Advances in ISCAP: Toward Unified Sensing, Data Transmission, and Wireless Powering

Phuoc B. T. Huynh
Department of Electronic Engineering
Hanyang University
Seoul, Republic of Korea
phuochuynh@hanyang.ac.kr

Mohsin Ali
Department of Electronic Engineering
Hanyang University
Seoul, Republic of Korea
mohsin0987@hanyang.ac.kr

Sunwoo Kim
Department of Electronic Engineering
Hanyang University
Seoul, Republic of Korea
remero@hanyang.ac.kr

***Abstract*—Integrated sensing and communication (ISAC) has appeared as an important technology in next-generation wireless systems, enabling high-resolution awareness of the environment and effective reuse of the spectrum. Similarly, simultaneous wireless information and power transfer (SWIPT) has emerged as an exciting solution to assist the energy-limited and battery-constrained wireless networks. The integration of the two technologies constructs an integrated sensing, communication and power transfer (ISCAP) which brings together sensing, data transfer, and wireless energy delivery in a unified transmitted signal and a single hardware setup. This paper outlines the recent developments in ISCAP within four main dimensions, which include waveform design, multi-input-multi-output (MIMO)-enhanced architectures, reconfigurable intelligent surface (RIS)-assisted systems, and optical ISCAP. We highlight the advanced waveform strategies, the MIMO spatial processing, and RIS technologies that reconfigure the propagation environment to improve multi-user ISCAP performance. Additionally, the first experimental demonstration of optical ISCAP that offers high bandwidth without interference is reported. By summarizing these developments, this survey shows fundamental design principles, addresses the inherent tradeoffs between sensing, communication, and powering, and outlines some of the pending obstacles in implementing a practical ISCAP in future 6G networks.**

***Index Terms*—Integrated sensing and communication (ISAC), simultaneous wireless information and power transfer (SWIPT), integrated sensing communication and power transfer (ISCAP), reconfigurable intelligent surface (RIS), 6G, wireless communication.**

I. Introduction

The recent increase of research on integrated sensing and communication (ISAC) and simultaneous wireless information and power transfer (SWIPT) indicates a shift where communication signals can be reused as a medium of sensing as well as a power source to low-power devices [1], [2]. In light of the growing scarcity of spectral and energy resources, spectral convergence of ISAC and SWIPT is expected to be a key stage of 6G network development. This unification leads to integrated sensing, communication, and power transfer (ISCAP), which defines a paradigm that enables simultaneous sensing, data communication and wireless energy transfer to be executed in a single architectural implementation, as shown in Fig. 1. ISCAP offers significant benefits of increasing spectral and hardware efficiencies, reducing system cost, and elevating synergies across functional domains [3]. Nevertheless, the implementation for ISCAP is considerably more complicated than the simple combination of the individual practices of ISAC and SWIPT due to the inherent differences in the principles of operation. The three constituent operations use naturally differentiated transmission of waveforms, allocations of power and performance targets. Specifically, sensing in the time-frequency domain requires very high stability, the communication needs robust modulation and coding schemes, and the power transfer needs high-power signals for energy harvesting. The practical implementation of ISCAP systems, therefore, requires novel waveform, spatial, and architectural designs that can resolve such inherently incompatible demands. In order to address such challenges, this paper provides a comprehensive survey of multifunctional ISCAP systems in four research areas: (1) waveform design for ISCAP, (2) multi-input-multi-output (MIMO)-enhanced ISCAP, (3) reconfigurable intelligent surface (RIS)-assisted ISCAP, and (4) optical ISCAP. In each field, exemplary developments are outlined, fundamental design considerations are covered and recent solutions that reduce the inherent tradeoffs between sensing accuracy, communication functionality, and energy-harvesting (EH) efficiency are indicated. Through the aggregation of these advances, this survey aims to provide a concise picture of the state-of-the-art ISCAP research and to provide insights that can inform the creation of future 6G systems with the capability of supporting multifunctional wireless networks.

