

Dual Function of Sensing and Backscatter Communication in Cellular Networks

Diluka Galappaththige, Shayan Zargari, and Chintha Tellambura

Abstract—With rapidly advancing ambient-powered Internet of Things (IoT) and wireless networks, the synergy between sensing and backscatter communication (BackCom) has emerged as a research frontier. This study thus delves deep into integrating sensing functionalities with BackCom, leading to the Integrated Sensing and Backscatter Communication (ISABC), a burgeoning field with significant implications for ambient IoT networks. By drawing parallels between radar sensing and BackCom, fundamental insights into ISABC and its functionalities are attained. Additionally, various possible ISABC system configurations, applications, and future research directions are delineated. Furthermore, a quantitative analysis of system performance and qualitative communication and sensing performance assessments are provided. The proposed ISABC framework demonstrates enhanced performance and adaptability across diverse applications, a pivotal attribute for future IoT applications.

Index Terms—Ambient-powered Internet of Things, Integrated sensing and communication, Backscatter communication.

I. INTRODUCTION

Integrated sensing and communication (ISAC) has been recognized as one of the six main next-generation wireless technology trends by the *ITU-R M.2516* technical report [1]. Moreover, the 3GPP has opened a new ISAC study item, outlining the potential applications in several areas, including indoor (e.g., home, office, and factory), highway (e.g., automotive, traffic monitoring, and intrusion detection), high-speed railway (e.g., autopilot and intrusion detection), weather forecast (e.g., rainfall and flooding) unmanned aerial vehicles (e.g., flight trajectory tracing and collision and intrusion detection), traffic management (e.g., tourist/sports hot-spot detection and car parking), health monitoring (e.g., heart-beating, breathing, and sleeping), and extended reality (e.g., gaming and metaverse) [2].

The 3GPP Release 19 RAN-1 study considers six main ISAC configurations/topologies to facilitate sensing in communication systems [2], [3]; (i) mono-static sensing via user equipment (UE), (ii) mono-static sensing via next-generation Node B (gNB), (iii) bi-static sensing from gNB to UE, (iv) bi-static sensing from UE to gNB, (v) bi-static sensing from gNB to gNB, and (vi) bi-static sensing from UE to UE. The IEEE also formed a WLAN sensing workgroup to exploit the physical layer and medium access control layer attributes of IEEE 802.11 stations to acquire measurements that may be used to estimate the features (e.g., range, velocity, angular, motion, etc.) of objects (e.g., human, animal, etc.) in areas of interest (e.g., home, enterprise, vehicles, etc.) [4]. Thus, the

progress and attention given to ISAC by standards organizations indicate the potential and significance of merging sensing and communication into a cohesive framework.

Conversely, ambient power-enabled (i.e., battery-free) Internet of Things (IoT) has become an active research area as the 3GPP launched new study items [5]. These networks connect devices that can sense, collect, and communicate information about their surroundings autonomously. They are equipped with sensors and microprocessors, allowing them to communicate and share data in real-time. Ambient IoT networks have numerous applications, such as smart homes and cities, industrial IoT, and healthcare. For example, ambient IoT devices track patients' vital signs and activities and alert medical personnel to potential health issues.

IoT devices powered by batteries must be changed or recharged manually, increasing maintenance costs, environmental issues, and even safety hazards (for example, wireless sensors for the electricity and petroleum sectors). Conversely, existing cellular devices with a peak power consumption of 10 mW might not perform well with energy harvesting (EH) techniques due to their low output power, i.e., typically ranges from 1 μ W to a few hundred μ W [5]. As a remedy, battery-free devices with no energy storage capabilities, known as passive devices, or devices with limited energy storage, known as semi-passive devices, will accommodate massive connectivity demands [6]. Specifically, such backscatter communication (BackCom) systems may allow future ambient IoT networks and applications, including smart homes, cities, autonomous vehicles, industrial IoT, healthcare, etc. [5]. These applications require not just low-power connectivity but also superior sensing capabilities. A smart-home sensor, for example, may move and measure temperature in various areas, allowing the network to extract critical sensing/state information like range, velocity, or angle for tracking and environment learning and mapping.

Integrated sensing and backscatter communication (ISABC) has recently been proposed for facilitating the simultaneous sensing and communication tasks in ambient power-enabled IoT networks [7]. Specifically, this paradigm utilizes reflections (i.e., backscatter) of tags to estimate their state parameters. This differs from ISAC, which uses random target reflections. ISABC thus allows opportunistic sensing in BackCom systems, employing tag-reflected and/or unintentionally reflected signals.

This study comprehensively explores ISABC, examining its potential to revolutionize IoT by integrating sensing capabilities with BackCom. This work addresses several fundamental questions about ISABC: (i) What motivates the integration of sensing with BackCom? (ii) What are the commonalities between BackCom and radar/sensing? (iii) Why is integrating

D. Galappaththige, S. Zargari, and C. Tellambura with the Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, T6G 1H9, Canada.

