Integrated Sensing and Communication: Who Benefits More?

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Abstract: This paper compares the benefits of communication-assisted sensing and sensing-assisted communication in the context of integrated sensing and communication (ISAC). Communication-assisted sensing leverages the extensive cellular infrastructure to create a vast and cooperative sensor network, enhancing environmental perception accuracy and coverage. On the other hand, sensing-assisted communication utilizes advanced sensing technologies to improve predictive beamforming and channel estimation performance in high-frequency and high-mobility scenarios, thereby increasing communication efficiency and reliability. To validate our analysis, we present an example of channel knowledge map (CKM)-assisted beam tracking. This example demonstrates the practical advantages of incorporating CKM in enhancing beam tracking accuracy. Our analysis confirms that communication-assisted sensing may offer greater development potential due to its wide coverage and cost-effectiveness in large-scale applications.

Keywords: communication-assisted sensing; integrated sensing and communication (ISAC); sensing-assisted communication; 6G; vehicle-to-everything (V2X)

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1 Introduction

Integrated sensing and communication (ISAC) is gaining widespread attention as a crucial technology for future wireless systems[1]. The International Telecommunication Union (ITU) has regarded ISAC as one of the key potential technologies for the 6G mobile communication systems[2]. Future 6G networks are expected to utilize wide-bandwidth radio signals, large-scale antenna arrays, and multiple network nodes to offer efficient sensing capabilities including detection, localization, tracking, activity recognition, and environmental reconstruction, which brings the ultimate vision of the interconnected, intelligent, and perceptive world into reality[3 – 6]. Moreover, in future 6G wireless networks, ISAC will support higher data rates, enhanced communication reliability, and improved network coverage.

ISAC provides substantial gains by combining communication and sensing functions into a unified framework. This integration results in increased spectrum and hardware utilization efficiency, collectively known as integration gain. More importantly, coordination gain is achieved through the mutual assistance of communication and sensing, enhancing overall system performance[1]. ISAC allows the communication system to serve as a sensor[3], utilizing radio wave transmission, reflection, and scattering to perceive and understand the physical environment[7], thereby offering a broader range of new services. Additionally, high-precision localization, imaging, and environmental reconstruction can significantly improve communication performance by enabling more accurate predictive beamforming[8], faster link recovery[9], and reduced overhead for tracking channel state information (CSI)[10 – 11].

To enhance the integration gain, researchers have considered three design approaches: communication-centric design, radar-centric design, and joint optimization design[12 – 13]. On the other hand, to enhance the collaborative gain, two approaches have been adopted[1]: communication-assisted sensing and sensing-assisted communication. In particular, communication-assisted sensing leverages existing cellular network protocols and architectures to utilize available radio resources for sensing based on communication signals. Wireless communication networks enable distributed sensing and enhance sensing performance to address the limitations of monostatic sensing. In perceptive mobile networks (PMN), existing works have shown that distributed ISAC systems can improve localization accuracy and moving target detection probability by offering extensive angle observations and a wide range of spatial diversity[14].

However, distributed ISAC imposes a demanding requirement on time and frequency synchronization among distributed sensing nodes[14]. The main challenges of communication-assisted sensing include self-interference cancellation, interference management, network resource scheduling, and synchronization[1, 5, 14], which will be detailed later. Sensing-assisted communication refers to the use of radar sensing to assist communication in high-mobility scenarios, effectively reducing communication overhead and improving communication reliability[15–16]. In sensing-assisted wireless networks, the estimated location and speed of a moving terminal can be utilized for fast link establishment and handover, thus reducing access delay[17–19]. The main challenges of sensing-assisted communication include the limited sensing range, the mismatch between the sensed state and CSI, and the requirement for full-duplex operation to eliminate strong interference from transmitted signals to the echoes.

