Guest Editorial Special Issue on Integrated Sensing and Communication—Part I

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I. On the Special Issue

DRIVING a gradual integration of the physical and digital worlds is perceived to become a reality in the 6G era, from vehicles to drones, from surveillance facilities in cities to agricultural tools in the countryside. Jointly motivated by recent advances in communication and signal processing, radio sensing functionality can be integrated into a 6G radio access network (RAN) in a low-cost and fast manner. That is, future networks have the ability to "see" the physical world through imaging and measuring the surrounding environment, which enables advanced location-aware services, ranging from the physical to application layers. In essence, a radio emission could simultaneously convey communication data from the transmitter to the receiver and deliver environmental information from the scattered echoes. Therefore, sensing and communication (S&C) functionalities are possible to be co-designed to utilize resources efficiently and to assist each other for mutual benefits. This type of research is typically referred to as integrated sensing and communication (ISAC).

Technological trends are now driving ISAC to become a reality. To date, the combined use of mmWave frequencies and massive multi-input multi-output (MIMO) technology results in striking similarities between communication and sensing systems in terms of the hardware architecture, channel characteristics, and information processing pipeline. Through the shared use of spectral, hardware, and even signaling resources between communication and sensing, ISAC can be realized by a synergistic design to pursue the integration gain. Moreover, it can also be implemented from a co-design perspective, wherein the communications and sensing functionalities can mutually assist each other. Benefiting from these two advantages, applications of ISAC have been extended to numerous emerging areas, including vehicular networks, environmental monitoring, the Internet of Things, as well as indoor services such as human activity recognition.

This two-part Special Issue (SI) aims at bringing together contributions from both academia and industry to highlight the recent progress of ISAC. Our call for papers led to strong responses not only from the research community of wireless communications and signal processing but also from that of information theory, radar, and mobile edge computing. We have received 90 high-quality submissions in total. Given the limited available slots and tight publication schedule, however, only 32 articles were eventually accepted for publication as a double-issue, which have been further grouped into six categories, namely, 1) Fundamental Performance Bounds and Optimization, 2) Time-Frequency Signal Processing, 3) Spatial Signal Processing, 4) Networking and Resource Allocation, 5) ISAC With Emerging Communications Technologies, and 6) ISAC Applications. This Guest Editorial of the first issue of the SI briefly overviews the contribution from the first three groups and part of the fourth group.

The Part I of this double issue starts with an overview paper [A1] written by the Guest Editorial team, which was reviewed by the Senior Editors of the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS. The article demonstrates the panorama of the ISAC framework, by shedding light on the basic performance tradeoffs, waveform designs, and receiver designs in ISAC systems, as well as the mutual assistance between S&C at a network level. Our hope is that this paper can provide a reference point for researchers working in this area, by offering both bird's eye view and technical details regarding state-of-the-art ISAC innovations.

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II. Fundamental Performance Bounds and Optimization

In [A2], Mehrotra and Sabharwal take the first step toward quantifying the fundamental performance tradeoffs between imaging and communication supported simultaneously using the same network resources. A unified signal space analytical framework is proposed in the high signal-to-noise ratio (SNR) regime, followed by a dual-function joint processing scheme named decode-and-image. The benefits of exploiting the uplink signals for imaging are further highlighted.

In [A3], Sohrabi proposes a general deep-learning framework for active sensing problems in wireless communications. In particular, a long short-term memory (LSTM) network is proposed to exploit the temporal correlations in the sequence of observations and to map each observation to a fixed-size state information vector. The proposed approach is verified by the examples of mmWave beam alignment and reflection alignment for reconfigurable intelligent surface (RIS).

In [A4], Chen *et al.* study the joint transceiver beamforming design for the dual use of MIMO radar and multiuser MIMO (MU-MIMO) communication. The performance tradeoff between S&C is characterized by defining an achievable performance region of the dual-functional system. Both radar-centric and communication-centric optimization designs are formulated to achieve the performance boundary.

In [A5], Ye *et al.* propose a novel approach for Doppler-resilient sequence (DRS) design for radar sensing and communications, where a new concept called low-ambiguity zone (LAZ) is proposed to optimize the ambiguity function within a certain range of Doppler and delay. Based on this, a set of theoretical performance bounds are further derived for unimodular DRSs with and without spectral constraints.