BackCom and sensing beneficial compared to cellular networks? (iv) What are the benefits and drawbacks of ISABC? (v) What are the configurations and applications of ISABC? Additionally, what are the future research directions for IS-ABC?

These critical concerns have remained largely unexplored, as ISABC is still in its infancy [7]. This paper builds on that foundation to offer deeper insights into the technical framework and potential of ISABC for next-generation IoT networks.

II. RADAR SENSING AND BACKCOM

Before delving into these questions, comparing and contrasting conventional radar sensing and BackCom is worthwhile.

A. Radar Sensing

Radar (radio detection and ranging) is a system that uses electromagnetic (EM) waves to detect, locate, and track objects. It transmits a narrow beam of EM energy toward targets, such as aircraft, ships, vehicles, or weather phenomena, and observes the reflected echoes [8]. The radar receiver, often near the transmitter but sometimes separate, captures these reflections to determine an object's distance, speed, direction, and size. A signal of interest comprises the reflected signal from a target, such as an airplane, while the reflected signals from other sources, like the ground or rain, act as interference, which degrades target detection performance [8]. Some radar systems time-share a single antenna for transmitting and receiving [8]. Radar is widely used in navigation, weather forecasting, military operations, and traffic control.

The performance of a radar system primarily depends on its resolution, which is its ability to distinguish closely spaced targets [8]. Resolution is determined by range, angular, and Doppler resolution. Range resolution depends on pulse duration, with shorter pulses providing better resolution; for example, a 1 μ s pulse achieves about 150 m resolution [8]. Angular resolution is influenced by the antenna's beamwidth, with narrower beams offering finer resolution, typically from a few degrees to less than 1°. Doppler resolution differentiates between targets moving at different speeds. Factors like frequency bandwidth and antenna size also affect resolution [8]. For instance, weather radar typically achieves 1° angular resolution and 150 m range resolution, while military radars can achieve angular resolutions as fine as 0.1° with range resolutions in the hundreds of meters [8].

In 3GPP, the concept of ISAC involves the dual functionality of communication and radar-like sensing. Specifically designed signals may be employed for communication between two geographically separated devices, such as gNB(s)/UE(s), while also enabling these devices to perform radar-like sensing [2], [3]. The sensing function can be executed in either a mono-static or bi-static manner. In the former, the same device conducts both signal emission and radar-like sensing (i.e., radar reception). In the latter, two geographically separated devices carry out signal emission and sensing. Consequently, various combinations of devices, such as gNB(s)/UE(s), may

engage in communication and sensing in either a mono-static or bi-static topology [3].

Traditionally, radar-based sensing and the ISAC rely on processing reflected signals from objects/targets for sensing/detection. These sensing functions can be executed in a mono-static or bi-static topology (Section IV).

B. BackCom

BackCom networks use backscatter devices (tags) that do not generate their radio frequency (RF) signals. Instead, tags reflect and harvest external RF signals. The reflections encode the data bits, which is done by adjusting the impedance presented to the antenna [9]. Moreover, tags harvest energy by absorbing part of the external RF signal. Such EH and backscatter modulation achieve ultra-low power operations. For instance, such a tag has ultra-low power consumption ranging from nW to μ W, short communication ranges of up to 6 m, and low data rates of up to 1 bps/Hz [9]. Thus, tags can operate without batteries and EH only. This leads to three design types: (i) passive tags without energy storage, (ii) semi-passive tags with limited energy storage, and (iii) active tags with energy storage and independent signal generation capabilities. Devices of types (i) and (ii) employ BackCom without independent signal generation, whereas devices of type (iii) utilize active components for their own RF signal generation¹ [5], [9].

In addition to tags, a reader and an emitter are required. These have active RF components and do not rely on EH. The emitter (the RF source) transmits the RF signal that the tags reflect (type (i) and (ii)). The emitter can be a dedicated beacon signal producer or an ambient transmitter, such as a TV tower or a cellular base station (BS). The reader performs demodulation and decoding of data from tags. BackCom has three main configurations, each tailored for specific application scenarios, i.e., mono-static, bi-static, and ambient [9]. The emitter and reader are co-located in a mono-static BackCom setup, whereas in a bi-static setup, they are separated. In ambient BackCom, an ambient RF source is utilized instead of a dedicated RF source.

C. Relationship Between Radar Sensing and BackCom

Both BackCom systems and radar systems rely on reflected signals for data detection/decoding and target detection, respectively, creating a direct relationship between BackCom and radar functions. Additionally, both systems employ mono-static and bi-static topologies, making practical deployment and integration into existing systems more feasible. These similarities at the signal and topological levels prompt the exploration of the potential and feasibility of obtaining sensing/state parameters (such as the target's location, velocity, etc.) of backscatter tags using their reflected/echo signals [7]. For instance, state parameters can be extracted from backscattered signals, which also carry data, by exploiting the properties,

¹As the type (iii) devices do not rely on backscattering, we only consider the type (i) and (ii) devices in this study. For more information on the fundamentals of BackCom and tags types, interested readers can refer to [9] and the references therein.

such as time of arrival (ToA), angle of arrival (AoA), angle of departure (AoD), time difference of arrival (TDoA), received signal strength (RSS), and Doppler frequency/shifts [10].