II. Recent Advancement of ISCAP Technology

A. Unified Waveform Strategies for ISCAP

Waveform design plays a critical role in enabling ISCAP technology since the transmitted signal must jointly support high-quality information transfer, accurate sensing estimation, and efficient RF-to-DC energy conversion. In conventional ISAC systems, a variety of waveforms have been explored, including orthogonal frequency-division multiplexing (OFDM), orthogonal time-frequency space (OTFS), orthogonal chirp-division multiplexing (OCDM), frequency-modulated continuous wave (FMCW), and single carrier schemes [4]. For SWIPT systems, multisine waveforms have gained considerable interest because their pronounced peak structure more effectively drives the nonlinear rectifier, thereby improving

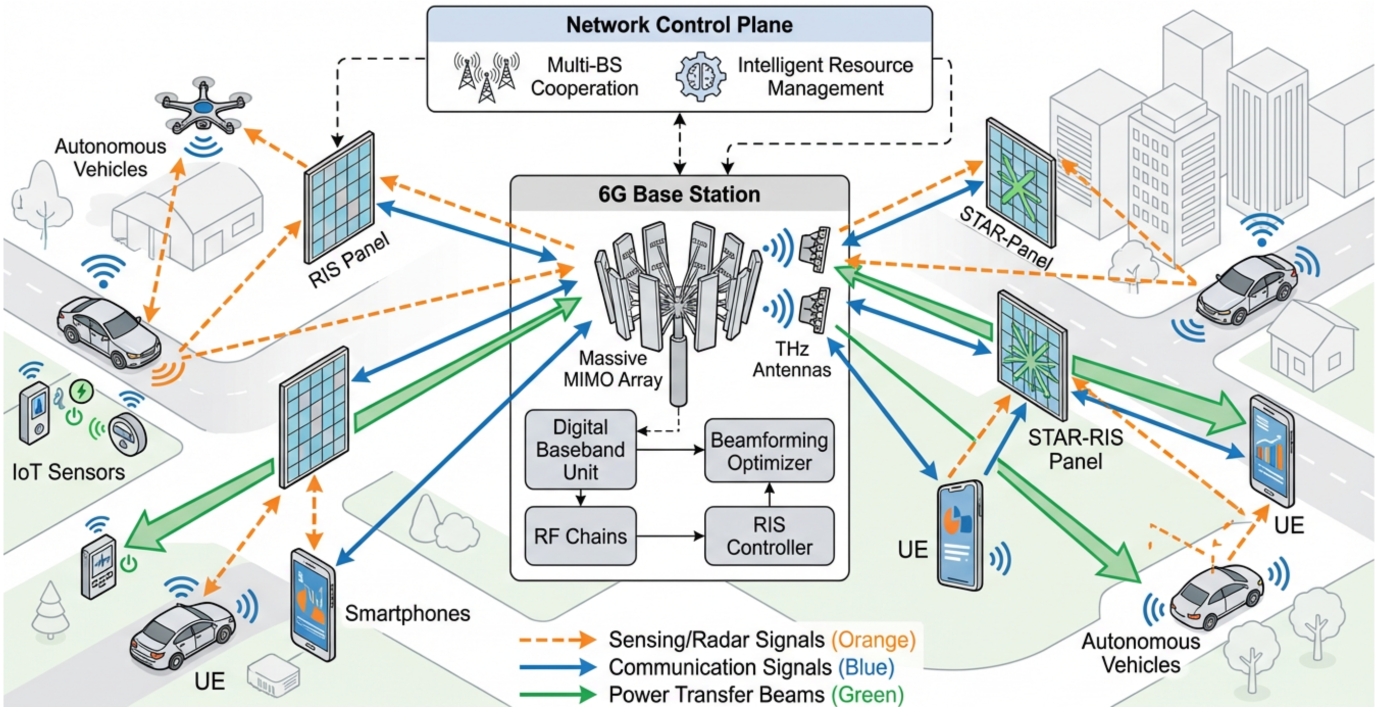

Figure 1. Integrated sensing, communication, and power transfer (ISCAP) technology.

EH efficiency compared to traditional single carrier transmission [5]. These developments naturally motivate new triple-functional waveform designs for ISCAP, where the underlying signaling must simultaneously satisfy the reliability demands of communication, the structural requirements of sensing, and the desired characteristics for wireless power transfer (WPT).

