

A Survey on Integrated Sensing and Communication: Signal Processing Perspective

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Abstract. Integrated Sensing and Communications (ISAC) is a revolutionary technology that will be used in future wireless communication systems. It assimilates the features of communication and sensing strategies into a merged architecture. ISAC intends to redefine how equipment observes and collaborates with its related context. Researchers and engineers can leverage the same hardware, spectrum, and waveforms to optimise both services by integrating wireless sensing functionalities directly into communication devices. This convergence not only enhances the performance of mobile computing devices but also enables seamless communication and sensing capabilities. This paper covers the different use cases of ISAC related to the signal processing perspective, requirements and limitations.

Keywords: Integrated Sensing and Communication · 6G · Signal processing · Use cases

1 Introduction

Wireless communication systems have evolved drastically since the 1980s. These technologies, from 1G to 5G, have been used in various fields such as cellular mobile communication, biomedical, satellite communication, etc. With the realisation of 5G, wireless networks experience low latency, faster speed, and greater capacity with different resource allocation strategies. With the continuation of 5G, 6G supports the Internet of Everything (IoE) to transform the connected people and devices into connected intelligence. Also, 6G supports sensing applications such as indoor localisation for navigation, Wi-Fi sensing for smart home, and radar sensing for autonomous vehicles. Usually, the design and operating spectrums for sensing applications and communication systems are different [1]. Due to the strong deployment of millimetre Wave (mmWave) and massive Multiple Input Multiple Output (MIMO), communication signals have strong resolution in time and angle, which ensures high-accuracy sensing using communication signals. Therefore, it is possible to jointly design the communication and

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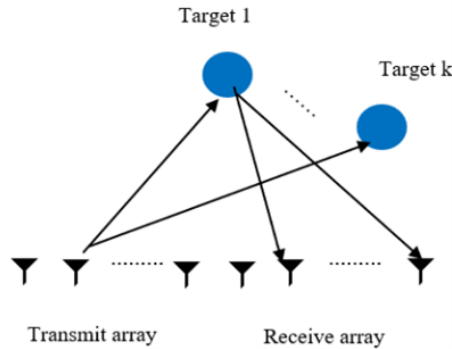


Fig. 1. Mono-static phased array.

sensing systems that can share the same frequency band and hardware, thereby enhancing spectrum efficiency further and reducing costs. These concepts result in the concept of Integrated Sensing and Communication (ISAC).

This article covers a comprehensive review of the recent research works on the signal processing perspective of the ISAC Systems.

2 Types of Integrated Sensing and Sensing

The sensing is categorised into two types such as device-free sensing and device-based sensing [2].

2.1 Device-free sensing

The sensing does not depend on the transmitter or receiver of the target in the case of device-free sensing. A few examples of device-free sensing procedures are phased array radar, MIMO radar and phased-MIMO radar.

In a phased array, many antennas are arranged at a specific wavelength, distances in such a way as to obtain a high-gain beam in a desired direction [3]. Depending on the transmitter and receiver setup up it is categorised as a mono-static phased array, as illustrated in Figure 1 and a bi-static phased array [2] as shown in Figure 2. If the same antenna array setup is utilised for transmission and reception, termed as a mono-static array, that is, the transmitter and receiver are placed together. If the transmitter and receiver phased array antennas are placed in different locations for sensing is called a bi-static phased array.

The decorrelated signals are transmitted from the MIMO radar to overcome the radar cross-section scintillations [4]. If the transmitter and receiver are placed in the same location, it is termed a collocated MIMO radar, as shown in Figure 3.

The transmit and receive antennas are distributed in different locations, and the spacing is greater than the wavelength. The diversity gain is enhanced by

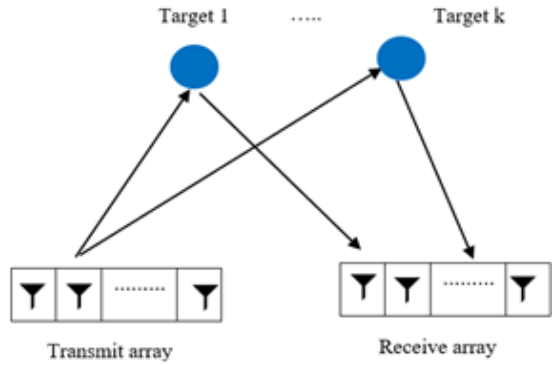


Fig. 2. Bi-static phased array.