In contrast, conventional cellular uses modulated RF signals primarily optimized for communication. Physical resources like time, frequency, spatial, bandwidth, signal power, etc., would be needed when introducing sensing. Thus, integrating sensing into conventional cellular, i.e., ISAC, necessitates a performance trade-off: improved sensing performance comes at the cost of communication performance and vice versa. BackCom signals behave similarly to radar or sensing signals, especially when modulated by on-off keying [8], [9]. While meeting the communication performance requirements through backscattering technology, the reflected signals can also be leveraged to enhance sensing performance. In essence, combining BackCom with sensing functionality represents an ISAC system with practical applications. Unlike conventional BackCom, sensing in a BackCom system is an additional service. Therefore, this approach's properties and advantages motivate the integration of sensing into BackCom, thus introducing the unique paradigm of ISABC.

III. INTEGRATED SENSING AND BACKSCATTER COMMUNICATION

ISABC differs from standard ISAC systems in incorporating tags and sensing. It thus combines the strengths of both ISAC and BackCom. The sensing in ISABC can be either tag-based or non-tag object-based (i.e., an external target/object not registered with the radio network). Specifically, in tag-based sensing, traditional sensing/radar targets in ISAC systems are replaced with backscatter tags. This falls under the umbrella of device-based ISAC [11]. Conversely, non-tag object-based sensing utilizes the transmitted signal for BackCom to sense unregistered external targets/objects in the surroundings. This belongs to the device-free ISAC category [11]. However, both enable opportunistic sensing, i.e., using accidentally reflected signals to learn and map the environment [7].

Conventional ISAC systems sense either passive objects, such as vehicles, which neither transmit nor receive sensing signals, or active devices, such as mobile phones, which engage in transmitting and/or receiving [11]. In contrast, tag-based ISABC pivots around backscatter tags. Thus, the backscatter tags serve as the sensing targets, conveying additional data to the user/reader while allowing the emitter/reader to estimate the tags' state information [7]. This is essential in applications such as smart homes, warehousing, and more, where tracking and environmental mapping are required [2]. For example, in a smart home, a tag could be a sensor that transmits background information to the user/reader. The emitter (or reader) can use the tag-reflected signals for estimating its state information, such as range, velocity, or angle, to track or map and monitor the environment. Conversely, non-tag object-based ISABC resembles conventional device-free ISAC systems. However, the shared characteristics between backscatter and radar-sensing signals provide greater flexibility than standard cellular signal-based ISAC systems [8].

Furthermore, ISABC systems enhance communication and sensing capabilities by harnessing sensing and backscatter data

[7]. However, the RF source and/or reader/user may need more advanced decoding mechanisms, such as self-interference (SI) cancellation and successive interference cancellation (SIC) (Section IV) [7]. ISABC, conversely, utilizes the unintentionally received backscattered signals at the BS or reader for sensing purposes, needing no additional RF resources, hardware cost, or modifications to backscatter tags [7]. ISABC builds upon these foundational frameworks.

As mentioned above, sensing in ISABC systems can be classified into two groups based on the sensing objective, i.e., (i) sensing tag(s) and (ii) sensing non-tag object(s).

Sensing tag(s): The objective is to sense/acquire the tag's sensing/state information, such as location, range, velocity, etc., using its backscattered signal. The data is embedded in the backscattered signal from a tag. Such signals optimized for BackCom purposes are expected to have poor sensing performance and vice-versa. Therefore, there is an inherent trade-off between communication and sensing with tag signals (i.e., data-embedded signals) for the dual function of sensing and communication.

Sensing non-tag object(s): The intention is to utilize backscatter signals to sense non-tag objects/targets. The carrier signal emitted for BackCom of the tags is also reflected by other objects/targets in the environment, i.e., the objects that do not manipulate the radio signals (not-a-tag). Such signals reflected by the objects/targets can be detected by the reader and/or carrier emitters/RF sources for sensing purposes. Therefore, the carrier being transmitted for BackCom can be used for sensing non-backscatter objects.

It is important to emphasize that signal processing techniques required to sense a tag differ notably from those used for sensing non-tag objects [10]. For instance, in mono-static sensing by the carrier emitter or in bi-static sensing by the reader, and tag communication in bi-static topology, the signals received from the tag and the sensing object are superposed over two distinct channels (Section IV). Conversely, when sensing a tag (with the tag being the sensing target) with bi-static communication, radar-like receiver processing is conducted at the reader in bi-static sensing, alongside data detection/decoding. Here, the reader may enhance sensing performance by leveraging information regarding the communication link, such as channel parameters (e.g., path loss, AoA/AoD estimates, etc.) [10].

Tagging billions of objects can be costly, impractical, and inefficient in hardware use [2]. Examples include tagging each package in an online retailer's warehouse or monitoring livestock on farms. Installing a tag circuit may be unfeasible in specific applications, such as remote health monitoring or detecting animal intrusions on highways [2]. Thus, depending on the scenario, using sensing tags, sensing non-tagged objects, or a combination of both is often more feasible, cost-effective, and efficient in terms of hardware and power usage.

