A Survey on Integrated Sensing and Communication: Integrated System of RIS, UAV, Multiple Access

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***Abstract*—Integrated Sensing and Communication (ISAC) is attracting attention as a core technology of mobile communication systems after 5G. This paper provides a comprehensive survey on the integration of ISAC systems with cutting-edge technologies. Specifically, the following topics are covered: First, the integration of ISAC with next-generation multiple access (MA) techniques. Second, ISAC integrated reconfigurable intelligent surfaces (RIS). Third, ISAC integrated unmanned aerial vehicles (UAVs). Fourth, ISAC utilization in vehicular networks. We review the latest research trends in these integrated systems and provide insights and guidelines for the effective utilization of ISAC.**

***Index Terms*—ISAC, UAV, RIS, Multiple Access.**

I. Introduction

Integrated sensing and communication (ISAC) share the same radio resources and hardware for sensing and communication to achieve high spectral efficiency and low hardware cost. ISAC is considered one of the core technologies for mobile communication systems beyond 5G due to two core reasons[1]. First, various appearance of new applications, such as autonomous driving and transportation, consumer robotics, telehealth, and extended reality, and the interconnection of these applications. These applications require massive connectivity, lower latency, and ultra-high reliability; however, spectrum resources are limited, which poses serious challenges. Second, the adoption of massive MIMO technology and the use of millimeter-wave beyond 5G will enable future communication signals to achieve high resolution in both time and angular domains, opening up the possibility of ISAC [2]. Accordingly, ISAC has attracted research interest and attention for beyond 5G.

The pioneering works on ISAC focused on the design, optimization, and analysis of signal waveforms and beamforming design to be used in ISAC [3]-[5]. While this area of research is needed, we review research on several integrated systems in this area to understand their collaboration and integration with current state-of-the-art technologies and provide useful insights and guidance for better leveraging of ISAC. In this study, we begin by reviewing existing research on the integration of next-generation multiple access (MA) and ISAC systems. We then provide a comprehensive and exhaustive survey of the integration of ISAC with reconfigurable intelligent surfaces (RIS) and unmanned aerial vehicles (UAV). Finally, we investigate the utilization of ISAC in vehicular networks to stimulate further research in these areas.

II. ISAC aided systems

A. ISAC aided state-of-art multiple access schemes

ISAC has been investigated for integration with state-of-art MA schemes such as non-orthogonal MA (NOMA) and (rate-splitting MA) RSMA using the SIC technique since the signals for communication and sensing are superposition. NOMA superpositions multiple users' signals and sensing signals on the power domain at the transmitter and transmits them, and uses successive interference cancellation (SIC) technology at the receiver to reduce inter-user-interference (IUI) or interference caused by sensing signals. Wang et al. designed a beamforming scheme to maximize the weighted sum of communication throughput and adequate sensing power in the NOMA-ISAC system [6]. In the communication model, the SIC of NOMA is used to mitigate user interference, while in the sensing model, the communication signal is used to maximize the effective sensing power in the target direction. It is demonstrated that NOMA-ISAC provides greater freedom for radar detection in the underloaded regime in the case of high channel correlation [6].

RSMA divides each user's message into a common part and a private part through message segmentation, combines the common part into a common stream, encodes it, and transmits it. The receiver decodes the common stream and the private stream using SIC. Interference is partially decoded and partially processed as noise through the common stream to effectively manage it. RSMA is a generalized MA scheme that includes existing multiple access techniques, including SDMA and NOMA, as special cases. Xu et al. proposed an RSMA-ISAC system to manage interference between radar and communication functions and interference between users [7]. Utilizing a common stream and a SIC receiver demonstrated better performance than the SDMA-based ISAC system in both the weighted sum rate for communication and the mean square error for radar performance. In particular, the common stream of RSMA can replace the role of radar sequence and perform communication functions at the same time, which means that spectrum resources can be used more efficiently because no additional radar sequence is needed [7].

Zhang et al. proposed a new system called Semi-ISAC, which divides the total bandwidth for wireless communication, ISAC, and radar detection [8]. They demonstrated that Semi-ISAC can achieve better channel capacity than the conventional ISAC, and by analyzing the evolution from OMA to NOMA, they demonstrated that NOMA outperforms OMA.