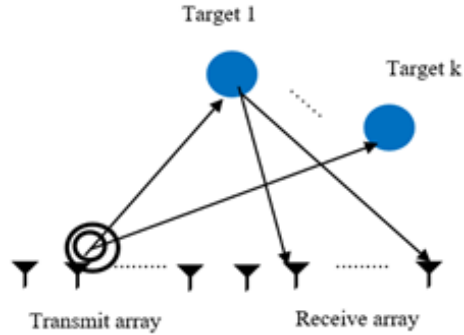


Fig. 3. MIMO distributed array.

sensing the target multiple times from different angles. Figure 4 shows the distributed MIMO radar.

The diversity gain and high beam gain could be achieved by combining the features of phased array and MIMO array [5]. In this structure, the phased-MIMO array is split into small sub-arrays. Every sub-array is designed to focus on the desired directions, thereby increasing the gain of the beam radiation. By transmitting different waveforms from the sub-array, diversity gain is obtained in the case of a phased-MIMO array.

2.2 Device-based sensing

In device-based sensing, the locations of the target device are estimated based on the reference signal transmitted between the target device and the reference device. The locations of the target can be obtained by the parameters such as time of arrival, angle of arrival, time difference of arrival and received signal strength.

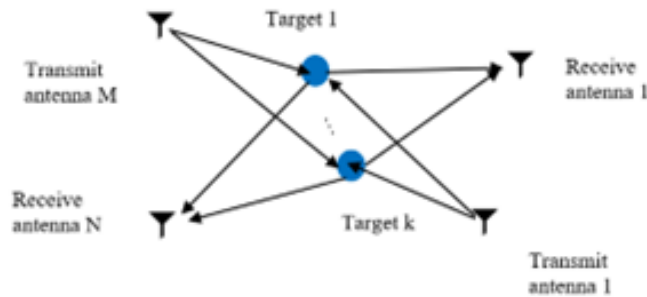


Fig. 4. Collocated MIMO array.

3 Use Cases and Applications

The potential use cases of the ISAC are discussed in this section [6].

3.1 Gesture Recognition in Industry

The communication between humans and robots has become essential in contemporary manufacturing, requiring effective synchronisation among humans, collaborative robots (cobots), and other robotic systems, as shown in Figure 5. Cobots are engineered to augment human abilities by performing repeated, physically demanding, or highly precise tasks in proximity to human workers. In factories, touch panels and portable devices may not work well because of protective gloves, having to do more than one thing at once, or loud conditions. Gesture-based interfaces let you engage with cobots without touching them, which is more natural. These interfaces use pattern recognition and object detection to understand pre-defined gestures that are related to certain activities. This makes it easy for people and cobots to work together. There are several types of gestures, such as hand and arm motions, body postures, head gestures, and face expressions. This makes communication more sophisticated. Gesture recognition systems need to make sure that security and data integrity are in place to stop anyone from getting in without permission and giving harmful instructions.

3.2 Vibration Monitoring in Industry

In factories, vibration monitoring is very important for keeping machines in good shape and running smoothly. Imbalances, misalignments, gear troubles, and environmental conditions may all generate vibrations. These vibrations can hurt factory and process automation, causing equipment to wear out, misalign, lower product quality, and process interruptions as shown in Figure 6. The benefits of the ISAC in vibration monitoring is summarised in Figure 7.