Extracting sensing information from low-power backscatter signals poses many technical challenges due to low signal strength, interference, environmental noise, and power constraints. These challenges are particularly critical in dynamic and cluttered environments where weak backscatter signals may suffer from significant degradation. However, the parallels

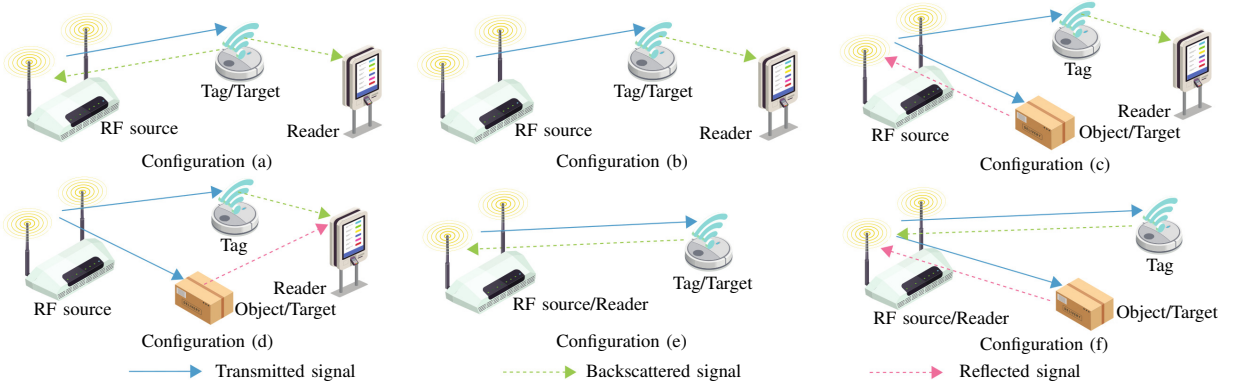


Fig. 1: ISABC system configurations.

between radar echoes and backscatter signals, as well as advances in radar technologies, offer promising solutions for ISABC [8]. Techniques such as adaptive filtering, coherent detection, and beamforming can enhance signal strength and mitigate interference, while multi-antenna arrays and interference mitigation strategies like frequency-hopping and spread spectrum techniques improve signal integrity in noisy environments [8]. Addressing power constraints, energy-efficient hardware designs and the use of ambient-powered backscatter devices ensure that sensing and communication operations can be sustained without compromising performance [6], [9]. Furthermore, robust signal processing algorithms, including spatial filtering and multi-path interference cancellation, enable ISABC systems to operate reliably in complex environments, distinguishing between desired reflections and noise [6], [8], [9]. By leveraging established radar methodologies and adapting them to backscatter systems, these challenges can be effectively mitigated, laying a strong foundation for ISABC's deployment in real-world applications.

In summary, the pioneering concept of ISABC harnesses the advantages of both BackCom and sensing, paving the way for many novel applications in wireless networks.

IV. ISABC SYSTEM CONFIGURATIONS

There are six configurations based on the sensing objective (tag or non-tag object), sensing detector (RF source or reader), and mono-static or bi-static sensing (Fig. 1): (a) Mono-static sensing and bi-static BackCom with co-located tag and sensing target, (b) Bi-static sensing and bi-static BackCom with co-located tag and sensing target, (c) Mono-static sensing and bi-static BackCom with separated tag and sensing target, (d) Bi-static sensing and bi-static BackCom with separated tag and sensing target, (e) Mono-static sensing and mono-static BackCom with co-located tag and sensing target, and (f) Mono-static sensing and mono-static BackCom with separated tag and sensing target. For configurations (a)-(d), the direct link between the RF source and the reader may be utilized for primary communication, i.e., the communication between the RF source and the reader/user. Table I summarizes each configuration's sensing objective, functionalities, and technical requirements.

Configuration (a) – Mono-static sensing and bi-static BackCom with co-located tag and sensing target: The objectives are to obtain the tag's state information by exploiting

its backscattered signal at the RF source and any data the tag intends to transmit, e.g., if the tag is attached to a parcel, information such as parcel ID, temperature, or address, at the reader. The sensing occurs at the RF source, operating either in half-duplex (HD) or full-duplex (FD) mode. In HD mode, the RF source sends the signal and becomes silent like in a regular radar. The tag uses this intermittent RF source for tag data transmission. However, FD operation is required for continuous or long-term carrier emission scenarios. Thus, the main challenge is to mitigate SI due to simultaneous transmission and reception. Before sensing, the RF source has to employ SI cancellation techniques.

Configuration (b) – Bi-static sensing and bi-static BackCom with co-located tag and sensing target: The intent is to acquire the tag's state information and backscatter data by capturing its backscattered signal at the reader. As both data decoding and sensing happen at the reader, direct transmission interference must be minimized. The reader must utilize SIC to reduce interference. In addition, since the tag's backscattered signal is used for both data decoding and sensing, the reader must strike a compromise between BackCom and sensing performance.