III. Time–Frequency Signal Processing

In [A6], Xiao and Zeng propose a novel full-duplex (FD) ISAC scheme that utilizes the waiting time of conventional pulsed radars to transmit communication signals, under the scenario of monostatic ISAC transmission. A comprehensive performance analysis is provided by taking the residual self-interference (SI) into account, in terms of the probability of detection and ambiguity function for sensing, as well as the spectral efficiency for communications.

In [A7], Shi *et al.* consider device-free sensing in an orthogonal frequency division multiplexing (OFDM) cellular network to enable ISAC. A novel two-phase sensing framework is proposed to localize the passive targets that cannot transmit/receive reference signals to/from the base stations (BSs), where the ranges of the targets are estimated based on their reflected OFDM signals to the BSs in Phase I, and the location of each target is estimated based on its values of distance to the BSs in Phase II.

In [A8], Li proposes a novel integrated sensing and communication (ISAC) transmission framework based on the spatially spread orthogonal time–frequency space (SS-OTFS) modulation by considering the mismatch of the reflection signal strengths between radar sensing and communication. A symbol-wise precoding design and power allocation strategies are proposed for S&C, through the comprehensive analysis of channel models, pair-wise error probability, and miss-detection probability.

In [A9], Wu *et al.* develop a novel sensing framework for OFDM waveforms with full or reduced cyclic prefix (CP). The proposed approach has a complexity only dominated by a Fourier transform and also provides the flexibility in adapting to different sensing needs, and is superior to the prior art in terms of the signal-to-interference-plus-noise ratio (SINR) and range-Doppler map (RDM).

IV. Spatial Signal Processing

In [A10], Cheng and Liao investigate the transmit hybrid beamforming (HBF) design and direction-of-arrival (DOA) estimation for multi-carrier dual-function radar-communication (DFRC) systems. In the designed system, communication symbols are embedded into radar pulse intervals with multiple orthogonal waveforms, and the HBF is optimized to focus the transmit energy within the spatial sectors of interest by imposing quality-of-service (QoS) constraints of users.

In [A11], Wu *et al.* develop a space–time coding scheme for both radar beamforming and communication information embedding, without their cross interference. The radar transmit beampattern is optimized under both shape approximation and integrated power approximation criteria. Moreover, direct constellation mapping (DCM) and phase-rotation constellation mapping (PRCM) methods are proposed to embed information symbols.

In [A12], Liu *et al.* propose a novel DFRC system that combines space–time adptive processing (STAP) and symbol-level precoding methods. In particular, the radar SINR is maximized by jointly optimizing the transmit waveform and receive filter, while satisfying the communication QoS constraint and various waveform constraints including constant-modulus, similarity and peak-to-average power ratio (PAPR).

In [A13], Liu *et al.* consider the design of a MIMO transmitter which simultaneously functions as a MIMO radar and a BS for downlink multiuser communications. A multiuser SINR balancing problem and a sum-rate maximization problem are formulated and solved by considering dirty paper coding (DPC) for multiuser communications, subject to radar waveform covariance constraint.

In [A14], Johnston *et al.* study the design of the radiated waveforms and the receive filters for a MIMO DFRC system, by resorting to an OFDM transmission format and a differential phase-shift keying (DPSK) modulation. A broad family of radar-oriented objectives, including both detection and estimation metrics, are optimized, under constraints of the average transmit power, the power leakage towards specific directions, and the error probability of each user, thus safeguarding the communication QoS.

In [A15], Yu *et al.* investigate the precoding design for one-bit digital-to-analog converter (DAC) DFRC system, which minimizes a weighted sum of communication multi-user interference (MUI) and radar waveform similarity metrics, under both the one-bit and waveform covariance constraints. A multi-variable alternating minimization (MVAM) framework is proposed to achieve near-optimal solutions for the optimization problem.

V. Networking and Resource Allocation

In [A16], Mu *et al.* investigate a novel concept of non-orthogonal multiple access (NOMA)-aided joint radar and multicast-unicast communication (Rad-MU-Com). Employing the same spectrum resource, a multi-input-multi-output (MIMO) dual-functional radar-communication (DFRC) BS detects the radar-centric users (R-user) while transmitting mixed multicast-unicast messages both to the R-user and to the communication-centric user (C-user). A beamformer-based NOMA-aided joint Rad-MU-Com framework is proposed for the system having a single R-user and a single C-user and is further extended to the scenario of multiple pairs of R- and C-users.