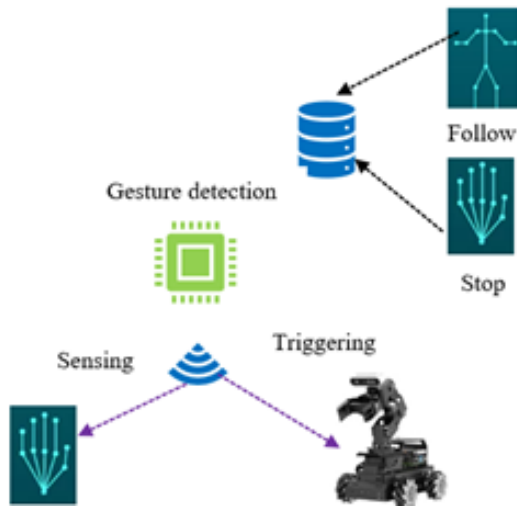


Fig. 5. Gesture Recognition in Industry.

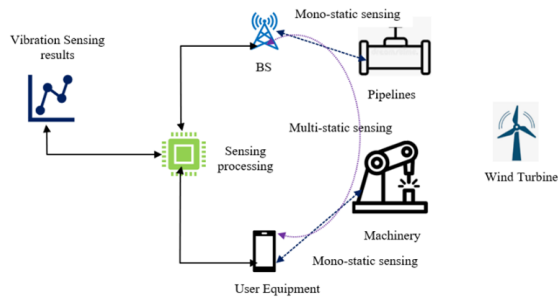


Fig. 6. Vibration Sensing in Industry.

3.3 Stockpiles Monitoring

In factories, keeping an eye on stockpiles is important for managing inventories, keeping people safe, and making operations go more smoothly. It helps with planning for buying and making things, keeps a steady supply of raw materials, and avoids overstocking and shortages. Keeping an eye on stockpiles also helps keep track of the amount and quality of materials, make sure they are safe for the environment, and keep people safe by preventing things like dust emissions or unstable stacks from happening. The benefits of the stockpile monitoring is illustrated as shown in Figure 8.

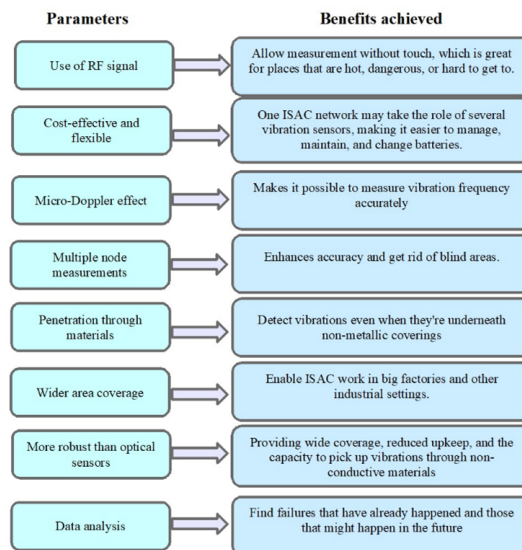


Fig. 7. Benefits of Vibration Sensing in Industry.

3.4 Flexible Production flow optimisation using ISAC

Flexible production processes are very important in today's manufacturing since they help satisfy consumer needs. The "Everything as a Service" paradigm in smart factories connects production systems, logistics, and staff management into a digital infrastructure that runs on a network and cloud platform. ISAC makes this even better by keeping an eye on the motions of people, carts, and AGVs all the time, which makes things safer and more efficient. ISAC keeps an eye on locations and movements in real time, which helps with production processes, safety rules, and resource management. Some of the benefits are:

- Better productivity by making choices based on data and optimising processes
- Less downtime by making it easier for materials to move around
- Keeping a safe distance between people and machines to avoid accidents

3.5 Prevention of Hazards in Industry

ISAC technology may greatly improve safety in factories by preventing dangers that might hurt workers or damage property. Safety in factories is very important since accidents may cause lasting damage or death. Electrocution, crashes, falls, and being in risky places for too long are all common safety dangers.