This paper investigates the comparative analysis of communication-assisted sensing and sensing-assisted communication, including their applicable scenarios, sources of benefits, and technical details. We aim to determine which method holds greater research significance and performance gain in future 6G scenarios, such as intelligent transportation systems and smart cities. In this paper, we first introduce the basic concepts, main challenges and usage scenarios of ISAC. Then, we discuss the mutual benefits of sensing and communication, and investigate which one benefits more. In the end, we present an example of channel knowledge map (CKM)-assisted beam tracking to illustrate how communication-assisted sensing enhances beam tracking accuracy in complex vehicle-to-everything (V2X) scenarios in the presence of multipath and channel variations.

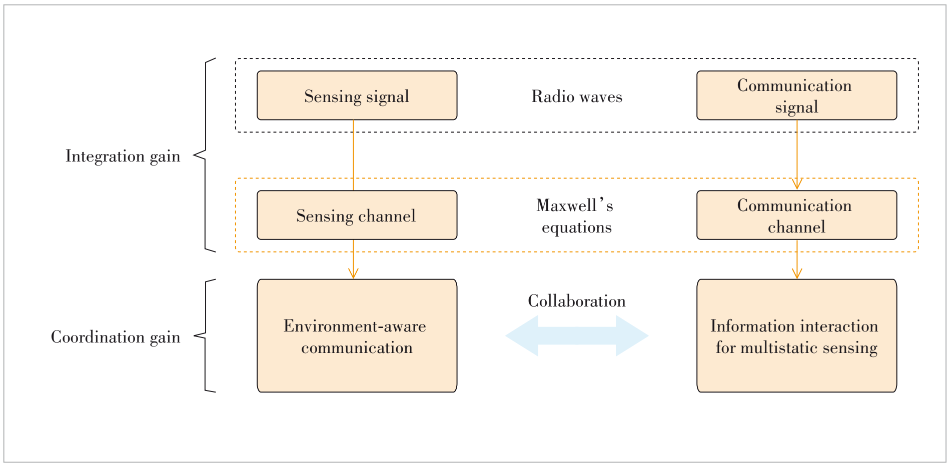
2 Fundamentals of ISAC

2.1 ISAC Definition and Models

ISAC aims to achieve dual functions of communication and radar through integrated design in hardware platforms, resource allocation, and signal processing, addressing the issue of scarce spectrum resources[3].

The main advantage of ISAC over independent sensing or communication is integration gain. As shown in Fig. 1, both sensing and communication (S&C) utilize radio waves as their signal carriers, and the propagation of these signals follows Maxwell's equations. This commonality implies that the components or resources used for sensing and communication can be effectively coupled to achieve more efficient resource utilization. For example, ISAC can divide the antenna array into two groups, one for communication and the other for sensing, using the same hardware to fulfill their respective purposes. Spectral efficiency can be readily pursued by employing a dual-mission signal[13]. Consequently, by sharing spectrum and hardware, system spectral efficiency, energy efficiency, and hardware efficiency can be improved, thereby achieving integration gain. Furthermore, the mutual assistance between sensing and communication functions can further enhance their respective performances, leading to coordination gain. As depicted in Fig. 1, environment-aware communication can be achieved by incorporating the sensed information, such as the user terminal state and the environment radio map[4, 8], into the communication design. Multistatic sensing can be achieved via proper information interaction among distributed sensing nodes.

