Editorial
Issue on "Information Theoretic Foundations of Future Communication Systems"

INFORMATION theory, starting with Shannon's groundbreaking work, has fundamentally shaped the way communication systems are designed and operated. Information theoretic principles form the underpinnings of modern communication networks. This issue explores how new advances in information theory can impact future communication systems. Several papers address issues at the heart of next generation wireless and wired networks: Multiple access, including access by a massive number of devices, multi-hop, large antenna arrays, communication security, and timeliness of information. Others consider new applications such as joint communication and sensing, communication for learning and inference, wireless imaging, and new storage mediums such as DNA, thereby providing the information theoretic foundations of modalities beyond human-to-human communications.

Paper [A1] by Zaidel *et al.* offers a timely and insightful information-theoretic study of the achievable spectral efficiency of regular sparse non-orthogonal multiple access (NOMA), a prominent multiple-access technique for future communication networks beyond 5G. By using advanced mathematical tools from the spectral theory of large random graphs, the paper derives an explicit closed-form expression for the optimum spectral efficiency of regular sparse NOMA in the large-system limit. Notably, it is proved rigorously in this paper that regular sparse NOMA is spectrally more efficient than its irregular and partly-regular counterparts as well as (dense) randomly-spread code- division multiple access (CDMA).

An information-theoretic treatment of the problem of massive access is given in [A2], by Hsieh *et al.* Specifically, the paper works with the model of many-access channel, for which the number of users grows with the length of the channel code. This channel model accurately captures the massive number of devices in Internet-of-Things (IoT) applications. The regime of interest is when the number of users becomes asymptotically large, while the considered performance measure is the fraction of user messages decoded in error, which is termed User Error Rate (UER). The paper presents a rigorous analysis of the performance of coding schemes based on random linear models and computationally-efficient decoding that utilizes Approximate Message Passing (AMP). The introduced coding scheme is based on spatially coupled Gaussian matrices and it approximates well the converse bound for a large range of user densities.

Energy efficient relaying is considered in [A3], where Jain *et al.* treat the problem of unicast between a source and a destination with the help of an arbitrary network of half-duplex relays. The network of n half-duplex relays has 2^n possible states and previously it has been shown that using only $n+1$ of those states is sufficient to achieve the approximate capacity. The main contribution of this paper is that it considers arbitrary topology and derives the network conditions under which it is sufficient to approximate the capacity by having at most one transmitting relay. This results in an energy-efficient operation, as it minimizes the number of transmitters at each instant. Finally, the authors propose a time-block relaying scheme for which, in each block, the $n+1$ energy-efficient states are operated in a fixed order.

Paper [A4] by Gomez-Cuba studies the fundamental performance of the single-input multiple-output (SIMO) wireless channel as a function of several parameters. SIMO systems are of potential interest in future terahetrz (THz) bands where it is both feasible and desirable to give dedicated spectrum to each active user. The paper assumes channel-state information is not available a-priori and compares two schemes: pilot-assisted transmission and energy modulation. Under high-mobility conditions (e.g., short coherence length), it is shown that energy modulation can out-perform pilot-assisted transmission.

Suresh *et al.* [A5] consider a communication channel where the channel between the transmitter and the receiver is causally snooped by an adversary, which actively injects errors. Such an adversary could, for example, arise in a wireless network with active eavesdroppers or hardware trojans. These errors are in the form of erasures in binary erasure channels, and in the form of bit-flips in binary symmetric channels. The adversary has a total power budget in that it can inject errors only to a fraction of the channel uses. The paper provides information-theoretic capacity characterizations for these channel models. The analysis identifies the worst case adversarial attacks for both models, and proves the existence of coding schemes that achieve rates equal to the capacity for each case.

Timeliness of information is studied in [A6], where Baturalp *et al.* analyze the scaling of the so called version age as a function of the network size in a hierarchical network configuration. Specifically, they investigate how timely can the nodes in the network be informed about the status of a source as the size of the network grows. The nodes in the network

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are organized in disjoint clusters: updates in each cluster are propagated by a cluster head; furthermore, different flows of information, enabled by different degrees of gossip within each cluster, are considered. For all these scenarios, the authors provide a rigorous characterization of the version age experience by each nodes, and of its behavior as a function of the network size, using a stochastic hybrid system approach.

The interplay between information timeliness and energy is discussed in [A7], where Abd-Elmagid and Dhillon consider an energy harvesting communication system with a finite sized battery and focus on the freshness of delivered information. The paper uses the stochastic hybrid systems method to derive closed form expressions for the average age of information as well as its moment generating function under several queueing disciplines at the transmitter, including non-preemptive and source agnostic/source aware preemptive in service strategies. The results provide several useful system design insights, such as, the observation that the achievable age performance improves with the size of the available battery and the rate of the energy arrivals into the battery.

The joint use of a transmitted waveform for both communication and sensing can help support the requirements of connected and automated devices in next generation wireless systems. To better understand the fundamental limits in such a setting, paper [A8] by Joudeh and Willems presents an information theoretic analysis of a system that supports joint communication and sensing. The setup is that a transmitter sends a message to two receivers. One receiver wants to decode the message while another receiver wants to estimate the fixed but unknown binary state of the channel, treating the message as known side information. Rate-exponent regions, with achievability and converse results, are derived to establish tradeoffs between communication and sensing for binary symmetric and Gaussian communication channels.

