Theories and Methods for Advanced Wireless Relays - Issue I

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THE demand for wireless access continues to increase rapidly in both military and civilian communities. The modern internet and modern personal-area devices have made billions of users around the world accustomed to data hungry applications such as videos. This has an inevitable effect on the users' desire for the same through wireless media. Because of the limited radio frequency spectrum, wireless access will always be a bottleneck in the world of information. As the radio spectrum becomes more crowded each year, new technologies must be developed to increase the network-wise spectral efficiency. One approach to achieving this goal is to reduce the size of wireless cells through infrastructure redevelopment. But the pace and/or the cost of such redevelopment may not be able to match the users' needs. A faster, often more economical and/or complementary alternative to achieving the same goal is to deploy advanced wireless relays. Unlike traditional wireless repeaters, advanced wireless relays should be channel aware, cognitive of their environments, cooperative with neighboring nodes, inflict minimum interference to the network, and utilize advanced technologies of signal processing, antenna and chip designs.

With the above vision, a Call for Papers was published in January 2011. The invited topics included MIMO relays, full-duplex relays, cooperative relays, relay channel estimation, relay channel coding and modulation, relay channel scheduling, networking issues of relays, security issues of relays, and RF/DSP system design of relays. By the deadline in August 2011, we received 108 submissions of manuscripts. Such a large volume of submissions appears to be a rare event in the history of JSAC. Each of these papers was handled by one of us as Guest Editors[1] and independently reviewed by two or more experts. The first round of decisions was made in December 2011. The revised papers were further reviewed in the second round. The final decisions were made in May 2012. Because of the time constraint on this special issue, we had to reject a few papers even though they contain important contributions but would require further major revisions. With the help from more than 230 experts in this field, we finally accepted 46 papers. The decision on each paper was made completely based on the merit of the paper, which was not influenced by the fact that each JSAC issue has a limited page budget. For this reason, we have to divide the 46 papers into two groups to be published in two separate issues under the same theme - "Theories and Methods for Advanced Wireless Relays".

The first issue includes papers on relay performance bound, MIMO relay beamforming, relay channel estimation, two-way and shared relays, full-duplex relays and their performances. The second issue includes papers on coding for relay network, medium access control for relays, implementation and system performance study, and security for relay network.

A brief description of each of these papers is provided below for reader's convenience.

I. First Issue (the current issue)

A. Relay performance bound

The paper by Yang, Choi, Lee, and Paulraj, entitled "Achievable Sum-Rate of MU-MIMO Cellular Two-Way Relay Channels: Lattice Code-Aided Linear Precoding," presents a sum-rate lower bound of the multiuser multiple-input multiple-output (MU-MIMO) cellular two-way relay channel assuming a decode-and-forward relay approach. The MIMO base station communicates with a MIMO relay that communicates with a set of single antenna mobile stations. The approach introduced allows network coding in a decode-and-forward relay even with non-cooperative mobile stations. The lower sum-rate bound achieves a cut-set bound in the high SNR regime when the ratio of the base-to-relay SNR to relay-to-mobile SNR is large.

The paper by Gerdes, Riemensberger, and Utschick, entitled "On Achievable Rate Regions for Half-Duplex Gaussian MIMO Relay Channels: A Decomposition Approach," addresses the maximum achievable rate for a decode-and-forward relay. Assuming perfect channel knowledge at all nodes and per node peak power constraints, an approach for developing inner and outer rate bounds is constructed. The capacity results involve an optimization that removes dependency upon specifics of the relay protocol.

B. MIMO relay beamforming

The paper by Sanguinetti, D'Amico, and Rong, titled "A Tutorial on the Optimization of Amplify-and-Forward MIMO Relay Systems" provides an up-to-date overview of the fundamental results and practical implementation issues of designing AF MIMO relay systems. This tutorial covers optimization of MIMO relay systems with various architectures including one-way/two-way two-hop/multi-hop relays with linear/non-linear transceivers. Practical issues such as channel state information acquiring and robust design are discussed. The

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[1]Papers coauthored by Guest Editors were handled independently by Senior Editors.

authors also point out some interesting open issues that are likely to be the basis for future research in the optimization of relay networks.

The paper by Kim, Park, and Park, titled "Beamforming of Amplify-and-Forward Relays under Individual Power Constraints" investigates distributed beamforming in an AF relay network with the second-order statistics on the channel state information and individual power constraint at each relay node. A greedy search algorithm is proposed to find beamforming weights iteratively. The authors analyze the necessary and sufficient conditions for the optimality of the proposed algorithm. Compared with the semidefinite programming-based approach, the greedy search algorithm has a smaller computational complexity.