B. RIS-assisted ISAC system

The most active area of research we have investigated is the RIS-assisted ISAC system. Wang et al. proposed a method to jointly optimize constant-modulus waveform and discrete RIS phase shift to minimize IUI while satisfying the Cramer-Rao Bound (CRB) lower bound constraint on the degree of arrival (DoA) estimation of the target in a RIS-assisted ISAC system [9]. The constant modulus waveforms improve the performance of radar and communications systems, especially in environments sensitive to multiple targets or interference. He et al. jointly optimized the beamforming of radar and RIS with the purpose of maximizing the communication SINR while ensuring radar detection performance [10]. Luo et al. jointly optimized the active beamforming of the base station and the passive beamforming of the RIS, aiming at maximizing the achievable aggregate throughput of communication users in an ISAC system [11]. The deployment of RIS in an ISAC system can significantly improve the performance, with a slight performance difference compared to a communication-only system; however, this is due to the trade-off between communication and radar detection performance.

An active-RIS-assisted system, which integrates amplifiers into the RIS elements to amplify the incident signal rather than simply reflecting the signal, was investigated in [12]. Zhu et al. achieved higher SNR than passive-RIS by using amplifiers, but integrating amplifiers into the RIS elements incurs higher hardware cost and power [12]. Furthermore, a Simultaneously Transmitting And Reflecting (STAR)-RIS-assisted ISAC system capable of simultaneously transmitting as well as reflecting signals has been investigated in [13]. In [13], the entire space is not used for communication and sensing simultaneously but is divided into sensing space and communication space using STAR-RIS. Numerical experiments show that the proposed STARS-based ISAC system outperforms the existing RIS. Still, it has the disadvantage of not being able to use sensing and communication simultaneously in the entire space. This shortcoming is also evident in a more recent study [14]. To address this half-space problem, Xue et al. integrate NOMA, mentioned in subsection A, into the STAR-RIS-aided ISAC system [15]. The system consists of multiple communication users and detection targets and divides the entire space into reflection space and transmission space through STAR-RIS to provide ISAC service to the entire space. In addition, cluster-based NOMA is introduced to secure additional spectral efficiency and beamforming design flexibility [15].

C. UAV assisted ISAC

When UAVs take over the role of BS, they can provide flexible sensing and enhanced communication capabilities depending on the location of the UAV. This flexibility of UAVs is expected to revolutionize the existing ISAC system and promise a more flexible joint design. In particular, for sensing functions that show good performance when the LoS component is distinct, the flexibility of the system is expected to increase significantly since UAVs can provide LoS links through mobility. Meng et al. proposed a novel ISAC mechanism that takes into account the asymmetry between detection frequency and communication requirements [16]. They jointly optimize UAV trajectories, user connections, target detection selection, and transmit beamforming to achieve flexible trade-offs between detection frequency, detection power requirements, and communication performance, thereby maximizing the achievable throughput of the system [16].

In UAV-assisted ISAC systems, the jitter effect considering the UAV's movement, attitude change, and vibration of UAV must be considered. Jhao et al. integrated UAV sensing, communication, and control to achieve low-latency information transmission [17]. The authors defined the system state as the UAV's position, velocity, and attitude angle and assumed that various sensor data such as gyroscope, accelerometer, and GPS can be integrated. In [17], they attempted to implement a UAV-assisted ISAC system robust to the jitter effect by integrating and optimizing sensing, communication, and control functions.

D. ISAC in Vehicular System

Detecting the status of vehicles and other objects in vehicular networks, such as their position and speed, is critical to realizing collision avoidance and practical real-time road safety [18]. Yuan et al. designed predictive transmission beamforming for vehicles in a vehicular-ISAC system consisting of RSUs and multiple vehicles, with the goal of maximizing spectral efficiency in vehicle state detection and downlink communication [19]. The authors demonstrated that beamforming prediction can utilize the vehicle's kinematic parameters based on ISAC to predict the vehicle's position and velocity at the next time instant, thereby eliminating the need for a pilot for beam pairing and reducing the overhead of channel estimation [19]. In [19], the authors used orthogonal time frequency space transmission, while Liu et al. [20] developed a beamforming design framework targeting sum-rate maximization using CRB lower bound-based sensing constraints considering MA interference. [19] and [20] both demonstrated that the communication overhead resulting from pilot transmission for beamforming based on ISAC can be reduced.