Recent works have investigated ISCAP waveform design through extensions of OFDM. In particular, [6] introduces a multifunctional OFDM framework that employs non-zero-mean asymmetric Gaussian signaling at each subcarrier. By jointly optimizing the subcarrier mean and variance, the system maximizes the harvested energy while satisfying the constraints on communication rate and the average-sidelobe-to-peak difference required for reliable sensing. Beyond OFDM, orthogonal time-sequency multiplexing (OTSM) has emerged to address challenges in doubly spread channels (DSCs), which offers similar performance robustness to OTFS while achieving lower complexity than OFDM in high-mobility scenarios. Complementary to OTSM, delay-Doppler alignment modulation (DDAM) has been proposed to address dispersion effects at mmWave and sub-terahertz frequencies by aligning symbols within delay-Doppler bins. By applying these innovations, a recent research [7] explores the integration of OTSM and DDAM for mmWave massive MIMO ISCAP systems. This combination OTSM-DDAM waveform enables a unified framework in which communication symbols, sensing reflections, and energy-carrying components are jointly processed in the delay-time, and delay-sequency domains. In addition, the fractional delay-Doppler shifts, hardware impairments, and massive-MIMO spatial processing are considered for analytical derivation of key performance indicators such as bit-error rate (BER), spectral efficiency (SE), the Cramér-Rao bound (CRB) for sensing accuracy, and the harvested energy from WPT. By employing this approach, an on-policy deep reinforcement learning (DRL) solution based on the advantage actor-critic framework with a greedy refinement strategy has been proposed to optimize the ISCAP waveform. The learning agent jointly adapts precoding, power loading, time/power splitting ratios, beam alignment, and receive combining to minimize transmit power and CRB while satisfying constraints on SE, BER, interference, harvested energy, and the overall power budget. Simulation results using real-world and deep-learning-generated datasets demonstrate significant performance gains, including reduced peak-to-average power ratio (PAPR), enhanced SE, improved sensing accuracy, and greater robustness in high-mobility DSC conditions. These findings highlight the importance of waveform co-design as a key enabler for practical and scalable ISCAP deployments.

B. MIMO-enhanced ISCAP

MIMO has emerged as a pivotal component not only for ISAC, SWIPT but also for ISCAP, providing spatial degrees of freedom (DoF) that allow simultaneous optimization of sensing accuracy, communication quality, and wireless power delivery. A unified multifunctional MIMO system is investigated in [8], in which a hybrid access point (H-AP) employs multiple antennas to concurrently transmit data to an information user, deliver energy to an EH user, and sense radar targets through received echoes. The study characterizes the fundamental tradeoffs among estimation accuracy, achievable communication rate, and harvested energy represented as the CRB rate and energy metrics. By considering both point-target and extended-target radar models, the authors define a complete CRB-rate-energy (C-R-E) region and derive its Pareto boundary through convex optimization. Their optimal covariance solutions reveal how transmit spatial resources should be allocated to balance sensing, communication, and powering, outperforming benchmark schemes such as time-division operation and eigenmode transmission. A study in [9] extends MIMO ISCAP to a multi-user setting where a multi-antenna base station (BS) simultaneously serves an information receiver (IR) while transferring energy to an EH receiver, and performing target sensing. The target is modeled as either a point scatterer or an extended surface. When IR and ER occupy distinct spatial locations, beamforming is optimized to strengthen the sensing performance while ensuring communication rate and harvested power constraints for all users. When IR and ER are co-located, power-splitting ratios are jointly optimized with the transmit beamformers to balance communication and energy delivery. Through Schur complement transformation, rank-reduction strategies, and semi-definite relaxation (SDR), the authors solve the underlying non-convex problems and demonstrate clear performance tradeoffs among sensing, communication, and wireless power transfer. They also further analyze the target-positioning capability of the system, emphasizing how spatial resources and beam patterns influence ISCAP sensing accuracy.

To increase energy-efficient operation, [10] studies hybrid analog-digital (HAD) MIMO architectures, recognizing that large antenna arrays can incur substantial power consumption. The authors propose a novel HAD transmitter structure capable of dynamically switching RF chains and phase shifters on-off via a reconfigurable switch network. A comprehensive power-consumption model, which accounts for nonlinear power amplifier (PA) efficiency and the non-transmission consumption of RF hardware, is incorporated into the joint design of hybrid beamforming and switching control. The objective is to minimize the BS power consumption while satisfying constraints on communication rate, sensing CRB, harvested power, antenna transmit limits, and constant-modulus analog beamforming. Through alternating optimization, sequential convex approximation, and semi-definite relaxation, an iterative algorithm is developed to obtain feasible high-quality solutions, followed by an efficient decision rule to determine the binary on-off states of the RF components. This approach highlights the importance of energy-aware spatial processing in practical large-scale ISCAP deployments. Security considerations have also emerged in MIMO ISCAP, particularly in near-field regimes enabled by extremely large-scale antenna arrays (ELAA). The work in [11] examines secure MIMO ISCAP operation where a BS transmits confidential messages to a communication user while simultaneously charging multiple ER and sensing a point target. Because ER and the sensing target may act as potential eavesdroppers, the system transmits additional sensing/energy beams that also serve as artificial noise (AN) to degrade unauthorized interception attempts. The authors maximize the secrecy rate under constraints on sensing CRB and harvested energy by solving a challenging non-convex beamforming problem using semi-definite relaxation, fractional programming, and a one-dimensional search. Alternative designs based on zero-forcing and maximum ratio transmission are also provided for reduced-complexity implementation. Numerical results show that near-field ELAA provides enhanced distance-domain resolution, enabling precise control of spatial energy and information leakage, thereby improving secrecy while meeting sensing and powering requirements.