The paper by Park and Lee, titled "Beamforming for Virtual MIMO Broadcasting in Multi-Hop Relay Networks" develops a new framework for the broadcast virtual MIMO system by developing an innovative max-min/min-max beamforming technology optimized for the multi-hop relay network. Compared with conventional singular value decomposition-based or random beamforming technologies, the max-min/min-max beamforming significantly improves the end-to-end channel throughput up to the optimal bound for the broadcast virtual MIMO system over a multi-hop relay network.

The paper by Xing, Xia, Gao, and Wu, titled "Robust Transceiver with Tomlinson-Harashima Precoding for Amplify-and-Forward MIMO Relaying Systems" investigates robust transceiver design with Tomlinson-Harashima precoding (THP) for multihop amplify-and-forward MIMO relaying systems. The source employs THP to mitigate the spatial intersymbol interference. A joint Bayesian robust design of THP at source, linear forwarding matrices at relays and linear equalizer at destination is proposed that reduces the effects of channel estimation errors. The structure of the optimal nonlinear transceiver is derived and an iterative water-filling solution is proposed to obtain unknown variables.

The paper by Park, Park, Ko, and Alouini, titled " Alternate Transmission Relaying based on Interference Alignment in 3-Relay Half-Duplex MIMO Systems" proposes a linear precoding/decoding scheme and an alternate relaying protocol in a dual-hop half-duplex system with three relays. A phase incoherent method in relays is considered in which the source alternately transmits to the different relays. In addition, a linear interference alignment scheme is proposed that suppresses the inter-relay interference resulting from the phase incoherence of relaying. It is shown that the proposed scheme achieves higher degrees of freedom compared to the conventional half-duplex relaying.

The paper by Song, Lee, and Lee, titled "MMSE-based MIMO Cooperative Relaying Systems: Closed-form Designs and Outage Behavior" uses the minimum mean squared error (MMSE) criterion to investigate amplify-and-forward cooperative strategies in multiple antenna relaying network with direct link. A novel sub-optimal solution for the relay amplifying matrix is proposed. Using diversity-multiplexing tradeoff, the performance of the proposed scheme is analyzed and it is shown that this scheme outperforms existing suboptimal schemes and achieves near optimal performance with lower complexity compared to the iterative optimal scheme.

The paper by Li, Lin, Yu, Zhu, and Dong, entitled "Optimal Design of Dual-Hop MIMO Relay Networks over Rayleigh Fading Channel," addresses a MIMO amplify-and-forward relay. It is assumed that all nodes, source, relay, and destination have multiple antennas. Given optimal beamformers, analytic forms for outage probabilities and error rates for M-PSK and M-QAM modulations are evaluated. Results from simulations demonstrate accuracy of the analytic forms.

The paper by Zhong, Ratnarajah, Jin, and Wong, titled "Performance Analysis of Optimal Single Stream Beamforming in MIMO Dual-Hop AF Systems" considers a two-hop three-nodes MIMO relay system where the relay performs a channel-independent amplify-and-forward operation. The authors formulated a SNR at the destination based on a single-stream transmit beamformer at the source and a single-stream receive beamformer at the destination. Based on this SNR, they further carried out a statistical analysis of the system's outage probability, average symbol error rate and ergodic capacity.

C. Relay channel Estimation

The paper by Jing and Yu, titled "ML-Based Channel Estimations for Non-Regenerative Relay Networks with Multiple Transmit and Receive Antennas" considers a channel estimation problem for a two-hop amplify-and-forward relay system where the source and destination each have multiple antennas and the relay has a single antenna. The authors developed a maximum likelihood (ML) estimation algorithm for the end-to-end channels and also the individual channels. They also developed an SVD based approximation of the ML algorithm. They described how their methods can be used for multiple relays and multiple antennas on each relay.

The paper by Lioliou, Viberg, and Matthaiou, titled "Bayesian Approach to Channel Estimation for AF MIMO Relaying Systems" presents linear MMSE and expectation maximization (EM)-based maximum a posteriori (MAP) channel estimation algorithms for AF MIMO relaying systems. These algorithms provide the destination with full knowledge of all channel parameters involved in the transmission. The authors also derive the Bayesian Cramér-Rao bound for this channel estimation and demonstrate that by incorporating the prior knowledge of the channel statistics, the MSE of channel estimation can be reduced.