III. Conclusion

In this paper, we have performed a comprehensive survey on the integration of the ISAC system with various state-of-the-art technologies. Most of the studies investigated show that if the constraints for detection performance are loose, the communication performance improves, and if the constraints for detection performance are tight, the communication performance deteriorates. This is because the goals of the detection and communication tasks are not completely aligned. The main points are as follows: First, the integration of ISAC with next-generation MA techniques such as NOMA and RSMA can improve spectral efficiency and improve interference management. This can improve the disadvantages arising from the trade-off between sensing and communication. Second, the RIS-supported ISAC system can significantly improve performance. Third, UAV-supported ISAC can provide flexible sensing and enhanced communication capabilities. Fourth, in vehicular networks, ISAC can significantly reduce the channel estimation overhead and improve spectral efficiency through beamforming prediction. These integrated systems significantly improve the performance of ISAC and demonstrate its potential for various applications. Future research needs to focus on the practical implementation and performance optimization of these integrated systems.

Acknowledgment

This work was supported in part by the National Research Foundation of Korea (NRF), South Korea grant funded by the Korea government (MSIT) (No. 2022R1A4A5034130), in part by the MSIT (Ministry of Science and ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2024-RS-2022-00156353) supervised by the IITP (Institute for Information and Communications Technology Planning and Evaluation), South Korea.

References

[1] F. Liu et al., "Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 6, pp. 1728-1767, June 2022, doi: 10.1109/JSAC.2022.3156632.

[2] A. Liu et al., "A Survey on Fundamental Limits of Integrated Sensing and Communication," in IEEE Communications Surveys & Tutorials, vol. 24, no. 2, pp. 994-1034, Secondquarter 2022, doi: 10.1109/COMST.2022.3149272.

[3] Z. Wei, H. Qu, W. Jiang, K. Han, H. Wu and Z. Feng, "Iterative Signal Processing for Integrated Sensing and Communication Systems," in IEEE Transactions on Green Communications and Networking, vol. 7, no. 1, pp. 401-412, March 2023, doi: 10.1109/TGCN.2023.3234825.

[4] H. Hua, J. Xu and T. X. Han, "Optimal Transmit Beamforming for Integrated Sensing and Communication," in IEEE Transactions on Vehicular Technology, vol. 72, no. 8, pp. 10588-10603, Aug. 2023, doi: 10.1109/TVT.2023.3262513.

[5] Z. He, W. Xu, H. Shen, Y. Huang and H. Xiao, "Energy Efficient Beamforming Optimization for Integrated Sensing and Communication," in IEEE Wireless Communications Letters, vol. 11, no. 7, pp. 1374-1378, July 2022, doi: 10.1109/LWC.2022.3169517.

[6] Z. Wang, Y. Liu, X. Mu, Z. Ding and O. A. Dobre, "NOMA Empowered Integrated Sensing and Communication," in IEEE Communications Letters, vol. 26, no. 3, pp. 677-681, March 2022, doi: 10.1109/LCOMM.2022.3140271.

[7] C. Xu, B. Clerckx, S. Chen, Y. Mao and J. Zhang, "Rate-Splitting Multiple Access for Multi-Antenna Joint Radar and Communications," in IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1332-1347, Nov. 2021, doi: 10.1109/JSTSP.2021.3110312.

[8] C. Zhang, W. Yi, Y. Liu and L. Hanzo, "Semi-Integrated-Sensing-and-Communication (Semi-ISaC): From OMA to NOMA," in IEEE Transactions on Communications, vol. 71, no. 4, pp. 1878-1893, April 2023, doi: 10.1109/TCOMM.2023.3241940.