Configuration (c) – Mono-static sensing and bi-static BackCom with separated tag and sensing target: This system gathers state information about the non-tag object/target by capturing reflections of the RF source's transmitted signal at the source. Sensing takes place at the RF source, hence it requires FD mode and SI cancellation methods.

Configuration (d) – Bi-static sensing and bi-static BackCom with separated tag and sensing target: This acquires state information about the non-tag object/target by utilizing reflections of the transmitted signal from the RF source at the reader. Because the sensing occurs at the reader, it must minimize interference from direct and backscatter transmissions, necessitating SIC.

Configuration (e) – Mono-static sensing and mono-static BackCom with co-located tag and sensing target: The reader and RF source are co-located. The objective is to obtain the tag's state information by capturing its backscattered. As the sensing and backscatter data decoding occur at the RF source, the RF source must employ SI cancellation to minimize SI before sensing. In addition, since the tag's backscattered signal is used for both data decoding and sensing, the RF source must strike a compromise between BackCom and sensing

TABLE I: ISABC system configurations and their technical requirements.

Configuration	Sensing objective	RF source function(s)	Reader function(s)	Technical requirements
(a)	Sensing tag(s)	Transmitting and sensing	Data decoding	SI cancellation at the RF source is required to mitigate the SI before performing sensing
(b)	Sensing tag(s)	Transmitting	Data decoding and sensing	SIC at the reader is necessary to eliminate interference from backscatter data before performing sensing
(c)	Sensing non-tag object(s)	Transmitting and sensing	Data decoding	SI cancellation and SIC at the RF source are needed to minimize the SI and interference from the tag's backscattered signal before performing sensing
(d)	Sensing non-tag object(s)	Transmitting	Data decoding and sensing	SIC at the reader is needed to mitigate interference from the tag's backscattered signal before performing sensing
(e)	Sensing tag(s)	Transmitting, data decoding, and sensing	–	SI and SIC at the RF source/reader are needed to mitigate SI and interference from the tag's backscattered signal before performing sensing
(f)	Sensing non-tag object(s)	Transmitting, data decoding, and sensing	–	SI and SIC at the RF source/reader are needed to mitigate SI and interference from the tag's backscattered signal before performing sensing

performance.

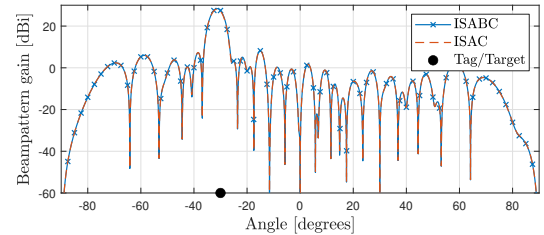
Configuration (f) – Mono-static sensing and mono-static BackCom with separated tag and sensing target: A co-located reader and RF source are used. The goal is to acquire state information about a non-tag object/target by utilizing reflections of the transmitted signal. Since both sensing and backscatter data decoding occur at the RF source, the RF source must employ SI cancellation and SIC to mitigate SI and backscatter interference before performing sensing.

Table II presents a concise comparison of the mono-static (i.e., (a), (c), and (e)) and bi-static (i.e., (b), (d), and (f)) ISABC configurations, evaluating their sensing accuracy, energy efficiency, deployment cost, multi-path interference, signal blockages, signal processing, scalability in complex environments, and deployment complexity.

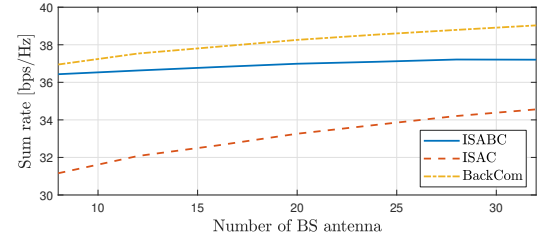
V. ISABC FEASIBILITY STUDY

To investigate the feasibility and performance of ISABC configuration (a), simulation examples are presented. The comparative benchmarks are conventional ISAC and BackCom systems. The BS with M antennas, the single-antenna user/reader, and the single-antenna tag are placed at $\{0, 0\}$, $\{12, 0\}$, and $\{5, -2.8\}$, respectively. The sensing direction from the BS to the tag/target is thus -30° . The communication-only channels, i.e., RF-source-reader and tag-reader, are modeled as Rayleigh fading, whereas the channels between the RF-source and tag, i.e., both forwards and reflected, are modeled as line-of-sight (LoS) channels [12]. Other simulation parameters can be found in [12].

