of the Southeast University, China. He received his Ph.D. degree in Electrical and Electronic Engineering from The University of Hong Kong, M.S. degree in Communications and Electronic systems, and B.S. degree in Wireless Communications Engineering from Xidian University, China.

Dr. Zheng serves as an Associate Technical Editor of IEEE Communications Magazine, an Editor of IEEE Communications Surveys & Tutorials, an Associate Editor of IEEE/OSA Journal of Optical Communications and Networking, and an editorial board member of several other refereed journals. He has guest-edited eight special issues for different refereed journals and magazines, including IEEE Network and IEEE JSAC, Wiley Wireless Communications and Mobile Computing, and Springer Mobile Networks and Applications, all as Lead Guest Editor. He has served as the founding General Chair of AdHocNets'09, General Chair of AccessNets'07, and TPC or Symposium Co-Chair of several international conferences and symposiums, including IEEE GLOBECOM'08, IEEE ICC'09, and GLOBECOM'10. He has also served on the technical program committees of a number of international conferences and symposia.

Dr. Zheng's research interests includes the design and analysis of network architectures and protocols for efficient and reliable communications, and their applications to different types of networks, covering wireless networks, optical networks, and IP networks. He has co-authored (first author) the book Optical WDM Networks: Concepts and Design Principles and is the Lead Editor of the book Wireless Sensor Networks: A Networking Perspective, both published by Wiley-IEEE Press. He has published more than 80 technical papers in refereed journals and magazines, and peer-reviewed conference proceedings. Dr. Zheng is a senior member of the IEEE.

Nirwan Ansari (S'78-M'83-SM'94-F'09) received the B.S.E.E. (summa cum laude) from the New Jersey Institute of Technology (NJIT), Newark, in 1982, the M.S.E.E. degree from University of Michigan, Ann Arbor, in 1983, and the Ph.D. degree from Purdue University, West Lafayette, IN, in 1988. He is Professor of Electrical and Computer Engineering at NJIT. He authored Computational Intelligence for Optimization (Springer, 1997) with E.S.H. Hou, and edited Neural Networks in Telecommunications (Springer, 1994) with B. Yuhas. His current research focuses on various aspects of broadband networks and multimedia communications. He has also contributed over 300 technical papers, over one third of which in refereed journals and magazines.

He is a Senior Technical Editor of the IEEE Communications Magazine, and also serves on the Advisory Board and Editorial Board of five other journals. He has been serving the IEEE in various capacities such as Chair of IEEE North Jersey COMSOC Chapter, Chair of IEEE North Jersey Section, Member of IEEE Region 1 Board of Governors, Cluster Chair of IEEE COMSOC Networking TC Cluster, Chair of IEEE COMSOC Technical Committee on Ad Hoc and Sensor Networks, and Chair/TPC Chair of several conferences/symposia. Some of his recent awards and recognitions include an IEEE Fellow (Communications Society), IEEE Leadership Award (2007, from Central Jersey/Princeton Section), the NJIT Excellence in Teaching in Outstanding Professional Development (2008), IEEE MGA Leadership Award (2008), the NCE Excellence in Teaching Award (2009), and designation as an IEEE Communications Society Distinguished Lecturer.

Victor O.K. Li (S'80-M'81-SM'86-F'92) (http://www.eee.hku.hk/staff_personal/vli.htm) received SB, SM, EE and ScD degrees in Electrical Engineering and Computer Science from the Massachusetts Institute of Technology, Cambridge, Massachusetts, in 1977, 1979, 1980, and 1981, respectively. He joined the University of Southern California (USC), Los Angeles, California, USA in February 1981, and became Professor of Electrical Engineering and Director of the USC Communication Sciences Institute. Since September 1997 he has been with the University of Hong Kong, Hong Kong, where he is Associate Dean (Research) of Engineering, and Chair Professor of Information Engineering. He also served as Managing Director of Versitech Ltd. (http://www.versitech.com.hk/), the technology transfer and commercial arm of the University, from September 1997 to June 2004. Prof. Li serves on various corporate boards. His research is in information technology, including all-optical networks, wireless networks, and Internet technologies and applications. Sought by government, industry, and academic organizations, he has lectured and consulted extensively around the world. Prof. Li is very active in the research community, and has chaired various international conferences and served on the editorial boards of various international journals. He has given distinguished lectures at various universities around the world, and keynote speeches at many international conferences. Prof. Li has received numerous awards, including, most recently, the PRC Ministry of Education Changjiang Chair Professorship at Tsinghua University, Beijing, the UK Royal Academy of Engineering Senior Visiting Fellowship in Communications, the KC Wong Education Foundation Lectureship, the Croucher Foundation Senior Research Fellowship, and the Order of the Bronze Bauhinia Star, Government of the Hong Kong Special Administrative Region, China.