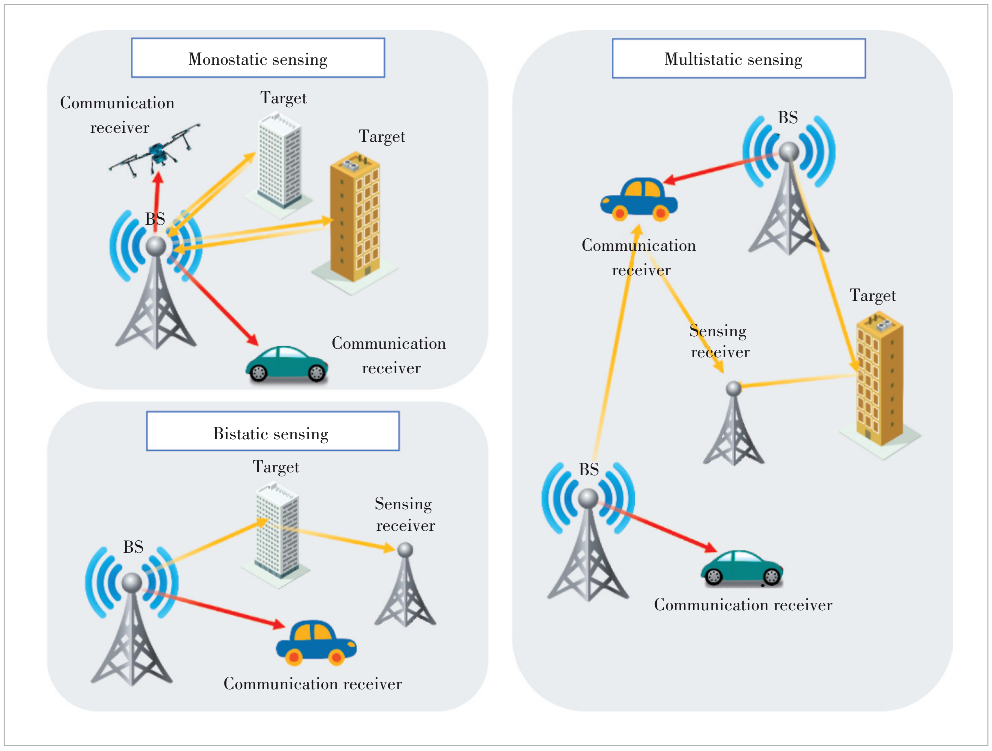
Fig. 2 illustrates three types of ISAC systems, including monostatic sensing, bistatic sensing, and multistatic sensing. In all these scenarios, the base station (BS) transmits ISAC signals to perform communication and sensing tasks simultaneously. The red arrows represent communication channels, while the yellow arrows indicate sensing channels. The BS communicates with users via the communication channels and detects the position, speed, and other kinematic parameters of targets through sensing channels. In a monostatic ISAC system, the BS receives echoes reflected from targets at the same time. Nevertheless, a full-duplex BS is necessary for the simultaneous transmission and receiving of signals, as any remaining interference signal could deteriorate the BS's sensing capabilities[3]. To circumvent this limitation, bistatic and multistatic ISAC systems have been proposed, where the sensing receiver is physically separated from the transmitter and almost does not suffer from the residual interference, and thus hardware modifications for a full-duplex BS are avoided. The bi-



▲Figure 1. Two main advantages of integrated sensing and communication (ISAC): integration gain and coordination gain

static ISAC system includes one BS and one sensing receiver. The multistatic ISAC system comprises multiple base stations that together form a sensing cluster. This configuration includes various combinations, such as several transmitters with multiple receivers, a single transmitter with multiple receivers, or multiple transmitters with one receiver, to provide sensing services.

Based on whether the sensing target has the requirement and capability of communication, targets can be categorized into communication objects and non-communication objects. Communication objects refer to cooperative targets that can transmit, receive, and process signals, allowing the BS to sense them by receiving signals sent or reflected by the targets. Sensing based on communication objects is common in vehicle-to-everything (V2X) or unmanned aerial vehicle (UAV) networks, where the BS aims to communicate with the car or UAV while simultaneously acquiring and tracking their location and velocity. Communication objects within a scenario can also be classified based on their sensing requirements. For instance, between fixed BSs, only the channel state information (CSI) needs to be sensed. However, in more complex scenarios with dynamic interference, it is necessary to sense not only the CSI but also the radar cross-section, movement velocity, and other kinematic parameters of the targets[11, 20–21]. Non-communication objects, on the other hand, lack baseband functionality and cannot send or receive signals. They can only reflect signals to the BS, enabling the BS to sense their states. Non-communication targets are usually considered a part of the surrounding environment and their information can facilitate environment-aware communication[4].