Distributed learning and inference, arising in applications such as federated learning or swarm robotics, require designing task-aware communication networks. Paper [A9] by Xu and Huang considers the task of distributed hypothesis testing in a two-user network. Each user observes one component of a two-dimensional source, and communicates a finite number of bits to a central processor. The joint source distribution either follows the null hypothesis or the alternative. The goal is to characterize the error exponent of this hypothesis test. The paper presents a geometric approach in the distribution space, and characterizes the optimal error exponent under some assumptions.

Imaging is one of the new applications envisioned for future THz wireless operation. Paper [A10] by Mehrotra and Subharwal studies the impact of multipath propagation, or rich scattering, as opposed to line-of-sight (LoS) propagation on the resolution of a multi-input multi-output (MIMO) imaging system. For communication purposes, it has long been known (e.g., the pioneering work of Foschini) that dense multipath scattering can actually improve the capacity of a point-to-point MIMO link compared with LoS propagation. Mathematically, rich-scattering reduces the condition number of the propagation matrix, thereby increasing the number of degrees-of-freedom (DoF). The paper studies imaging from the standpoint of DoF, and argues that rich-scattering can be beneficial for imaging.

Information theory has shaped modern data storage systems such as the compact disc, and continues to impact design of distributed storage systems. Paper [A11] by Ravi *et al.* considers DNA storage, an emerging medium with very high storage capacity. The paper frames the DNA storage problem as one of shotgun sequencing, where the sequence to be reconstructed from its substrings comes from a codebook, rather than being chosen randomly by the nature. The codebook represents the stored data, which is later retrieved via sequencing. The authors describe a new channel model which they call the shotgun sequencing channel and provide an exact characterization of its capacity as a function of the read length and coverage depth.

We hope you will enjoy this special issue. We would like to thank the authors and reviewers for contributing their time and expertise. A special thanks to the former JSAIT Editor-in-Chief Andrea Goldsmith, whose encouragement and dedication made this issue possible. We also would like to thank the current JSAIT Editor-in-Chief Tara Javidi for her continued support and Alison Larkin for ensuring a smooth editorial experience.

ELZA ERKIP
Department of Electrical and Computer Engineering
New York University
Brooklyn, NY 11201 USA
E-mail: elza@nyu.edu

GIUSEPPE DURISI
Department of Electrical Engineering
Chalmers University of Technology
41296 Gothenburg, Sweden
E-mail: durisi@chalmers.se

ROBERT W. HEATH, JR.
Department of Electrical and Computer Engineering
North Carolina State University
Raleigh, NC 27606 USA
E-mail: rwheathjr@ncsu.edu

THOMAS L. MARZETTA
Department of Electrical and Computer Engineering
New York University
Brooklyn, NY 11201 USA
E-mail: tom.marzetta@nyu.edu

PETAR POPOVSKI
Department of Electronic Systems
Aalborg University
9220 Aalborg, Denmark
E-mail: petarp@es.aau.dk

MEIXIA TAO
Department of Electronic Engineering
Shanghai Jiao Tong University
Shanghai 200240, China
E-mail: mxtao@sjtu.edu.cn

SENNUR ULUKUS
Department of Electrical and Computer Engineering
University of Maryland at College Park
College Park, MD 20742 USA
E-mail: ulukus@umd.edu

APPENDIX: RELATED ARTICLES

[A1] B. M. Zaidel, O. Shental, and S. Shamai, "Regular sparse NOMA: Ultimate performance in closed form," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3153249.

[A2] K. Hsieh, C. Rush, and R. Venkataramanan, "Near-optimal coding for many-user multiple access channels," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3158827.

[A3] S. Jain, M. Cardone, and S. Mohajer, "Optimality of energy-efficient scheduling and relaying for half-duplex relay networks," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3157829.

[A4] F. Gomez-Cuba, "The SIMO block Rayleigh fading channel capacity scaling with number of antennas, bandwidth, and coherence length," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3157519.

[A5] V. Suresh, E. Ruzomberka, C.-C. Wang, and D. J. Love, "Causal adversarial channels with feedback snooping," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3158230.

[A6] B. Baturalp, B. Melih, and S. Ulukus, "Version age of information in clustered gossip networks," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3159745.

[A7] M. A. Abd-Elmagid and H. S. Dhillon, "Age of information in multi-source updating systems powered by energy harvesting," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3158421.

[A8] H. Joudeh and F. M. J. Willems, "Joint communication and binary state detection," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3157999.

[A9] X. Xu and S.-L. Huang, "On distributed learning with constant communication bits," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3157797.

[A10] N. Mehrotra and A. Subharwal, "When does multipath improve imaging resolution?" *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3160185.

[A11] A. N. Ravi, A. Vahid, and I. Shomorony, "Coded shotgun sequencing," *IEEE J. Sel. Areas Inf. Theory*, vol. 3, no. 1, Mar. 2022, doi: 10.1109/JSAIT.2022.3151737.