ISAC can find these dangers and let workers know or ask for help if they need it, as when someone falls or gets stuck. ISAC can keep an eye on the surroundings, find impediments, and keep track of worker movements by integrating radio

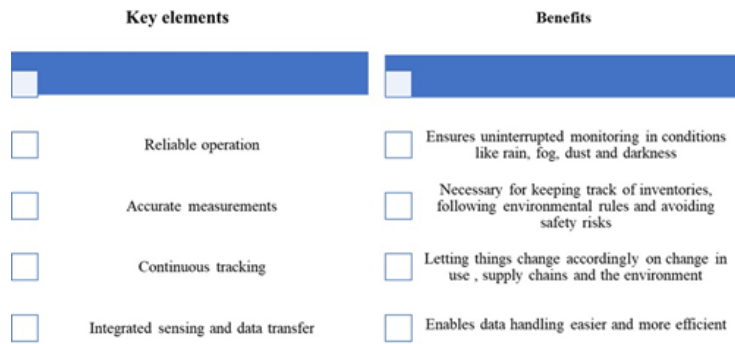


Fig. 8. Benefits of Stockpile Monitoring.

signals from base stations with data from other sensors, such cameras and gravity sensors.

The system works by setting a baseline for normal circumstances and then sending any unusual events to an application server for examination. Base stations can tell where an item is, how big it is, or how fast it is moving, but they need other sensors to get information about things like the weather, fires, gas leaks, or the identification of workers. For instance, workers may wear gravity sensors that set off warnings for falls, which base stations nearby can pick up.

Base stations and user equipment (UE) operate together to keep an eye on the area and the workers, finding obstructions, motions, and forecasting actions to help with coordination. In an emergency, the system sends important information such as emergency warnings, locations, and the best routes for getting help. ISAC helps keep industrial areas safe by promptly finding any dangers and sending out alerts when they are needed.

4 Requirements of Signal Processing

Signal processing in ISAC is essential, as it is utilised in numerous industry use cases. The commonly used signal processing techniques are discussed in this section [7].

4.1 Clutter removal

The goal of sensing applications is to find the targets by watching how they affect the wireless signal over time. In a rich scattering environment, the received radio signal may also include undesired echoes from things in the surroundings, in addition to the signal that is dispersed from the target. This includes the direct signal from the transmitter to the receiver. These unwanted signals might mess up the target sensing and make it less accurate since they don't have much information about the target. These propagation channels that aren't connected

Table 1. Summary of clutter removal algorithms.

Reference	Approach/Algorithm proposed
[8]	The spatial decoder is designed to enhance the signal-to-clutter ratio.
[9]	The static clutter is removed using background subtraction by taking the average of the inputs over time and then subtracting the average values from the inputs.
[10]	The plan was to get rid of the direct current (DC) part of the range-Doppler map from each range bin to cut down on the clutter.
[10]	Created the delay-line canceller method, which uses a filter to maintain the difference between two successive channel estimate coefficients so that the effect of static objects may be removed.

to the goal are called clutter. They come from static items in the environment. The summary of clutter removal is listed in the table1.

4.2 Range-Doppler Map

A range-Doppler map is a common method for processing radar that uses a matched filter to compare the received waveform with the broadcast waveform. There are two-time axes on a range-Doppler map: a fast time axis and a slow time axis. In each slow time occurrence, there is one received sample from one radar pulse, or one data processing unit (with a pilot signal and/or one data frame) in a communication waveform. various fast speeds are linked to various propagation delays or ranges. The identical collecting procedure happens again and over again on the slow time axis, with pulse interval TPRI. As illustrated in Figure 9, when the system has more than one reception channel because it includes more than one antenna element, the 2-D data matrix may be layered along these channels to form a 3-D data matrix. By looking at the correlations along the fast time axis, you can get the target’s delay and turn that into the distance the signal travels from the transmitter to the target and the receiver. After that, by setting the range bin along the fast time axis and performing a fast Fourier transform (FFT) along the slow axis for a certain coherent process interval (CPI) TCPI, the Doppler feature may be found for each range bin, which corresponds to a fixed delay bin. Beamforming may also be used on the received channels to acquire the target’s spatial attributes.