For simplicity of discussion, a typical scenario where a BS transmitting a signal \mathbf{x} intended for a user, where $\mathbf{x} = (1 - \beta)\mathbf{w}x_d + \beta\mathbf{s} \in \mathbb{C}^{M \times 1}$ is considered. Here, $x_d \in \mathbb{C}$ is the data symbol for the user/reader with unit power, i.e., $\mathbb{E}\{|x_d|^2\} = 1$, $\mathbf{w} \in \mathbb{C}^{M \times 1}$ is the BS communication beamformer associated with the user and the tag (backscattering), and $\mathbf{s} \in \mathbb{C}^{M \times 1}$ is the dedicated sensing signal with covariance matrix $\mathbf{S} \triangleq \mathbb{E}\{\mathbf{s}\mathbf{s}^H\}$ [12], [13]. Covariance \mathbf{S} is designed to increase the degrees of freedom of the transmit signal to enhance sensing performance. Moreover, $\beta \in [0, 1)$ is an indicator variable that enables or disables sensing depending on the system as well as a power allocation coefficient for sensing and communication, i.e., $\beta \neq 0$ for ISABC and ISAC



(a) Beampattern gain.



(b) Sum rate versus the number of BS antennas.

Fig. 2: Beampattern gain and sum rate performance comparison of ISABC, ISAC, and BackCom.

systems while $\beta = 0$ for BackCom system. In the ISABC system, direct (i.e., BS-to-user) link and BackCom (i.e., tag-to-user) link rates are achievable at the reader while sensing is performed at the BS with $\beta \neq 0$. In the BackCom system, due to the absence of sensing (i.e., with $\beta = 0$), only direct link and BackCom link rates are achievable at the reader, i.e., no sensing at the BS. In the ISAC system with $\beta \neq 0$ and conventional target, only the direct link rate is achievable at the reader while sensing is performed at the BS, i.e., no BackCom link.

We maximize the communication sum rate while meeting a sensing rate target and adhering to the BS power constraint. For ISABC and BackCom systems, both direct and backscatter rates are considered. In contrast, only the direct link rate is considered for the ISAC system.

Fig. 2a shows the transmit-receive combined beampattern gains [13, Eqn. (45)] for ISABC and ISAC. Observe that the highest beampattern gain is achieved in the target/tag direction at an angle -30° . Interestingly, ISABC achieves almost the same beampattern gain as the ISAC, i.e., introducing a sensing target into a BackCom system does not adversely affect sensing performance. Intuitively, the backscattered tag signal

TABLE II: A comparison of mono-static and bi-static ISABC configurations.

Feature	Mono-static ISABC configurations	Bi-static ISABC configurations
Sensing accuracy	- High accuracy for range and time-of-flight measurements. - Simple signal interpretation.	- Can provide more detailed target information from different angles. - Requires more complex processing for range and positioning.
Energy efficiency	- More energy-efficient due to a single device handling both transmitting and receiving. - No synchronization.	- Requires more energy to operate separate transmitter and receiver. - Additional energy is needed for synchronization between devices.
Deployment cost	- Lower deployment due to a single device. - Simplifies infrastructure and reduces hardware costs.	- Higher deployment cost as separate hardware at transmitter and receiver. - More infrastructure required for synchronization.
Multi-path interference	- More prone to multi-path fading, as transmission and reception occur along the same path. - More interference in cluttered environments.	- Less affected by multi-path interference due to spatial separation of the transmitter and receiver. - Can capture stronger reflections from different paths.
Blockages	- More susceptible to signal loss if an obstacle blocks the direct path between the transmitter and target.	- More robust to blockage, as the signal can still reach the receiver via alternative paths.
Signal processing	- Easier signal processing due to direct transmission and reception paths. - Simpler time-of-flight and range calculations.	- More complex processing is needed to account for the separate transmitter-receiver geometry. - Requires advanced algorithms to determine target distance and position.
Complex environments	- Suitable for open or controlled environments where obstacles and interference are minimal (e.g., indoor, rural).	- Ideal for cluttered or urban environments where obstacles are common and NLoS detection is beneficial.
Deployment complexity	- Simple to deploy with a single device for transmitting and receiving. - Easy to maintain.	- More complex to deploy and synchronize separate devices, requiring careful alignment and coordination.

Note that the comparisons are based on general characteristics of mono-static and bi-static ISABC configurations and may vary depending on the system design, parameter configurations, and algorithms employed.

behaves similarly to ISAC radar/sensing signals.

Fig. 2b shows the communication sum rate versus the number of BS antennas for the three systems, with the BS at 30 dBm. More BS antennas raise the sum rate due to spatial multiplexing gains. ISABC outperforms ISAC without sacrificing sensing performance. For instance, with 20 BS antennas, it enhances the sum rate by 11.2% compared to ISAC.

However, the ISABC system achieves a slightly lower sum rate than the conventional BackCom system, e.g., 3.3% less with 20 BS antennas, due to power allocation to the sensing signal (i.e., $\beta \neq 0$). Nevertheless, ISABC offers highly accurate sensing capabilities, which conventional BackCom systems lack.

This example demonstrates ISABC systems' feasibility and performance benefits compared to classical ISAC and BackCom. In conclusion, ISABC without sacrificing sensing constraint/target achieves a better rate than ISAC, and therefore, integrating backscattering with sensing is beneficial.

VI. ISABC APPLICATIONS

ISABC can facilitate every application that both conventional BackCom and ISAC support (Fig. 3).