▲Figure 2. Typical integrated sensing and communication (ISAC) systems, where the sensing target can be the communication receiver itself in all the scenarios

2.2 Challenges of ISAC

2.2.1 Joint Waveform Design and S&C Tradeoff

One of the primary challenges in ISAC is designing a unified waveform that can perform both target sensing and information transmission. The design methodologies can typically be categorized into three approaches: radar-centric design, communication-centric design, and joint design. The inherent similarities in channel parameters between sensing and communication serve as a primary driving force behind the design of ISAC waveforms. For example, in the monostatic ISAC system shown in Fig. 2, communication signal detection is based on one-way transmission from the BS to the user, while sensing relies on echoes received at the BS following round-trip propagation. But for both sensing and communication, the physical environment between the user and the BS is the same. Despite this, there is an inevitable tradeoff between sensing and communication due to different performance metric priorities for each function. We consider a general linear Gaussian channel model as follows[22]:

$$\boldsymbol{Y} = \boldsymbol{H}(\eta)\boldsymbol{S}(\xi) + \boldsymbol{Z}, \tag{1}$$

where $\boldsymbol{Y}$, $\boldsymbol{H}$, $\boldsymbol{S}$, and $\boldsymbol{Z}$ represent the received signal at the BS, the channel, the transmitted signal, and the Gaussian noise, respectively. These elements can be in the form of scalars, vectors, or matrices. The channel $\boldsymbol{H}$ is dependent on the physical parameters, e.g., range, angle, and velocity. The transmit signal $\boldsymbol{S}$ may be encoded/modulated with some information codeword ξ.

From the communication perspective, the fundamental problem is getting the codewords ξ back from $\boldsymbol{Y}$. The channel $\boldsymbol{H}$ can be estimated a priori via pilot training. On the other hand, from the sensing perspective, the primary objective is to accurately estimate the target parameter η contained within $\boldsymbol{H}$ based on the known $\boldsymbol{Y}$ and $\boldsymbol{S}$. When $\boldsymbol{S}$ is a known deterministic signal, ξ can be left out because the radar waveform does not contain any information. Then, the ISAC system model can be written as[3, 22]:

$$\begin{cases} \text{Sensing signal model: } \boldsymbol{Y}_{\mathrm{r}} = \boldsymbol{H}_{\mathrm{r}}(\eta)\boldsymbol{S} + \boldsymbol{Z}_{\mathrm{r}} \\ \text{Communication signal model: } \boldsymbol{Y}_{\mathrm{c}} = \boldsymbol{H}_{\mathrm{c}}\boldsymbol{S} + \boldsymbol{Z}_{\mathrm{c}} \end{cases}, \tag{2}$$

where $\boldsymbol{S}$ is the ISAC signal's discrete representation. To distinguish between sensing and communication channels, we use the subscripts $(\cdot)_{\mathrm{r}}$ and $(\cdot)_{\mathrm{c}}$, respectively.

Since sensing and communication have distinct performance metrics and prefer different signal distributions, it is crucial to achieve a balance between these two functions. In ISAC systems, there are two types of tradeoffs: the time-frequency tradeoff and the spatial tradeoff, also known as the deterministic random tradeoff (DRT) and the subspace tradeoff (ST)[22]. Sensing systems prefer deterministic signals to achieve steady sensing performance, but communication systems need random signals send as much information as feasible. Choosing the modulation order for random data results in a tradeoff between time and frequency: higher-order modulation improves communication rates but degrades sensing performance because the random and non-constant-modulus data raise side-lobe levels in the ambiguity function[3, 19, 22]. However, the choice of ISAC beamforming strategies is related to the spatial tradeoff. Aligning sensing-optimal and communication-optimal signals to their respective subspaces and managing resource allocation accordingly can enhance efficiency if their subspaces overlap. Conversely, no resources may be reused if two subspaces are orthogonal to each other, nulling any performance gain. More resources may be utilized between sensing and communication when there is a larger overlapping degree between two subspaces, which improves tradeoff performance[12].