D. Two-way and shared relays

The paper by Wang, Liew, and Guo, titled "Wireless MIMO Switching with Zero-forcing Relaying and Network-coded Relaying" considers an amplify-and-forward MIMO relay serving as a switching center for multiple users. Assuming that the number of users is no larger than the number of antennas mounted on the relay, the authors formulated two types of relay precoding matrices for a two-hop switching/routing between users for the two situations: one with no interference ("zero forcing") and one with only self-interference (a "PHY layer network coding" case). The authors then further explored the optimization of a set of tuning parameters of these matrices to maximize the minimum of the SNRs of the signals received by the users.

The paper by Xia and Aïssa, titled “Moments Based Framework for Performance Analysis of One-Way/Two-Way CSI-Assisted AF Relaying” proposes a moments-based framework for general performance analysis of channel-state-information (CSI) assisted AF relaying systems, which is applicable to both one-way and two-way relaying over arbitrary Nakagami-m fading channels. This new framework can be used to analyze, compare, and gain insights into system performance of one-way and two-way relaying techniques, in terms of outage probability, average symbol error probability, and achievable data rate.

The paper by Ding, Xu, Sharif, and Lu, titled “A General Transmission Scheme for Bi-directional Communication by Using Eigenmode Sharing” presents a bi-directional amplify-and-forward MIMO relay scheme for multiple pairs of users. This scheme decouples the interference between pairs of users using an eigenmode sharing, which also maintains a simple mixture of the signals from paired users and hence relaxes a constraint on the number of antennas at the relay. The authors also carried out performance analyses of this scheme under several different conditions. This paper distinguishes bidirectional relaying from two-way relaying.

The paper by Gong, Tajer, and Wang, titled ”Group Decoding for Multi-relay Assisted Interference Channels” proposes group decoding schemes for the relay interference channel where multiple relays assist the transmissions from the sources to destinations. The authors consider two types of relay systems, the hopping relay system with no direct source-destination links, and the inband relay system with direct source-destination links. For each relay system, relay assignment and the group decoding strategies at the relays and destinations are designed to maximize the minimum information rate among all source-destination pairs.

The paper by Hafeez and Elmirghani, titled “Analysis of Dynamic Spectrum Leasing for Coded Bi-Directional Communication” investigates cooperative relaying schemes in two way communication systems. A novel network coding is proposed in which the secondary users cooperatively relay the primary data and in exchange the primary grants exclusive access to the secondary users for their own activity. Devising a game theoretic framework for the division of leasing time between the primary cooperation and secondary activity phases, it is demonstrated that the proposed scheme provides both spectral and energy efficiency.

The paper by Amarasuriya, Tellambura, and Ardakani, entitled “Two-Way Amplify-and-Forward Multiple-Input Multiple-Output Relay Networks with Antenna Selection” proposes new transmit/receive antenna selection strategies for two-way MIMO AF relay networks and analyzes their performance analytically and numerically.

The paper by Lin and Yu, entitled “Fair Scheduling and Resource Allocation for Wireless Cellular Network with Shared Relays” examines the shared relay architecture for the wireless cellular network, where a single relay with multiple antennas is placed at the cell edge and is shared by multiple sectors, and formulates a network utility maximization problem for the shared relay system that considers the practical wireless backhaul constraint of matching the relay-to-user rate demand with the base-station-to-relay rate supply using a set of pricing variables. System-level simulations quantify the effectiveness of the proposed approach and show that the incorporation of the shared relay can improve the overall network performance.

E. Full-duplex relays and their performances

The paper by Day, Margetts, Bliss, and Schniter, entitled “Full-Duplex MIMO Relaying: Achievable Rates under Limited Dynamic Range” addresses the full-duplex MIMO relay concept. Upper and lower bounds on the relay performance are evaluated. The relay is full-duplex; thus, it can transmit and receive at the same time and same frequency if this is advantageous. A model for the dynamic range of the relay hardware is included in the performance bound evaluation.

The paper by Ju, Lim, Kim, Poor and Hong, titled “Full Duplexity in Beamforming-Based Multi-Hop Relay Networks” presents a statistical analysis of the impact of full duplexity on the delay and throughput of a multi-hop relay network. The authors assumed that each node is equipped with multiple omnidirectional antennas, each of them can be used for either transmission or reception, and the self-interferences are completely canceled. They considered a full-duplex relaying scheme and a full-duplex bi-directional exchange scheme. They compared the performance of full-duplex with that of half-duplex.

