Guest Editorial
Special Issue on Sensing: Fundamental Limits and Modern Applications

SENSING has emerged as a key feature of modern wireless communication systems and networks. Traditionally, advances in the design, optimization and deployment of sensing and communication systems have evolved somewhat independently of each other. In recent times however, we are beginning to appreciate the benefits offered by the synergy between sensing and related areas in communication, largely driven by modern applications such as autonomous driving, motion sensing in health applications, target detection and localization in smart cities, dual-function radar and communication systems, and optimal beam selection and alignment in millimeter wave communication. We are pleased to announce that in this special issue we have collected exciting recent results on a broad range of different domains and applications that rely on sensing, with a focus on fundamental contributions that explore the performance limits of sensing problems and offer innovative solutions.

The issue starts with three Shannon-type information-theoretic papers that analyze the rate-distortion or rate-detection error tradeoff in integrated sensing and communication (ISAC) problems. More specifically, the paper by Chang et al. [A1] presents the fundamental limits of a single-transmitter and single-receiver ISAC system where the channel depends on a fixed state parameter that is to be sensed at the transmitter. A main takeaway message of this paper is that in a closed-loop system where the information from the backscattered signals can be exploited for sensing and communication purposes, strategies that jointly estimate the message and state may outperform separation-based strategies. Somewhat related, the paper by Günlü et al. [A2] shows benefits of a joint approach in mitigating information leakage in a memoryless ISAC system where (a portion of) the message has to be kept confidential from an external eavesdropper of the channel. The paper by Ahmadipour and Wigger [A3] presents information-theoretic coding schemes that simultaneously implement collaborative sensing and collaborative communication in two-transmitter ISAC systems, and shows improved performances of this joint approach over previous works.

Our special issue also explores the ISAC problem from more of a communication and signal processing point of view. The paper by Liu et al. [A4] considers a two-node distributed filtering system whose goal is to infer the time-varying states using data obtained through sensing and communication. The authors study the asymptotic performance of the distributed filter and establish necessary and sufficient conditions of the sensing and communication capabilities of the nodes such that the mean-squared error of the distributed filter is bounded over time. Extracting information from coexisting radar and communication signals is also the topic of the article by Vargas et al. [A5] Specifically, this contribution considers the challenging case where neither the propagation channel nor the waveform of interest are known apriori at the receiver. To resolve this generally ill-posed problem, the authors resort to the assumption of sparse channels and employ atomic norm minimization to implement a blind deconvolution and recover the physical parameters of both the radar and communication waveforms (amplitudes, delays, Doppler shifts). Theoretical guarantees on the minimum number of samples required to identify the parameters are also provided.

Two articles of this issue focus on the problem of beam selection for the purpose of improving the underlying communication systems. The paper by Jiang et al. [A6] studies the two-sided beam alignment problem (from the transmitter and the receiver sides) for millimeter-wave communications. Beam alignment is essential to compensate for the significant path loss in very high-frequency bands. To solve this nontrivial task, the paper proposes an active-sensing framework based on deep neural networks to learn the adaptive sensing strategies and produce the final aligned beamformers. Results demonstrate significant and interpretable performance improvement, which is also extended for challenging multipath environments and scenarios with reconfigurable intelligent surfaces. The paper by Ronquillo et al. [A7] studies receive-side active beam selection for a scenario with an aerial mobile transmitter and a quasi-static receiver. Here the beam alignment problem is cast into the framework of partially-observable Markov decision problem (POMDP), and a dynamic programming solution is used to propose an efficient strategy for active joint sensing and communication.

High-resolution localization enabled by sensing is a key requirement of many modern applications. Localization belongs to a more general class of "inverse problems", where the goal is to extract parameters/signals of interest from limited and corrupted measurements under various constraints, including those imposed by the physical acquisition systems. Three papers in this special issue address inverse problems and sensing from a theoretical and signal-processing perspective.

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The paper by DeLude et al. [A8] introduces novel algorithms based on Slepian basis vectors for the localization of broadband sources, a task significantly more complex than its narrowband counterpart. This iterative process is shown to be robust, performing efficiently even in low SNR scenarios and showing superiority over traditional Fourier-based methods, especially in handling disparities in dynamic range and noise. The paper by Da Costa and Chi [A9] considers the problem of spike deconvolution, which is a prototypical super-resolution problem and whose goal is to recover the locations of point sources from their convolution with a point spread function. This paper studies the optimization landscape of a nonconvex least-squares objective function for recovering the point source amplitudes and locations. The authors establish a local, entry-wise linear rate of convergence for a preconditioned gradient descent algorithm, and they improve upon this method by introducing an adaptive preconditioner that has faster convergence independent of the dynamic range. The paper by Srinivasa et al. [A10] considers the joint reconstruction of low-rank matrices from linear measurements under the assumption that the matrices share a common column space. The authors establish theoretical guarantees for the performance of a convex estimator regularized by a certain pair of matrix norms, one of which is characterized using tensor norms. The results are robust to noise and support the advantage of joint recovery over individual recovery of the matrices.