2.2.2 Artificial Intelligence (AI) Enabled ISAC

Powerful AI algorithms offer new opportunities to ISAC. A large volume of data generated by ISAC at the BS need to be processed rapidly and accurately by AI algorithms, potentially in conjunction with sensing data from other model sensors such as cameras and LiDARs[18], to support applications with ultra-low latency requirements for sensing, communication, computation, and control. In data-rich and complex ISAC scenarios such as urban outdoor propagation environments, there exist plenty of noisy, discontinuous, or multimodal objective observations. The physical formulation of the system's nonlinear signal characteristics may be unknown or challenging to the model. In such cases, AI can be employed to simulate intricate communication/sensing channels, the surrounding environment, and even the system uncertainties. This approach addresses challenges that cannot be resolved solely through traditional mathematical models or signal-processing techniques.

However, integrating AI with ISAC systems poses significant challenges. The ISAC system can leverage its powerful sensing and communication capabilities to provide rich input data for the training AI models. Additionally, AI-enabled ISAC introduces complex tradeoffs between sensing, communication, and computation[1]. Firstly, defining performance metrics for an AI-enhanced ISAC system is challenging. This may involve integrating metrics such as AI model complexity, convergence speed, generalization ability, data dependency, and training computational cost with ISAC performance metrics. For example, it is necessary to define the overall latency for AI-enabled ISAC integrated services. If the processes of communication, sensing, and AI computation are sequential, the combined communication, sensing, and computation latency must not exceed the overall latency. Secondly, establishing an AI model dedicated to ISAC systems is challenging. For instance, the recently developed channel semantics provide an innovative perspective to ISAC signal processing. By combining the advantages of data-driven and model-driven techniques, a more reliable and effective ISAC system can be developed based on specific AI models[23]. Furthermore, data security and privacy protection within the AI-enabled ISAC integrated architecture are critical concerns that cannot be overlooked.

2.2.3 Collaborative ISAC

In multi-user and multi-target scenarios, collaborative ISAC systems face the challenge of coordinating multiple cooperative nodes to optimize resource utilization and improve sensing performance. Effective collaboration requires sophisticated algorithms to manage interactions among users and share sensing data. Cloud radio access networks (C-RAN) offer greater flexibility for ISAC through cooperation among multiple BSs, especially in resource-limited situations, providing additional cooperative gains for both communication and sensing functions[24].

To this end, it is crucial to develop advanced optimization algorithms and distributed sensing technologies to minimize information interaction overhead and enhance the efficiency of collaborative ISAC systems. For example, a joint communication and radar optimization resource allocation scheme is introduced, which supports the fusion of vast numbers of sensing data from both wireless infrastructure and vehicles to achieve optimal computation and resource allocation decisions[25]. High-precision clock synchronization among nodes is also necessary for collaborative sensing. Imperfect clock synchronization can deteriorate the ambiguity function of the sensing signals in distributed systems, leading to reduced localization accuracy. The synchronization error in several clocks must be within tens of picoseconds in order to achieve centimeter-level resolution precision[26]. This is a very strict synchronization requirement. While certain synchronization protocols, such as precision time protocol (PTP) and master-slave closed-up, can achieve a high degree of synchronization accuracy[27], advanced methods are expected to support higher precision sensing functions.

2.2.4 Privacy and Security Issues

Privacy and security issues are significant considerations. Integrating sensing and communication functions involve collecting and transmitting a large volume of user data and environmental information[28]. In practice, the sensed targets can potentially use the information-bearing signals to detect confidential information sent to the communication destination. This presents a significant tradeoff issue for the transmitter in ISAC systems. On one hand, the transmitter aims to enhance target sensing by focusing power on the target. On the other hand, it must limit the communication signal power reaching the target to prevent potential eavesdropping. Therefore, effective privacy protection measures and security mechanisms must be implemented to prevent information leakage and malicious attacks. Research and exploration in these areas are crucial for advancing the development and application of sensing and communication technologies.