Smart agriculture: Irrigation and disease control demand real-time data on environmental factors such as soil moisture, humidity, temperature, and climate changes [14]. Wireless sensor networks, including BackCom, can monitor these parameters. However, to create real-time maps and images of the agricultural field, knowing the sensors' locations is essential for analyzing micro-climate conditions. Deploying ISABC devices over large farms allows detailed insights without significant energy use or frequent maintenance.

Supply chain and logistics: Real-time monitoring of processes such as purchasing, production, storage, shipping, distribution, sales, returns, farming, mining, hazardous environments, and port inventories is essential [9]. ISABC devices embedded in packages or containers provide continuous, energy-efficient monitoring of location, temperature, humidity, and tampering, surpassing labor-intensive methods like RFID and barcodes.

Smart homes/cities: Dense deployment of ISABC devices enables continuous sensing and communication for smart home and city applications [9]. Attached to walls, ceilings, furniture, or parking spaces, they monitor temperature, humidity, pollution, gas leaks, and traffic, enhancing functionality and quality of life. Battery-free with long lifespans, low maintenance costs, and minimal environmental impact, these devices are essential for diverse smart home and city applications.

Healthcare: ISABC finds various applications in healthcare, including object, staff, and patient monitoring, individual identification, automatic data collection, and wearable health monitoring. Devices without active RF components meet the demand for compact and low heat-radiation applications [11]. They enable real-time position tracking for patient-flow monitoring and mobility tracking at specific locations. ISABC ensures continuous inventory for drug maintenance, monitoring, and material tracking, reducing the risk of items being left behind during surgeries. Overall, ISABC offers significant benefits for the healthcare sector.

VII. FUTURE DIRECTIONS AND OPEN ISSUES

The section discusses future directions and open issues in ISABC, focusing on waveform/signal design, signal processing, and achieving dual sensing and communication functions.

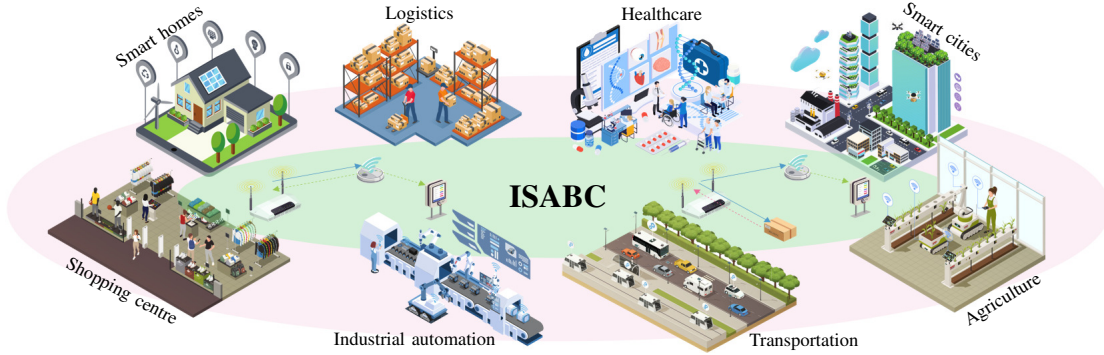


Fig. 3: ISABC applications.

Waveform/carrier signal design: BackCom relies on ambient or dedicated RF sources optimized for communication, limiting ISABC systems requiring waveforms for both communication and sensing [9]. Multi-functional waveforms can improve sensing resolution and communication performance. Advanced modulation schemes, such as OFDM and spread spectrum, enhance data rates while maintaining sensing integrity. Dynamic power allocation balances communication quality and sensing accuracy, ensuring efficient power use. Interference mitigation techniques, like adaptive beamforming and frequency-hopping, improve system reliability [11]. Adaptive waveform design further enhances performance in dynamic environments.

Key challenges include the absence of unified frameworks and the need for adaptive waveform design for dynamic environments. Future efforts should focus on developing unified frameworks for waveform optimization and exploring real-time interference cancellation and power control algorithms to ensure robust ISABC operation across various conditions.

Signal processing at the emitter/reader: Signal processing in ISABC systems varies across configurations, each presenting unique challenges and opportunities [9]. Configuration (a) requires advanced SI cancellation at the RF source to mitigate SI. Potential solutions include hybrid analog and digital SI cancellation techniques, where analog cancellation suppresses interference at the RF front end, and digital processing further reduces residual interference. This approach simplifies hardware by integrating sensing and communication at a single point.

In contrast, configuration (b) leverages spatial diversity but requires SIC at the reader to separate backscatter from sensing signals. Multiple-input and multiple-output (MIMO) technology can enhance spatial filtering, separating signals from multiple directions. Configuration (c) requires synchronization between the RF source and the reader. A potential solution involves estimating time delays through correlation methods and phase alignment algorithms to maintain coherent signal processing. Configuration (d) necessitates complex signal processing at the reader to differentiate between signals reflected by the tag and the sensing target. Machine learning-based signal separation and adaptive filtering techniques may enhance accuracy. Configuration (e) requires SI and SIC at the RF source/reader but integrates both functions into a single device. Finally, configuration (f) involves SI cancellation and SIC to handle separated signal paths, allowing diverse applica-

tion scenarios with high accuracy in both sensing and communication. Combining MIMO with beamforming can improve interference mitigation and enhance both communication and sensing performance.

