Introduction to the Special Issue on Models, Theory, and Codes for Relaying and Cooperation in Communication Networks

THE demand for ever larger, more efficient, reliable, and cost effective communication networks is motivating new network architectures, such as *ad hoc* networks, cognitive radio, relay extensions for cellular networks, sensor networks, and wireless mesh networks. The study of such networks requires a fundamental shift from thinking of a network as a collection of independent communication pipes each with separate source and channel coding, to a multiterminal channel where users cooperate via conferencing, relaying, and joint source–channel coding. As such, there has been significant activity in the past decade toward developing information theory and coding for networks. The goal of this Special Issue is to highlight this activity with a focus on information theory for network models involving relaying and cooperation.

The greatest triumph of Shannon information theory over the past 50 years has been the development of a complete understanding of many important point-to-point channels and practical codes that operate reliably near capacity (see, e.g., the IEEE TRANSACTIONS ON INFORMATION THEORY Special Issue on Codes and Graphs and Iterative Algorithms from February 2001). Multiterminal information theory, which aims to extend information theory to networks with several users, began with Shannon's paper on the two-way channel in the early 1960s. Finding capacity for networks has proved much more difficult than for point-to-point channels, however. Even today our understanding of the two-way channel has hardly progressed beyond Shannon's work, and the capacity of other basic multiterminal channels, such as relay and interference channels, remains unknown.

Fortunately, some multiterminal channel capacity problems admit solution, including multiple-access channels and important classes of broadcast and interference channels that model, for example, cellular wireless and digital subscriber line communications. Perhaps more interestingly, the solutions to these problems have yielded new promising communication techniques, such as binning, superposition coding, successive cancellation, dirty-paper coding, and network coding. There has also been significant recent progress in understanding the scaling behavior of large networks. In spite of this progress, network information theory has had little impact on practice, perhaps because of the difficulty of addressing coding in settings involving bursty sources, sources and devices constrained by delay requirements, and limited network knowledge.

As the Special Issue title suggests, solicited papers were meant to address network modeling, information theory, and code design. Several papers in this issue make fundamental headway on these fronts. The advances raise hope that new information theory and codes will improve networking practice.

The first three papers of the issue use the amplify-and-forward (AF) protocol to relay data. The paper by Borade, Zheng, and Gallager shows that AF achieves the same degrees of freedom as a point-to-point multiple-antenna system for a single source–destination pair. However, the performance degrades with increasing network size. Morgenshtern and Bölcskei examine AF for fading interference relay networks where multiple source–destination pairs communicate through half-duplex relays. If the number of relays increases fast enough with the number of source–destination pairs, AF decouples the network in the sense that the individual source–destination terminal pair capacities are strictly positive. Jafar, Gomadam, and Huang discover a surprising duality relationship between multiple-access and broadcast channels with layers of AF relays. The duality helps to characterize AF rate regions.

The next two papers emphasize the usefulness of compress-and-forward (CF) and multilayer broadcast techniques. The paper by Yuksel and Erkip focuses on the diversity–multiplexing tradeoff (DMT) for cooperative wireless networks. This work gives a comprehensive analysis of CF and shows that CF is DMT-optimal for relay channels with multiple-antenna nodes. Steiner, Sanderovich, and Shamai analyze the problem of communication between a remote transmitter and a destination that are helped by nearby nodes. The authors develop multilayer broadcast codes that improve AF, CF, and decode-and-forward (DF) protocols.

Three papers study relay channels with delays, fading, and joint source–channel coding. El Gamal, Hassanpour, and Mammen investigate the effect of link delays on the capacity of relay networks. The authors present capacity results when each relay has unlimited look-ahead, i.e., its transmitted symbols may depend noncausally on the entire received signal, and the relay-without-delay, where the relay transmission can depend on current and past received symbols. Liang, Veeravalli, and Poor characterize the capacity of several relay channels by optimally allocating power, time, or bandwidth. For example, they find the capacity of parallel relay channels with degraded subchannels. The paper by Gündüz and Erkip tackles source–channel communication over quasi-static fading channels with user cooperation, using the end-to-end distortion exponent as a performance metric. The authors couple source coding and cooperative channel coding and establish an upper bound on the distortion exponent that is tight for both small and large ratios of source and channel bandwidth.

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Four papers consider relaying in small- and medium-sized networks. Ong and Motani develop coding strategies and a cut-set outer bound for joint source–channel coding on multiple-access channels. The authors analyze which strategies perform better under different source correlation structures and network topologies. Nazer and Gastpar investigate the problem of reliably computing a function of several sources over a multiple-access channel. They show that one cannot separate source and channel coding even when the sources are independent, and that joint source–channel coding outperforms separation-based strategies even when the sources and the channel are not matched. Liang and Kramer study a relay network with one source node and two destination nodes where one destination can act as a relay to assist the other destination. They obtain capacity results for several such channels, including semideterministic channels and channels with orthogonal components. Marić, Yates, and Kramer establish capacity regions for the interference channel with a common message and with unidirectional cooperation, i.e., one sender knows the other sender's message. The capacity regions coincide with that of the compound multiple-access channel with a common message.

Scaling laws for the capacity of large wireless networks are developed in the next two papers. For a propagation model with signal attenuation and random phase, Özgür, Lévêque, and Tse use a hierarchical architecture combining elements of DF, multiple-antenna transmission, and CF to achieve linear capacity scaling for dense networks. They also find new capacity scaling laws for extended networks. Özgür, Lévêque, and Preissmann consider a similar propagation model without small-scale fading and find the capacity scaling. The scaling behaves similarly for low and high attenuation.