[9] X. Wang, Z. Fei, J. Huang and H. Yu, "Joint Waveform and Discrete Phase Shift Design for RIS-Assisted Integrated Sensing and Communication System Under Cramer-Rao Bound Constraint," in IEEE Transactions on Vehicular Technology, vol. 71, no. 1, pp. 1004-1009, Jan. 2022, doi: 10.1109/TVT.2021.3122889.

[10] Y. He, Y. Cai, H. Mao and G. Yu, "RIS-Assisted Communication Radar Coexistence: Joint Beamforming Design and Analysis," in IEEE Journal on Selected Areas in Communications, vol. 40, no. 7, pp. 2131-2145, July 2022, doi: 10.1109/JSAC.2022.3155507.

[11] H. Luo, R. Liu, M. Li, Y. Liu and Q. Liu, "Joint Beamforming Design for RIS-Assisted Integrated Sensing and Communication Systems," in IEEE Transactions on Vehicular Technology, vol. 71, no. 12, pp. 13393-13397, Dec. 2022, doi: 10.1109/TVT.2022.3197448.

[12] Q. Zhu, M. Li, R. Liu and Q. Liu, "Joint Transceiver Beamforming and Reflecting Design for Active RIS-Aided ISAC Systems," in IEEE Transactions on Vehicular Technology, vol. 72, no. 7, pp. 9636-9640, July 2023, doi: 10.1109/TVT.2023.3249752.

[13] Z. Wang, X. Mu and Y. Liu, "STARS Enabled Integrated Sensing and Communications," in IEEE Transactions on Wireless Communications, vol. 22, no. 10, pp. 6750-6765, Oct. 2023, doi: 10.1109/TWC.2023.3245297.

[14] Z. Liu, X. Li, H. Ji, H. Zhang and V. C. M. Leung, "Toward STAR-RIS-Empowered Integrated Sensing and Communications: Joint Active and Passive Beamforming Design," in IEEE Transactions on Vehicular Technology, vol. 72, no. 12, pp. 15991-16005, Dec. 2023, doi: 10.1109/TVT.2023.3294338.

[15] N. Xue, X. Mu, Y. Liu and Y. Chen, "NOMA-Assisted Full Space STAR-RIS-ISAC," in IEEE Transactions on Wireless Communications, vol. 23, no. 8, pp. 8954-8968, Aug. 2024, doi: 10.1109/TWC.2024.3357349.

[16] K. Meng, Q. Wu, S. Ma, W. Chen, K. Wang and J. Li, "Throughput Maximization for UAV-Enabled Integrated Periodic Sensing and Communication," in IEEE Transactions on Wireless Communications, vol. 22, no. 1, pp. 671-687, Jan. 2023, doi: 10.1109/TWC.2022.3197623.

[17] J. Zhao, F. Gao, W. Jia, W. Yuan and W. Jin, "Integrated Sensing and Communications for UAV Communications With Jittering Effect," in IEEE Wireless Communications Letters, vol. 12, no. 4, pp. 758-762, April 2023, doi: 10.1109/LWC.2023.3243590.

[18] W. Yuan, S. Li, L. Xiang and D. W. K. Ng, "Distributed Estimation Framework for Beyond 5G Intelligent Vehicular Networks," in IEEE Open Journal of Vehicular Technology, vol. 1, pp. 190-214, 2020, doi: 10.1109/OJVT.2020.2989534.

[19] W. Yuan, Z. Wei, S. Li, J. Yuan and D. W. K. Ng, "Integrated Sensing and Communication-Assisted Orthogonal Time Frequency Space Transmission for Vehicular Networks," in IEEE Journal of Selected Topics in Signal Processing, vol. 15, no. 6, pp. 1515-1528, Nov. 2021, doi: 10.1109/JSTSP.2021.3117404.

[20] C. Liu et al., “Learning-Based Predictive Beamforming for Integrated Sensing and Communication in Vehicular Networks,” in IEEE Journal on Selected Areas in Communications, vol. 40, no. 8, pp. 2317-2334, Aug. 2022, doi: 10.1109/JSAC.2022.3180803.