The paper by López-Valcarce, Antonio-Rodriguez, Mosquera, and Perez-Gonzalez, entitled “An Adaptive Feedback Canceller for Full-Duplex Relays Based on Spectrum Shaping,” addresses techniques for full-duplex relays that employ independent transmit and receive antennas simultaneously on the same frequency. The dominant issue is self interference mitigation. The proposed adaptive feedback cancellation approach operates on the time-domain waveforms directly, and enables use with amplify-and-forward relays. Results from a laboratory demonstration of performance are presented.

II. Second Issue (the next issue)

A. Coding for relay network

The paper by Hernaez, Crespo, and Ser, entitled “On the Design of a Novel Joint Network-Channel Coding Scheme for the Multiple Access Relay Channel” proposes a novel joint non-binary network-channel code for the Time-Division Decode-and-Forward Multiple Access Relay Channel (TD-DF-MARC), where the relay linearly combines the coded sequences from the source nodes. A method based on an EXIT chart analysis is derived for selecting the best coefficients of the linear combination. Monte Carlo simulations show that the proposed scheme outperforms, in terms of its gap to the outage probabilities, the previously published joint network-channel coding approaches.

The paper by Shi, Medard, and Lucani, titled “Whether and Where to Code in the Wireless Packet Erasure Relay Channel” proposes Markov chain models to analyze the throughput and energy performances of network coding strategies in erasure relay channels in which either or both the source and the relay perform random linear network coding. It is shown that using a random code at the relay alone is neither throughout nor energy efficient, while coding at the source alone can provide a good tradeoff between throughput and energy use. It is also shown that a very small amount of memory is required at the relay when coding is performed at the source only. Taking into account of throughput maximization and energy depletion, a framework for deciding whether and where to code is provided.

The paper by Du, Xiao, Skoglund, and Medard, titled “Wireless Multicast Relay Networks with Limited-Rate Source-Conferencing” investigates capacity bounds for a wireless multicast relay with two sources, two destinations and a relay node. Gaussian channels with known channel gains are shared by the two sources and relay. In addition, orthogonal limited-rate error-free conferencing links connect the two source nodes. Two genie-aided outer bounds for the capacity region of this network are presented. Three new cooperative coding schemes based on source cooperation, partial-decode-and-forward relaying and amplify-and-forward relaying are also presented and it is shown that the latter outperforms the other proposed schemes when the coherent combining gain is dominant.

The paper by Azmi, Li, Yuan, and Malaney, entitled “LDPC Codes for Soft Decode-and-Forward in Half-Duplex Relay Channels,” addresses coding approaches for relays. The paper investigates soft information relaying by employing a low-density parity-check (LDPC) code that allows additional parity information to be encoded at the relay. The paper addresses two main issues associated with this approach: how to embed the new parity bits at the relay, and how to compute the likelihood ratios at the receiver. In simulation, it is demonstrated that the proposed approach enables better performance than that found in the literature currently.

The paper by Kim and Chun, entitled “Reliability-Rate Tradeoff in Large-Scale Multiple Access Relay Networks,” discusses a random network coding scheme in which relays that decode a signal are modified by randomly chosen coefficients and forwarded to the destination. A bound on the probability of destination decoding error is presented. By using this bound, a reliability-rate tradeoff is developed. Rather than considering the reliability-rate tradeoff in the limit of high SNR, it is considered in terms of a large number of relay nodes. The optimal spectral efficiency in terms of reliability, rate, and node density is developed.

The paper by Nagpal, Wang, Jorgovanovic, Tse, and Nikolic, entitled “Coding and System Design for Quantize-Map-and-Forward Relaying,” develops a low-complexity coding approach for a half-duplex relay scheme. The source employs an LDPC code, and the relays employ low-density generator-matrix (LDGM) codes. Codes are developed that operate close to the information theoretic limits. The performance of the proposed approach is better than single-relay amplify-and-forward and decode-and-forward approaches at high SNR. The approach also reduces the channel feedback overhead compared to compress-and-forward approaches.

The paper by Abou-Rjeily, entitled “A Symbol-by-Symbol Cooperative Diversity Scheme for Relay-Assisted UWB Communications with PPM,” addresses relays in the context of impulse-radio ultra-wideband communications. The approach takes advantage of the pulse-position modulation employed commonly by impulsive radios to enable symbol-by-symbol cooperation that has reduced complexity compared to a traditional decode and forward approach. A power allocation strategy is discussed.