The next two papers develop multihop strategies for improving rates. Xie and Kumar show that a backward decoding scheme for networks comprising multisource–multidestination pairs with multiple relays achieves higher rates than sliding-window decoding. The scheme is also shown to be optimal for data downloading in a sensor network for certain geometries and with phase fading that is unknown to the sender. Gurewitz, de Baynast, and Knightly describe a low-complexity protocol where nodes receive information from both one-hop and two-hop neighbors. The approach generalizes three-node relay methods to apply to end-to-end flows and yields large throughput gains over hop-by-hop forwarding methods.

Three papers study the information theory of sensor networks. Baek and de Veciana use multipath transmission to aggregate and balance energy consumption across nodes. Various insights concerning source behavior and traffic spreading are obtained. Bajwa, Haupt, Sayeed, and Nowak propose a distributed joint source–channel communication architecture for energy-efficient estimation of sensor field data. Their paper analyzes relationships between power, distortion, and latency as a function of the number of sensor nodes. Liu and Ulukus treat joint source–channel coding in the context of Gaussian sensor networks, focusing on the scaling behavior as the number of sensors becomes large. For a broad class of Gaussian processes communicated over a cooperative multiple-access channel, the authors establish the best scaling by separating source and channel coding.

Most work on information-theoretic modeling of relaying and cooperation has taken a physical layer view and focused on characterizing achievable transmission rates and/or outage probabilities. However, relay protocols also impact higher layer network performance, in particular when there are stochastic variations in the offered traffic. The paper by Sadek, Liu, and Ephremides considers one such model and introduces random-access schemes that exploit cooperation opportunities arising from source burstiness. In this case, the maximum stable throughput and delay performance are the parameters of interest.

Network coding has been a hot topic during the past few years, and two papers of this Special Issue combine network coding with relaying. Sagduyu and Ephremides study network coding together with medium-access control. They develop a systematic method to construct wireless network codes that operate with random- or scheduled-access protocols. The paper by Xiao, Fuja, Kliewer, and Costello recommends to network code by using algebraic superposition of coded symbols. The codes are constructed so as to be iteratively decodable by the destination.

Code design is also the subject of the next three papers. Razaghi and Yu describe two types of low-density parity-check (LDPC) codes for relay channels: bilayer-expurgated and bilayer-lengthened codes. They further design these codes to approach the best possible DF rates on Gaussian noise channels. Instead of LDPC codes, the paper by Puducheri, Kliewer, and Fuja introduces a class of distributed fountain codes for relaying. The codes are designed specifically for low-complexity relays and perform substantially better than competing strategies. Damen and Hammons present a new class of distributed space–time codes that are delay tolerant. The codes are based on threaded algebraic space–time codes.

There are eight correspondence items. The correspondence by van der Meulen and Vanroose reports a correction of an early paper on relay channels, and gives a new capacity result for a relay-without-delay. Tannious and Nosratinia analyze the relay channel with private messages, where in addition to sending a message to the destination, the source sends a private message to the relay and the relay sends a private message to the destination. The correspondence by Atia, Sharif, and Saligrama focuses on diversity performance at low signal-to-noise ratios, and extends the optimality of bursty-AF protocols to general fading distributions. Tabet, Dusad, and Knopp propose a cooperative protocol that exploits automatic repeat requests (ARQ) and the space diversity offered by a relay. Xue and Sandhu establish upper and lower bounds on the capacity of diamond-shaped half-duplex relay channels. Sankar, Kramer, and Mandayam develop a DF offset encoding scheme that lets sliding-window decoding achieve the corner points of the backward decoding rate region but with a smaller delay. Ng, Jindal, Goldsmith, and Mitra show that transmitter cooperation outperforms receiver cooperation for a two-transmitter, two-receiver network with phase fading. Yeh and Berry study throughput optimal control policies that take queueing dynamics into account and describe a Maximum Differential Backlog algorithm. The correspondence by Liu, Parag, and Chamberland considers bursty traffic and char-

acterizes the advantages of cooperation in terms of the traffic that satisfies a constraint on the decay rate of the buffer occupancy for each user.

Finally, as Guest Editors we wish to thank the authors for submitting their papers and contributing to the success of this issue. We also wish to thank the reviewers for their prompt and detailed responses that improved the quality of the manuscripts. The Publications Editors Elza Erkip and Adriaan van Wijngaarden made the final stages of publication proceed smoothly, and our Senior Editor Nela Rybowicz provided her customary efficient and professional editing. We are grateful to H. Vincent Poor for supporting this project, and to the Mathematical Sciences Research Institute in Berkeley, CA, for hosting a workshop on relaying and cooperation in April 2006. We hope this Special Issue will stimulate progress on applying information theory to real-world networks, and will encourage researchers to continue to work on problems of relaying and cooperation.

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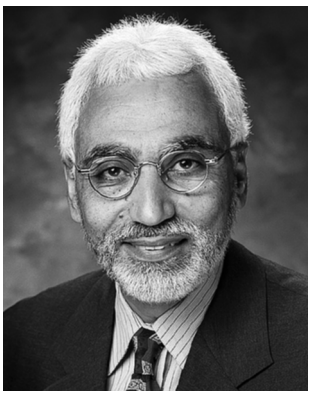
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