The issue also includes papers on certain practical sensing applications such as fire-prediction and Particle Beam Microscopy (PBM). Specifically, the paper by Xu et al. [A11] considers the wildfire prediction problem using multi-modal sensing data. A flexible spatio-temporal framework is proposed to first predict the wildfire risk in real-time, using discrete mutually exciting point process models and then a wildfire magnitude prediction set method is developed. The proposed approach is theoretically analysed and evaluated using real-data experiments, which demonstrate its effectiveness, flexibility, and scalability in large regions. The paper by Agarwal et al. [A12] explores potential advancements in PBM, an important technique in nanoscale imaging, through the adoption of a time-resolved measurement methodology. This innovative approach promises to markedly enhance estimation accuracy by reducing the prevalent issue of source shot noise. With a careful analysis of the underlying estimation theoretic problems, the study highlights the complexities of realistic imaging scenarios and offers new insights into how time-resolved data can substantially improve estimation quality in PBM, potentially ushering in significant progress in the field.

The two final papers of this special issue have a learning flavour. The paper by Mukherjee and Tajer [A13] develops a provably near-optimal algorithm for the exponential family of bandits based on a sequential hypothesis testing framework. A (reinforcement) learning approach is also used in the very last paper by Erdemir et al. [A14] which studies data release mechanisms in scenarios where a user wants to share certain information with a trusted-but-curious receiver that wishes to remain private. The paper presents policies that achieve significantly better privacy-utility trade-offs than random selection.

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Appendix: Related Articles

[A1] M.-C. Chang, S.-Y. Wang, T. Erdogan, and M. R. Bloch, “Rate and detection-error exponent tradeoff for joint communication and sensing of fixed channel states,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 245–259, 2023, doi: 10.1109/JSAIT.2023.3275877.

[A2] O. Günlü, M. R. Bloch, R. F. Schaefer, and A. Yener, “Secure integrated sensing and communication,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 40–53, 2023, doi: 10.1109/JSAIT.2023.3275048.

[A3] M. Ahmadipour and M. Wigger, “An information-theoretic approach to collaborative integrated sensing and communication for two-transmitter systems,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 112–127, 2023, doi: 10.1109/JSAIT.2023.3286932.

[A4] Z. Liu, A. Conti, S. K. Mitter, and M. Z. Win, “Continuous-time distributed filtering with sensing and communication constraints,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 61–74, 2023, doi: 10.1109/JSAIT.2023.3283911.

[A5] E. Vargas, K. V. Mishra, R. Jacome, B. M. Sadler, and H. Arguello, “Dual-blind deconvolution for overlaid radar-communications systems,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 75–93, 2023, doi: 10.1109/JSAIT.2023.3287823.

[A6] T. Jiang, F. Sohrabi, and W. Yu, “Active sensing for two-sided beam alignment and reflection design using ping-pong pilots,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 24–39, 2023, doi: 10.1109/JSAIT.2023.3276296.

[A7] N. Ronquillo, C.-S. Gau, and T. Javidi, “Integrated beam tracking and communication for (sub-)mmWave links with stochastic mobility,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 94–111, 2023, doi: 10.1109/JSAIT.2023.3284432.

[A8] C. DeLude, R. S. Srinivasa, S. Karnik, C. Hood, M. A. Davenport, and J. Romberg, “Iterative broadband source localization,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 453–469, 2023, doi: 10.1109/JSAIT.2023.3317094.

[A9] M. F. Da Costa and Y. Chi, “Local geometry of nonconvex spike deconvolution from low-pass measurements,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 1–15, 2023, doi: 10.1109/JSAIT.2023.3262689.

[A10] R. S. Srinivasa, S. Kim, and K. Lee, “Sketching low-rank matrices with a shared column space by convex programming,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 54–60, 2023, doi: 10.1109/JSAIT.2023.3283973.

[A11] C. Xu, Y. Xie, D. A. Z. Vazquez, R. Yao, and F. Qiu “Spatio-temporal wildfire prediction using multi-modal data,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 302–313, 2023, doi: 10.1109/JSAIT.2023.3276054.

[A12] A. Agarwal, M. Peng, and V. K. Goyal, “Continuous-time modeling and analysis of particle beam metrology,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 667–681, 2023, doi: 10.1109/JSAIT.2023.3304249.

[A13] A. Mukherjee and A. Tajer, “SPRT-based efficient best arm identification in stochastic bandits,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 128–143, 2023, doi: 10.1109/JSAIT.2023.3288988.

[A14] E. Erdemir, P. L. Dragotti, and D. Gündüz, “Active privacy-utility trade-off against inference in time-series data sharing,” *IEEE J. Sel. Areas Inf. Theory*, vol. 4, pp. 159–173, 2023, doi: 10.1109/JSAIT.2023.3287929.

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