The paper by Wu, Zhao, and You, titled “Joint LDPC and Physical-layer Network Coding for Asynchronous Bi-directional Relaying” addresses a decoding problem at the relay in a three-node two-way relay system. The authors formulated the problem by considering symbol and frame misalignments between the signals transmitted in the first phase of the two-way relay. They developed an efficient decoding algorithm for binary LDPC coding and BPSK modulation.

The paper by Lehmann, titled “Joint channel estimation and decoding for trellis-coded MIMO two-way relay networks”, considers a decoding problem for the multiple access phase of a two-way MIMO relay system serving the exchange of information between two users. The author focused on a space-time trellis code and a bit-interleaved coded modulation. He assumed that the fading dynamic of the MIMO channels follows a first-order autoregressive model. He presented an algorithm for joint channel estimation and packet decoding at the MIMO relay.

B. *Resource allocation for relays*

The paper by Huang, Zhang, and Cui, titled “Throughput Maximization for the Gaussian Relay Channel with Energy Harvesting Constraints” considers a three-node network with decode-and-forward relaying, in which the power of the source and relay is drawn from energy-harvesting sources. Assuming known energy arrival time and the harvested amount, the optimal power allocation and throughput maximization problem are investigated. It is shown that for delay constrained case, the joint source and relay power allocation over time is necessary to achieve the maximum throughput whereas for delay unconstrained case, separate source and relay power allocation is optimal. In addition, the necessary and sufficient conditions under which the unconstrained case outperforms the constrained case are obtained.

The paper by Yang, Huang, and Wang, titled “Dynamic Bargaining for Relay-Based Cooperative Spectrum Sharing” proposes a novel noncooperative bargaining-based cooperative spectrum sharing scheme between one primary user (PU) and one secondary user (SU), where the PU does not have complete information of the SU’s energy cost. The authors model the bargaining process as a dynamic Bayesian game and investigate the equilibria under both single-slot and multi-slot bargaining models. Theoretical analysis and numerical results indicate that both the PU and the SU could obtain increases in data rate via the proposed scheme.

The paper by Ho, Tan, and Sun, titled “Energy-Efficient Relaying over Multiple Slots with Causal CSI” studies the problem of minimizing the expected sum energy of delivering a message of a given size from a source to a destination via a relay node subjecting to time constraint. Causal channel state information (CSI) in the form of present and past SNRs of all links is utilized to determine the optimal power allocation between the source and relay nodes. It is shown that for Rayleigh and Rician fading channels, relaying is necessary for the minimum expected sum energy to be bounded, when only causal CSI is available.

C. Medium access control for relays

The paper by Sagduyu, Berry, and Guo, entitled "Throughput and Stability for Relay-Assisted Wireless Broadcast with Network Coding," evaluates the throughput and stability properties of wireless network coding for an arbitrary number of terminals exchanging broadcast traffic with the aid of a relay. Backpressure-like algorithms for jointly achieving throughput optimal scheduling and network coding are given for several network coding schemes.

The paper by Atapattu, Jing, Jiang, and Tellambura, titled "Relay Selection and Performance Analysis in Multiple-User Networks" investigates the relay selection problem in networks with multiple users and multiple common AF relays. The authors propose an optimal relay selection scheme which achieves full diversity but has a quadratic complexity in both the number of users and the number of relays. As a tradeoff, a suboptimal relay selection scheme is developed which has a decreased diversity order with the number of users, but has linear complexity in the number of relays and quadratic complexity in the number of users.

The paper by Zlatanov, Schober, and Popovski, titled " Buffer-Aided Relaying with Adaptive Link Selection" proposes a new relaying protocol in a three-node network in which based on the channel gains either the source or the relay transmits. The relay is equipped with a buffer to avoid data loss. For unconstrained transmissions, the optimal link selection scheme, power allocation and achieved throughput are characterized. For delay constrained case, two methods are proposed to control the induced delay at the relay and it is shown that the proposed methods achieve a higher throughput compared to conventional relaying with and without buffers where a fixed schedule is employed for reception and transmission.

The paper by Zaidi, Ghogho, McLernon, and Swami, titled "Achievable Spatial Throughput in Multi-antenna Cognitive Underlay Networks with Multi-hop Relaying" investigates the spatial throughput of multi-hop multi-antenna cognitive radio networks in which both secondary and primary users are assumed to employ maximum ratio transmission and maximum ratio combining for transmission and reception, respectively. In addition, secondary users are half-duplex and employ slotted-ALOHA medium access protocol. It is shown that by employing multiple antennas, primary users can meet desired QoS requirements while accommodating some secondary transmitters without performance degradation. A QoS aware multi-hop relaying strategy for secondary network is proposed and the optimal number of antenna and modulation scheme that maximizes the spacial throughput are characterized.