Xuemin (Sherman) Shen (IEEE M'97-SM'02-F'09) received the B.Sc. (1982) degree from Dalian Maritime University (China) and the M.Sc. (1987) and Ph.D. degrees (1990) from Rutgers University, New Jersey (USA), all in electrical engineering. He is a Professor and University Research Chair, Department of Electrical and Computer Engineering, University of Waterloo, Canada. Dr. Shen's research focuses on mobility and resource management, UWB wireless communications networks, wireless network security, and vehicular ad hoc and sensor networks. He is a co-author of three books, and has published more than 400 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen served as the Tutorial Chair for IEEE ICC'08, and the Technical Program Committee Chair for IEEE Globecom'07. He also serves as a Founding Area Editor for IEEE Transactions on Wireless Communications; Editor-in-Chief for Peer-to-Peer Networking and Application; Associate Editor for IEEE Transactions on Vehicular Technology, KICS/IEEE Journal of Communications and Networks, Computer Networks, and ACM/Wireless Networks. He has also served as Guest Editor for IEEE JSAC, IEEE Wireless Communications, and IEEE Communications Magazine. Dr. Shen received the Excellent Graduate Supervision Award in 2006, and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, and the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada. Dr. Shen is a registered Professional Engineer of Ontario, Canada, and a Distinguished Lecturer of IEEE Communications Society.

Hossam Hassanein is internationally recognized researcher in the School of Computing at Queen's University in the areas of broadband, wireless and variable topology networks architecture, protocols, control and performance evaluation. Before joining Queen's University in 1999, he worked at the department of Mathematics and Computer Science at Kuwait University (1993-1999) and the department of Electrical and Computer Engineering at the University of Waterloo (1991-1993). Dr. Hassanein obtained his Ph.D. in Computing Science from the University of Alberta in 1990. He is the founder and director of the Telecommunication Research (TR) Lab (http://www.cs.queensu.ca/~trl) in the School of Computing at Queen's. Dr. Hassanein has more than 300 publications in reputable journals, conferences and workshops in the areas of computer networks and performance evaluation. He has delivered numerous invited talks and tutorials at key international venues, including Unconventional Computing 2007, IEEE ICC 2008, IEEE CCNC 2009 and IEEE GCC 2009. Dr. Hassanein has organized and served on the program committee of a number international conferences and workshops. He also serves on the editorial board of a number of International Journals. He is a senior member of the IEEE and is currently vice-chair of the IEEE Communication Society Technical Committee on Ad hoc and Sensor Networks (TC AHSN). Dr. Hassanein is the recipient of Communications and Information Technology Ontario (CITO) Champions of Innovation Research award in 2003. In 2007, he received best paper awards at the IEEE Wireless Communications and Networks and the IEEE Global Communication Conferences (both flagship IEEE communications society conferences). Dr. Hassanein is an IEEE Communications Society Distinguished Lecturer.

Baoxian Zhang is currently a Professor with the College of Computing and Communication Engineering of Graduate University of Chinese Academy of Sciences, Beijing, China. He is Vice Director of Key Lab of Wireless Sensor Network and Communications, Shanghai Institute of Microsystem and Information Technology of Chinese Academy of Sciences, Shanghai, China. He received his BS, MS, and PhD degrees in electrical engineering from Northern Jiaotong University (Now Beijing Jiaotong University), China, in 1994, 1997, and 2000, respectively.

He has served as a Guest Editor of a special issue on Underwater Wireless Sensor Networks for Wiley Wireless Communications and Mobile Computing and a special issue on Recent Advances in Wireless Networks for ACM Mobile Networks and Applications. He has served as Symposium Co-Chairs of CHINACOM'08 Advances in Internet Symposium and IWCMC'09 Cross-Layer Optimized Wireless Networks Symposium. He has also served on technical program committees for many international conferences and symposia, including IEEE GLOBECOM, ICC, and WCNC. He has published over 70 refereed technical papers in archival journals and conference proceedings. His research interests include network architecture, protocol and algorithm design, wireless ad hoc and sensor networks, and performance evaluation. He is a member of the IEEE.