In [A17], Bai *et al.* study wireless radar sensor networks (WRSNs) by employing the innovative tool of the epidemic theory for modeling the data dissemination and analyzing the performance of WRSNs. The density of radar sensors is optimized by the epidemiological analytical method to maximize the throughput of the storage node by jointly considering the functions of radar detection and communication.

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Appendix: Related Articles

[A1] F. Liu, Y. Cui, C. Masouros, J. Xu. T.-X. Han, Y. C. Eldar, and S. Buzzi, "Integrated sensing and communications: Towards dual-functional wireless networks and beyond," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1728–1767, Jun. 2022.

[A2] N. Mehrotra and A. Sabharwal, "On the degrees of freedom region for simultaneous imaging & uplink communication," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1768–1779, Jun. 2022.

[A3] F. Sohrabi, T. Jiang, W. Cui, and W. Yu, "Active sensing for communications by learning," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1780–1794, Jun. 2022.

[A4] L. Chen, Z. Wang, Y. Du, Y. Chen, and F. R. Yu, "Generalized transceiver beamforming for DFRC with MIMO radar and MU-MIMO communication," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1795–1808, Jun. 2022.

[A5] Z. Ye, Z. Zhou, P. Fan, Z. Liu, X. Lei, and X. Tang, "Low ambiguity zone: Theoretical bounds and Doppler-resilient sequence design in integrated sensing and communication systems," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1809–1822, Jun. 2022.

[A6] Z. Xiao and Y. Zeng, "Waveform design and performance analysis for full-duplex integrated sensing and communication," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1823–1837, Jun. 2022.

[A7] Q. Shi, L. Liu, S. Zhang, and S. Cui, "Device-free sensing in OFDM cellular network," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1838–1853, Jun. 2022.

[A8] S. Li, "A novel ISAC transmission framework based on spatially-spread orthogonal time frequency space modulation," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1854–1872, Jun. 2022.

[A9] K. Wu, J. A. Zhang, X. Huang, and Y. J. Guo, "Integrating low-complexity and flexible sensing into communication systems," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1873–1889, Jun. 2022.

[A10] Z. Cheng and B. Liao, "QoS-aware hybrid beamforming and DOA estimation in multi-carrier dual-function radar-communication systems," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1890–1905, Jun. 2022.

[A11] W. Wu, G. Han, Y. Cao, Y. Huang, and T.-S. Yeo, "MIMO waveform design for dual functions of radar and communication with space-time coding," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1906–1917, Jun. 2022.

[A12] R. Liu, M. Li, Q. Liu, and A. Lee Swindlehurst, "Joint waveform and filter designs for STAP-SLP-based MIMO-DFRC systems," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1918–1931, Jun. 2022.

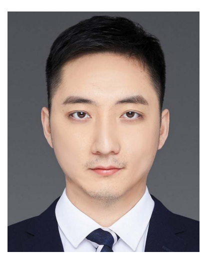
[A13] X. Liu, T. Huang, and Y. Liu, "Transmit design for joint MIMO radar and multiuser communications with transmit covariance constraint," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1932–1950, Jun. 2022.

[A14] J. Johnston, L. Venturino, E. Grossi, M. Lops, and X. Wang, "MIMO OFDM dual-function radar-communication under error rate and beampattern constraints," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1951–1964, Jun. 2022.

[A15] X. Yu, Q. Yang, Z. Xiao, H. Chen, V. Havyarimana, and Z. Han, "A precoding approach for dual-functional radar-communication system with one-bit DACs," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1965–1977, Jun. 2022.

[A16] X. Mu, Y. Liu, L. Guo, J. Lin, and L. Hanzo, "NOMA-aided joint radar and multicast-unicast communication systems," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1978–1992, Jun. 2022.

[A17] L. Bai, J. Liu, R. Han, and W. Zhang, "Wireless radar sensor networks: Epidemiological modeling and optimization," *IEEE J. Sel. Areas Commun.*, vol. 40, no. 6, pp. 1993–2005, Jun. 2022.



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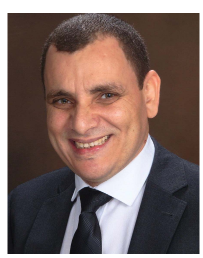

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