2.3 Use Cases for ISAC in 6G

The most prominent scenarios and use cases for ISAC span both civilian and military domains[1, 16]. From a civilian perspective, numerous emerging applications necessitate the joint design of sensing and communication, such as smart cities, smart homes, and intelligent manufacturing[5], as well as intelligent transportation applications like vehicular networks and autonomous driving[18]. From a military perspective, the development of radar, communication, and remote sensing systems has historically been isolated. By applying ISAC technologies, it is possible to significantly reduce the consumption of spectrum and hardware resources and enhance the performance of both communication and sensing.

2.3.1 V2X High-Accuracy Localization and Beam Tracking

V2X enhances traffic efficiency, road safety, and the availability of infotainment services. It encompasses vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I), and vehicle-to-network (V2N) communications. V2X requires Gbit/s-class data transmission with low latency and precise sensing for vehicle positioning[29]. Traditional technologies like global navigation satellite systems (GNSS) and dedicated short range communications (DSRC) are inadequate for these needs[30]. Robust beam tracking is essential in dynamic vehicular environments and millimeter-wave (mmWave) communications, extending the network coverage effectively[16].

Within the ISAC framework, the roadside units (RSUs) can predict and estimate the vehicle's state at each epoch and the beamforming can be designed to match the predicted channel. For example, a novel extended Kalman filtering (EKF)-based predictive beamforming was proposed to effectively track and predict movements[16, 21, 29, 31 – 32], employing ISAC echo signals for real-time vehicle position detection and state parameter estimation. With the use of the vehicles' state transition models and echo signals, a distribution of the estimated parameters is generated in a novel beamforming system based on probabilistic prediction[10]. However, many algorithms presuppose the availability of line-of-sight (LoS) links that are often obstructed in urban environments by high-rise buildings or other vehicles, leading to degraded channel time correlation and significantly impacting performance[18]. ISAC in a non-line-of-sight (NLoS) scenario deserves to be studied further.

2.3.2 Human Activity Recognition and Smart Home

ISAC-based Internet of Things (IoT) systems show great potential in various applications, including daily activity recognition, healthcare monitoring, home security, and driver attention monitoring[13]. Compared with sensor-based methods (such as cameras, Lidars, and ultrasonic sensors), current mmWave sensing has several benefits, such as a wider sensing range, fine-grained and directed sensing capacity, and resistance to illumination conditions[33]. Evaluating variations in the amplitude and phase of wireless signals can facilitate a range of human sensing activities, including human tracking and localization, activity recognition, monitoring vital signs, sound recovery, and human imaging. Integrating sensing capabilities into existing wireless communication devices will significantly enhance the quality of life by improving the living environment and ensuring better safety and health monitoring.

2.3.3 ISAC for IRS-Assisted System

Intelligent reflecting surface (IRS) adjusts the phase, amplitude, frequency, and polarization of incident signals using numerous low-cost reflecting elements, thereby modifying signal propagation[34]. The IRS usage is more appropriate for sensing and communication tasks because the ISAC system uses a common transmitter[1]. The LoS path between the radar and the target is critical for sensing functionality. In scenarios where the LoS path is obstructed, resulting in weak or non-existent signals, a virtual LoS channel can be established between the radar and the target using IRS to cover blind spots. This ensures reliable sensing performance and utilizes the NLoS channels established by the IRS for downlink multi-user communication. For changing the direction of the signal that arrives from the BS towards the users, the BS uses a backhaul control connection to reconfigure the phase shift corresponding to each element in real time via external signals[34]. This particular application of the IRS increases the BS's coverage area and improves the received signal energy at distant users. By simply adjusting these phase shifts to allow the BS to only do digital beamforming with fewer antennas, the IRS-assisted systems enable analog beamforming, lowering hardware costs and increasing energy efficiency.

However, the combined design issue including IRS is computationally hard, especially when designing optimal waveforms and allocating resources efficiently.