Achieving dual functions of sensing and communication: This goal requires advanced signal separation, channel estimation, and interference mitigation algorithms [11]. For example, signals can be separated in time, time, or space by orthogonal waveform designs. Moreover, non-orthogonal multiple access can minimize interference by separating signals in the power domain. For accurate channel estimation, pilot-based techniques, compressed sensing, and Kalman filtering offer efficient ways to map communication, backscatter, and sensing channels [11]. Beamforming and MIMO enhance spatial resolution and reduce multi-path interference by directing signals toward specific targets. Dual-functional radar-communication waveforms allow sensing and data transmission within the same signal, improving spectral efficiency. Future solutions may include ML-based signal separation to adapt dynamically and boost ISABC performance.

Key performance indicators (KPIs): Range accuracy, velocity measurement, and AoA are crucial for assessing the performance and reliability of ISABC configurations. For instance, ToA and TDoA can be used for precise range estimation [8]. In configuration (a), with mono-static sensing and bi-static BackCom setup involving a co-located tag and sensing target, ToA and TDoA accurately measure the distance between the RF source and tag/target. Based on Doppler shift analysis, velocity measurement is instrumental in dynamic environments. For example, in configuration (d), with bi-static sensing and separated tag and target, Doppler shift analysis tracks relative motion, estimating speed through frequency changes in reflected signals. Some configurations require a network node to achieve multiple objectives, such as simultaneous data decoding and parameter estimation (e.g., Reader) or generating dual-functional transmit waveforms/signals (e.g., RF source).

AoA estimation is essential for identifying the direction of incoming signals [8]. Techniques such as beamforming and high-resolution algorithms like multiple signal classification (MUSIC) process the received signal covariance matrix for precise AoA detection. MIMO systems improve spatial resolution and enable the detection of multiple targets by leveraging diverse signal paths. Additionally, sensor fusion and coherent processing across multiple receivers can further enhance AoA

accuracy and mitigate multipath effects.

Secure communication and sensing: Many networks, such as healthcare and supply networks, handle sensitive data, requiring enhanced security and privacy [11]. Common attacks on them include active jamming, passive eavesdropping, and security breaches. ISABC tags, with limited computing power, preclude advanced encryption schemes, leaving them vulnerable to threats that compromise performance and reliability. Traditional security methods, like cryptographic key sharing, may be revised to balance protection with simplicity. Despite existing BackCom research, developing security solutions for ISABC that align with its low-cost, low-power design remains challenging, and strategies to address active and passive attacks require further study.

For instance, lightweight encryption and physical layer security (e.g., signal interference or artificial noise) can offer basic protection without overburdening tags. Secure key exchange protocols for low-power devices and authentication schemes based on unique backscatter signal characteristics (e.g., channel state information) are promising. Distributed security approaches, where nodes collaborate to detect and mitigate attacks, can enhance system robustness. Additionally, secure beamforming can improve security while maintaining communication efficiency.

The above list is not exhaustive. Future ISABC research should prioritize developing hybrid signal processing techniques integrating ToA, TDoA, Doppler shift, and AoA estimation [8], [10]. By leveraging the strengths of these methods, sensing accuracy can be significantly enhanced and robust, paving the way for more reliable and versatile applications.

VIII. CONCLUSION

Ambient-powered IoT networks are emerging in the rapidly evolving digital landscape, powering new applications. Dual sensing and communication are critical parts of this. However, EH-based low-power devices must support the duality. ISABC has been proposed to address these needs by incorporating sensing into BackCom, which enables opportunistic sensing. The fundamentals of ISABC have been outlined, exploring the similarities between traditional radar sensing and BackCom. Furthermore, the features of ISABC, types of sensing information, various system configurations, prospective applications, and future research directions are highlighted. The feasibility of ISABC is also investigated through a simulation example, illustrating its advantages over traditional ISAC.

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Diluka Galappaththige [M] (diluka.lg@ualberta.ca) is a Postdoctoral fellow at the University of Alberta, Canada. He received his B.Sc. degree in electrical and electronic engineering from the University of Peradeniya, Sri Lanka, in 2017, and his Ph.D. in electrical and computer engineering from Southern Illinois University, USA, in 2021.

Shayan Zargari (zargari@ualberta.ca) is pursuing a Ph.D. in communications and signal processing at the University of Alberta, Canada. He received a B.Sc. in Electronic Engineering from Azad University, South Tehran, and an M.Sc. in Telecommunication Engineering from Iran University of Science and Technology in 2018 and 2020, respectively.

Chintha Tellambura [F] (ct4@ualberta.ca) is a Professor in the Department of Electrical and Computer Engineering at the University of Alberta. He received his M.Sc. degree in electrical engineering from the King's College, University of London, and his Ph.D. degree in electrical engineering from the University of Victoria, Canada. He has authored or co-authored over 600 journals and conference papers.