The range resolution is set by the fast time sampling rate. For instance, in a monostatic sensing deployment (where the transmitter and receiver are in the same place), the target range resolution may be found using the formula

$$\Delta_r = \frac{cT_s}{2} \quad (1)$$

where c is the speed of light and T_s is the sampling interval. The slow-time discrete-time Fourier transform (DTFT) retrieves the Doppler information of objects at a certain range.

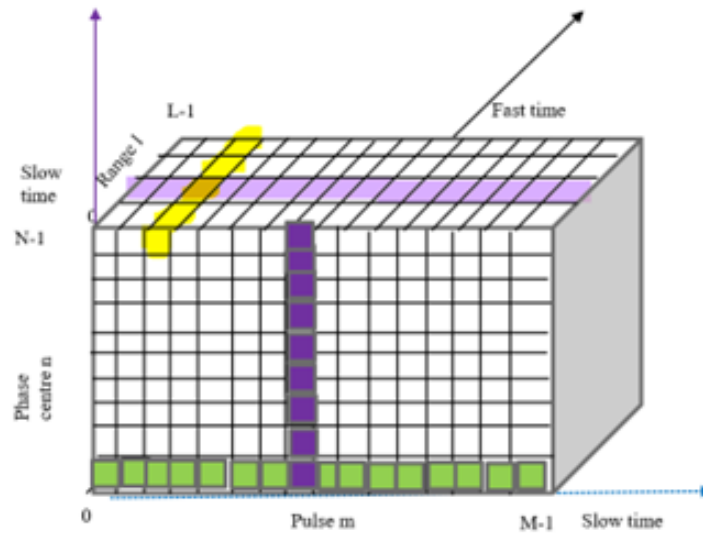


Fig. 9. Received data.

4.3 Sensing Parameter Estimation

There are a number of commonly used parametric estimating techniques that may be utilized to figure out sensor parameters. The techniques are summarized in the table.II.

4.4 Compressed Sensing

This sparsity-based sensing method works well when the target picture is sparse and just a few parameters need to be estimated, such delay, Doppler shift, AoA, Angle of Departure (AoD), and the amplitude of signal echoes from the target. When the target scene can be depicted with an appropriate sparse representation, measurements can be acquired below the Nyquist sampling rate, enabling reliable reconstruction of the target scene using sparsity sensing algorithms, including basis pursuit, convex optimization, and Bayesian approaches, among others [11, 12].

Compressed sensing applies to both on-grid and off-grid sensing. The on-grid sensing breaks the channel parameters down into a series of grid values. Off-grid sensing, on the other hand, may estimate continuous-value sensing parameters, but it is much more difficult to use in real time and requires a lot of computing power [16].

Compressed sensing is a common way to estimate the mmWave channel in mmWave communications by recovering sparse signals [17]. It has also garnered considerable attention in radar sensing to attain enhanced resolution and improved accuracy. When there is a lot of noise and a strong dominating clutter

Table 2. Sensing parameter estimation techniques.

Reference	Algorithm	Objective
[13]	CLEAN	<ul style="list-style-type: none"> – CLEAN is a computer program that breaks down a signal into its parts over and over again, assuming that the signal is made up of more than one part. – The processed signal is taken out of the signal space after the parameters are estimated in relation to the strongest signal component. – The processing goes on until a stop condition is reached. The CLEAN algorithm can do more than just wipe unwanted interference; it can also find weaker targets.
[14]	SAGE	<ul style="list-style-type: none"> – When there are a lot of factors to estimate, it's practically impossible to do a full search. The alternating-projections approach may be used to fix this problem. – The SAGE is an expectation-maximisation (EM) approach that finds the maximum-likelihood estimate (MLE). – It usually starts with the result of the CLEAN algorithm as an initial estimate and then goes back and forth between E and M phases until the entire process comes together. – SAGE improves the CLEAN estimate and gets rid of all the undesirable signals throughout the phases for estimating the parameter(s), but it costs more to do so.
[14]	RiMax	<ul style="list-style-type: none"> – It is another MLE approach that divides the parameters for dense and specular components into two independent sets. – It then estimates the parameters between these two sets to maximise the log-likelihood function. – RiMax works better than CLEAN and SAGE in a dense multipath environment, although it takes more time to compute.
[15]	MUSIC	<ul style="list-style-type: none"> – The noisy signal is divided into two parts: signal subspace and noise subspace. – Both use the spatial covariance matrix to figure out signal properties like Angle of Arrival (AoA), delay, and Doppler shift. – MUSIC looks through the spatial directions to discover the ones that are perpendicular to the noise space.
[11]	ESPRIT	<ul style="list-style-type: none"> – It has less computational complexity since it directly calculates the eigenvectors to get the angle. – However, the antenna array must be able to be split into two identical subarrays with a given distance between them. – MUSIC and ESPRIT are often less accurate than SAGE when it comes to estimating parameters, but they are also less complicated to use.