2.3.4 ISAC for UAV Networks

UAVs are characterized by high mobility, long range, wide coverage, and ease of deployment[35]. UAVs constantly serve as temporary BSs or relays for potential improvements in communication coverage when employed as an auxiliary communication platform in airspace[36]. Numerous advantages can be realized if the independent communication load and sensing load are replaced by the ISAC load. Because of the decreased load weight, UAVs will be more durable and flexible. Secondly, the ISAC UAV platform can achieve coordination gains. On the one hand, when the integrated waveform in the downlink communication channel between the BS and the UAVs encounters possible targets (such as buildings or uncooperative UAVs) during transmission, it will immediately be reflected back. The echo signal can then be cooperatively processed by the UAV network to detect the presence of a non-cooperative UAV and even pinpoint its location. This feature lowers the possibility of mishaps brought on by uncooperative UAVs, including privacy violations and flight disturbances. A more stable beam between UAVs and BS can be formed with the help of sensing the geographical relationship between the UAVs and the ground, which reduces the likelihood of mismatching in the beam management process.

3 Mutual Benefits of Communication and Sensing

3.1 Communication-Assisted Sensing

Integrated with sensing capabilities, 6G networks can function as a vast sensor network, continuously perceiving the physical world. A massive number of data provided by these networks contain rich channel knowledge, laying a solid foundation for communication-assisted sensing.

3.1.1 Networked Sensing

Communication-assisted sensing achieves gains in ISAC systems through sensing networks and cooperative sensing[14]. Due to the significant influence of incident angles on the scattering and reflection intensity of electromagnetic waves on object surfaces and the potential presence of obstacles obstructing LoS, the sensing capability of individual nodes is limited[11, 29, 37]. Existing communication devices reduce costs for establishing sensing platforms and provide numerous nodes and data sources. Through communication networks supporting multi-node cooperative sensing, nodes share sensing results and collectively sense their surrounding environment. This approach utilizes data fusion to reduce measurement uncertainties, expand coverage areas, enhance sensing accuracy and resolution, and even achieve sensing under NLoS conditions. Achieving optimal fusion of sensing results poses challenges in current research, focusing on addressing issues such as synchronization, joint signal and data processing, and efficient allocation of network resources.

3.1.2 CKM-Assisted Sensing

CKM is a comprehensive database that integrates environmental and channel state data to significantly enhance spatial coherence by correlating geographic positions with channel states[4]. This supports precise beam alignment and tracking[4, 38–39]. CKM is essentially a mapping between the location and CSI, which can facilitate environment-aware communication by providing a priori information on channels for transceiver design. Moreover, CKM can also be used in the opposite direction to improving sensing performance based on the measured CSI or channel parameters. Unlike traditional methods that rely on angle and signal energy[37], CKM uses a priori information for hypothesis testing in LoS link identification[11, 15]. This approach not only improves LoS detection but also aids in clutter suppression and interference elimination within ISAC systems. NLoS anchor nodes are known to be ineffective in improving localization accuracy, and when no prior knowledge of their NLoS pathways is available, they can even impair localization. In time-of-arrival wireless localization in complex environments that lack prior knowledge of NLoS path, only anchors with LoS paths to the agent increase localization accuracy. Based on the target's prior distribution, a unique CKM, i. e., LoS map[7], could greatly reduce the localization error by selecting anchor nodes that are suitable for position estimation. Besides, the channel features included in the CKM are usually more stable than the directly measured CSI. Thus, CKM-assisted sensing could be more robust to environment dynamics. Besides, the channel features included in the CKM are usually more stable than the directly measured CSI. Thus, CKM-assisted sensing could be more robust to environment dynamics. While real-time training overhead can be reduced by radar/LiDAR/vision-aided communications without consuming communication resources, the cost, size, and complexity of communication systems are increased due to the need for extra hardware, waveforms, and signal processing complexity. CKM-enabled communications leverage environment awareness and can be implemented without these additional requirements. Furthermore, CKM can leverage vision, LiDAR, and radar observations to provide more precise predictions.