C. *RIS-assisted ISCAP*

RIS and simultaneously transmitting and reflecting (STAR)-RIS have emerged as promising technologies for enhancing ISCAP systems by providing programmable control over the wireless propagation environment. By intelligently shaping reflections through passive or semi-passive elements, RIS enables improved energy focusing, interference management, and spatial diversity, thereby strengthening the joint performance of sensing, communication, and power transfer. In [12], an RIS-assisted ISCAP architecture is studied in which a multi-antenna BS simultaneously performs multi-target radar sensing, multi-user data transmission, and wireless power delivery. The design objective is to maximize the minimum harvested power across all users while ensuring beam pattern gain constraints for radar sensing and maintaining required SINR levels for communication users. To solve the underlying nonconvexity of this joint design problem, a block coordinate descent algorithm is embraced to sequentially optimize the BS transmit beamformer, the RIS phase-shift matrix and the power-sharing factors of the users. The transmit beamformer with tightness of the rank-one is relaxed through SDR and a successive convex approximation method through a penalty is used to optimize the RIS phase shifts. The joint design is further simplified with closed-form solutions of the ratios of power split. The development of a robust RIS-enhanced ISCAP scheme through the utilization of the Bernstein-type inequalities as a measure of dealing with the stochastic channel-estimation errors is also made. Mathematical analysis supports the fact that the optimized RIS based architecture considerably enhances the minimum energy recovered in comparison to the traditional baseline approaches.

In addition to traditional passive RIS, in recent studies, sensor-aided zero-energy RIS (SAZE-RIS) architectures are also pointed at to more efficiently improve ISCAP performance [13]. SAZE-RIS utilizes inbuilt low-power sensors and self-sustained energy-harvesting strategies, such that the RIS can run without any power supply and still offer dynamic reconfiguration. The work discusses the incorporation of SAZE-RIS into ISCAP describing the overall system architectures, operational protocols, and sample use cases in which zero-energy RIS technology can provide valuable benefits. The paper considers the possibility of harmonizing the conflicting needs of the communication reliability, sensing precision and wireless power delivery, using SAZE-RIS to adaptively control the reflection patterns based on the perceived environmental data. A case study with simulation results is given detailing the design decisions and tradeoffs involved in applying SAZE-RIS to ISCAP and showing an increase in energy efficiency, coverage and sensing quality. Open research challenges, such as real-time control, hardware modeling and co-design methodologies are also brought out in the work hence major directions to the future development of RIS-enabled ISCAP systems.

D. Optical ISCAP

Recently, optical technologies have become an attractive option to implement the functionality of ISCAP and provide high bandwidth, directionality, and natural electromagnetic isolation of current RF systems. An example of optical ISCAP is found in [14], which reports on the first successful experimental verification of an optical ISCAP system. The suggested framework brings together optical wireless communication, optical ranging, and optical energy harvesting on a single platform that is multifunctional and thus overcomes key shortcomings of the current RF-based systems with regard to the flexibility of resources and interoperability of the system. The authors consider the performance of the communication, sensing and power transfer modules by using a detailed experimental apparatus to investigate the effects of bias current, peak to peak drive voltage, and light-source wavelength on the modules performance. The system achieves a maximum data rate of around 632.58 Mbps, a range root-mean-square error of nearly zero, and a maximum harvested optical power of 10 mW, thus showing the potential of a high performance optical ISCAP system. Moreover, the influence of important optical parameters on the operating features of every functional block is systematically studied. The findings indicate that there exist strong correlations between modulation depth, optical source biasing, wavelength selection, and the tradeoffs that can be achieved between communication throughput, ranging accuracy, and energy-harvesting efficiency. Such strategy can be useful design principles in the next-generation optical ISCAP architecture, and it is important to note that the optical source, driving circuitry, and photodetector configuration need to be jointly optimized. It is a major advancement because it forms the first experimental basis of optical ISCAP systems, and it inspires further research on optical-domain ISCAP methods of upcoming 6G integrated communication and sensing networks.