The paper by Castiglione, Savazzi, Nicoli, and Zemen, titled "Partner Selection in Indoor-to-Outdoor Cooperative Networks: an Experimental Study" presents a medium access protocol for selecting pairwise partners among multiple users for cooperative amplify-and-forward relaying from an indoor environment to an outdoor access point. The authors considered the Rician fading channel model in developing their protocol. By computer simulation, they demonstrated that their protocol can save a substantial transmission energy for the indoor users.

The paper by Zhang, Liew, and Wang, entitled "Blind Known Interference Cancellation," addresses the problem in which the temporal structure of interference is known because data is being retransmitted as information propagates through the network; however the interference channel is unknown. The proposed approach employs adjacent symbols over which the channel is expected to be approximately static to mitigate the interference. This mitigation introduces distortion. A smoothing algorithm and a belief propagation algorithm are proposed to compensate for the distortion. The approach has relatively low complexity.

The paper by Lin, Liu, and Tao, entitled "Cross-Layer Optimization of Two-Way Relaying for Statistical QoS Guarantees" studies the cross-layer design and optimization for delay quality-of-service (QoS) provisioning in two-way relay systems and considers the problem of finding the optimal transmission policy to maximize the weighted sum throughput of the two users in the physical layer while guaranteeing the individual statistical delay-QoS requirement for each user in the data-link layer.

D. Implementation and system performance study

The paper by Guo and O'Farrell, entitled "Relay Deployment in Cellular Networks: Planning and Optimization" provides new simulation tools and extensive simulation studies for system performance with relay deployment. The capacity improvements demonstrated in this paper show that optimized relay deployment can improve capacity by up to 60% for outdoor and 38% for indoor users.

The paper by Devar, Karthik KS, Ramamurthi, and Koilpillai, entitled "Downlink Throughput Enhancement of a Cellular Network using Two-hop User-Deployable Indoor Relays" studies the performance of practical user-deployable indoor relays for the current WCDMA standard and shows that the overall system performance can be enhanced by such deployment.

The paper by Firooz, Chen, Roy, and Liu, titled "Wireless Network Coding via Modified 802.11 MAC/PHY: Design and Implementation on SDR" presents an implementation of a network coding scheme for a three-node relay system where a relay node serves the exchange of information between other two nodes. The authors modified the MAC and PHY layers of the IEEE 802.11 protocol stack on a software radio platform. Their experiment demonstrated an improved system throughput for the relay system using network coding.

The paper by Nazir, Stankovic, Attar, Stankovic, and Cheng, entitled "Relay-assisted Rateless Layered Multiple Description Video Delivery" addresses real-time video deliver over wireless networks. The concept of multiple description coding is extended to include random linear codes. Network resource allocation is optimized to minimize reconstruction distortion, given a statistical knowledge of the channel and source content. Video coding performance is investigated by using a H.264/AVC code on simulations of an LTE-A relay wireless system.

E. Security for relay network

The paper by Lai, Liang, and Du, entitled “Cooperative Key Generation in Wireless Networks,” extends the concept of generating secrecy keys via reciprocity by including relay nodes. It is shown that the key generation rate scales linearly with the number of relays. Multiple relay-assisted key-generation schemes are considered. By comparing to an information theoretic measure of security, it is shown that the proposed approach is optimal for single relays, and is asymptotically optimal as the SNR increases for multiple relay networks. Approaches in which the relay is or is not trusted with knowledge of the generated keys are both considered.

III. Acknowledgement

We would like to thank all authors and hundreds of reviewers for their important contributions to these issues. We hope that all these papers will inspire more innovations, making an important impact on the technology of future wireless networks and the quality of life for all. We would also like to thank JSAC Editor-in-Chief Martha Steenstrup, our Senior Editor Mentor Laurel Greenidge, and JSAC Managing Editor Sue Lange for their valuable assistance.

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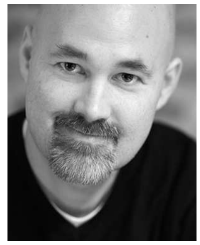

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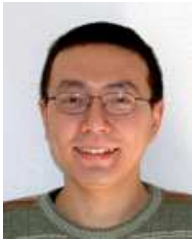

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