and direct signal, compressed sensing has been shown to work better than the subspace technique, such as the MUSIC algorithm.

4.5 Data Processing

The gathered sensing data (RSS, CSI, or received waveform) will be preprocessed to get rid of noise and/or retrieve the target-related information, including range and Doppler frequency shift, using the signal processing module. Also, the data processing algorithms will use the derived signal properties to help with different sensing applications. Data processing may be model-based, learning-based, or a mix of both, depending on the sensing applications.

Learning-based classification algorithms are increasingly often employed for recognizing human activity and gestures. These algorithms sort observed human motion into one activity from a group of distinct activities. For instance, Singh et al. [18] used mmWave radar for human activity identification measures. This study examined many learning-based methods, including the support vector machines (SVMs) classifier, multilayer perceptron (MLP) classifier, bidirectional long-short term memory (LSTM) classifier, and time-distributed convolutional neural network (CNN), using the measurement data.

Model-based algorithms reutilized to find targets and figure out sensory parameters. The work [15] employed ESPRIT for automobile radar to find multiple targets and estimate the range-Doppler. The authors of [19] also came up with a dynamic-MUSIC approach to find the human target by finding the reflected signal from the body. The suggested approach used coherent receiving signals to attain a location accuracy of greater than 0.6 m while the person being tracked moved. Another example of the MUSIC algorithm is [20], which uses CSI data to get Doppler velocity data using Doppler-MUSIC and Doppler and AoA data to figure out where people are going.

5 Challenges

The main challenges while using ISAC in the practical scenario are discussed in this section. To meet both communication needs (high throughput, low latency) and sensing needs (fine time-frequency resolution, Doppler sensitivity), you need to do multi-objective and fine-grained optimization. In addition, when spectral, temporal, and geographic resources are used by more than one person, they may interfere with each other. This means that smart resource allocation methods like adaptive beamforming and interference-aware scheduling are needed.

When it comes to dynamic environments, real-time scheduling and consistent sensing performance are hard to achieve since RF circumstances change quickly (mobility, obstacles, and varied consumption). However, balancing sensing and communication may frequently make things less accurate or less useful (for example, more pilot signals for sensing equals less data transfer).

Regarding sensing accuracy, it is hard to maintain high accuracy in crowded urban or indoor areas because of multipath, occlusions, and background noise, particularly when there are a lot of devices.

Finally, using complex AI models like CNNs and reinforcement learning on both the edge and the core might cause problems with power use, latency, and scalability. Automation and orchestration: To coordinate sensing and communication, you need strong automation for synchronization, data fusion, and managing many AI agents. Sensing data may reveal private information, which can cause privacy, surveillance, and legal issues that differ from one application to the next. Early initiatives like IEEE 802.11bf and 3GPP Release 19 have not led to broad acceptance since there are not yet stable, unified standards and the ecosystem is not ready (for example, hardware compatibility and testing frameworks are restricted).

6 Conclusion

ISAC is seen as a pivotal technology for future mobile communication systems, with the ISAC signal being of paramount significance. This article provides a comprehensive survey of the different classes of sensing techniques, use cases of ISAC in the various sections of Industry, and the different signal processing techniques. The challenges of ISAC while realizing in real-time scenario are discussed. In the next 5G and 6G epochs, it will be imperative to develop ISAC signals that are modifiable and adaptable to various circumstances.

Acknowledgment

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