III. Open Challenges and Future Research

Open challenges and future research on ISCAP include fundamental theory, scalable networking, and practical robustness. A key research direction is developing a unified theoretical framework that captures the joint tradeoffs among communication rate, sensing accuracy, and harvested energy across waveform, spatial, and architectural dimensions. The existing C-R-E formulations, which often rely on idealized assumptions such as linear RF energy harvesting models, Gaussian signaling, or single link MIMO, limit their applicability to the practical systems. To address this gap, future research must include nonlinear RF and optical rectification, finite block length sensing and communication, and heterogeneous quality-of-service (QoS) requirements across users and targets, which allows accurate understanding the impact of waveform structure, pilot overhead, duplexing strategies, and resource partitioning on the achievable data, sensing, and energy regions. Another critical bottleneck is the extension ISCAP from single target to multi-target scenario where there are unknown or dynamically variant scatterers. To overcome this challenge, new estimation bounds, joint detection-tracking formulations, sensing-based waveform and beamforming designs are necessary, which remain compatible with simultaneous communication and energy delivery. In particular, the interaction between multi-target resolvability, sensing latency, and energy transfer efficiency is not well-known and worth exploring further. At the network level, the extension of ISCAP from a single hybrid access point to multi-cell and multi-user deployments with massive MIMO, RIS, and coexisting RF and optical links introduces significant complexity. An efficient operation in such scenarios requires low-complexity coordinated beamforming, interference management, and user/target scheduling strategies, which consider jointly sensing, communication, and powering performances. The future research directions include hierarchical or distributed optimization frameworks, scalable scheduling mechanisms for large IoT devices, and cross-layer designs where medium access control and routing protocols are jointly optimized with ISCAP waveform and beamforming strategies, which leverages over-the-air computation and edge intelligence.

Robustness, security, and hardware implementation create another critical challenges to realize ISCAP. In terms of robustness, future ISCAP transceivers and RIS-assisted architectures must explicitly consider imperfect channel state information, angular mismatch, Doppler uncertainty, environmental clutter, and hardware impairments such as phase noise, nonlinear power amplifiers, low-resolution data converters, and finite-precision phase shifters. This motivates a shift from nominal designs toward robust or stochastic optimization frameworks that jointly protect sensing and communication performance under uncertainty. Security is also an emerging concern, as the triple-functional nature of ISCAP introduces new attack scenarios. In particular, sensing and energy beams can serve as information leakage channels or be exploited by adversaries for spoofing and jamming. Thus, a mechanism of physical layer security is required, including joint secure beamforming and artificial noise design, exploitation of near-field or distance-domain characteristics, and cross-layer approaches that fuse sensing outputs with adaptive security policies. Practical implementations on the hardware to implement operative ISCAP systems would be energy-conscious and cost-effective systems, including hybrid analog-digital or switch-based massive MIMO, low-power RF chains, and self-sustained or zero-energy intelligent surfaces that use their own energy to enable them to manage and sense themselves. A stable operation under highly variable harvested power conditions necessitates tight co-design of rectifiers, power management circuits, transceiver architectures, and higher-layer protocols. Finally, cross-domain RF-optical ISCAP remains largely unexplored. Combining the wide coverage and robustness of RF systems with the high bandwidth and interference isolation of optical links raises fundamental questions on joint mode selection, spectrum partitioning, and resource allocation. Moreover, multi-wavelength optical ISCAP with co-optimized laser diode, photodetector, and photovoltaic front-ends represents a promising avenue toward heterogeneous 6G networks that fully exploit the complementary strengths of RF and optical technologies.

IV. Conclusion

This survey presents recent developments in ISCAP across four key areas: waveform design, MIMO-enhanced architectures, RIS-assisted systems, and optical ISCAP. The advancement in waveform design demonstrates a potential scheme based on OTSM in conjunction with DDAM, which can jointly support sensing accuracy, communication reliability, and efficient power delivery. MIMO-enhanced ISCAP further leverages spatial DoF to balance the CRB performance and harvested energy, while hybrid beamforming and secure near-field processing enable practical and robust implementations. Meanwhile, RIS-assisted and SAZE-RIS architectures introduce environment reconfigurability that enhances multi-user coverage, sensing quality, and energy transfer efficiency with minimal overhead power consumption. Finally, the first experimental demonstrations of optical ISCAP highlight a promising new direction for high-bandwidth, interference-free integration of communication, ranging, and optical power transfer. In general, our review shows that ISCAP is rapidly evolving toward highly integrated, multifunctional systems and the researches on joint waveform-beamforming design, intelligent surfaces, energy-efficient architectures, and cross-domain optical-RF integration will be essential to realize ISCAP as a core technology for future 6G networks.

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