3.1.3 Wi-Fi Sensing

Due to the widespread usage and growing popularity of Wi-Fi devices, Wi-Fi signals, a part of the electromagnetic spectrum, can be found everywhere in everyday life and work[3]. In addition to traditional communication functions, Wi-Fi signals contain a wealth of environmental information that can be exploited to sense and locate people and objects. Wi-Fi sensing can be categorized into three types: estimation, recognition, and detection[40]. In a Wi-Fi system employing multiple-input and multiple-output orthogonal frequency division multiplexing (MIMO-OFDM), the CSI is a 3D matrix of complex numbers representing the amplitude attenuation and phase shift of multiple-path Wi-Fi channels that can be used for different wireless sensing applications[41]. For instance, CSI amplitude fluctuations in the time domain exhibit different trends for various humans, activities, gestures, and so on. These patterns may be applied to motion detection, human identification, fall detection, human presence detection, activity recognition, and gesture recognition. Human localization and tracking can be facilitated by CSI phase changes in the spatial and frequency domains, i.e., transmitting/receiving antennas and carrier frequencies, which are connected to signal transmission delay and direction[41]. However, using a Wi-Fi device for sensing can degrade network performance and the sensing performance can be influenced by network settings. This interplay between Wi-Fi sensing and networking poses challenges but also highlights future trends in Wi-Fi technology, where seamless coexistence of both functions will be essential.

3.2 Sensing-Assisted Communication

Sensing-assisted communication demonstrates significant technical advantages and application potentials in high-frequency and high-mobility scenarios.

3.2.1 High-Frequency Communication

High-frequency ISAC signal propagation exhibits two primary characteristics:

• It shows rapid energy attenuation and significant energy loss due to reflection;

• The communication channel highly depends on the geometrical features of the environment.

These two characteristics underscore the potential to bolster communication robustness through precise environmental sensing. In high-frequency environments, sensing-assisted communication derives substantial benefits from several factors. Firstly, high-frequency waves almost completely lose their capacity to pass through common obstacles like walls and human bodies. This could block the LoS path between user equipment to an access point, thereby limiting the coverage distance. In scenarios characterized by complex and obstructive environments, high-accuracy localization and map reconstruction become pivotal to optimizing access. These sensing services can proactively design beam directions that minimize blockage by acquiring channel information a priori, thereby reducing disruptions[11,15]. Secondly, the extensive bandwidth in the high-frequency band enables the system to distinguish between different scattering points along the distance axis with centimeter-level resolution[42]. Given that channel parameters in high-frequency scenarios are intimately linked to the physical environment, a realistically reconstructed scenario from accurate sensing data can faithfully mirror the propagation dynamics of communication signals. Consequently, this allows for tailored energy allocation and beamforming to significantly enhance the achievable communication rate.

3.2.2 High-Mobility Communication

In high-mobility environments, beam training results in considerable overhead and significant latency[41–42]. Owning beam tracking capacity is essential to adapt to fast-changing channels. In the context of V2I networks, sensing-assisted communication can reduce frequent beam sweeping overheads, while improving localization accuracy and robustness in high-mobility scenarios. Leveraging ISAC signals, RSUs can extract angle parameters from reflected echoes, thereby predicting angles and beam directions for the next moment[10, 21]. In high-mobility scenarios, the users may need to handover frequently between different BSs. Different from traditional detect-and-correct methods, a predict-and-prevent process that reduces the beam scanning area and offers early interventions for timely cell switching can be rendered possible by the sensing-assisted beam management method.

In summary, sensing-assisted communication in high-frequency and high-mobility scenarios not only significantly enhances the performance and reliability of communication systems through optimized beamforming and alignment strategies but also effectively reduces communication costs and complexity. The application potential of this technology promises substantial technological advancements and socio-economic benefits in future intelligent transportation, vehicular networks, and dense urban network domains.

3.3 Who Benefits More?

In summary, the relative advantages of communication-assisted sensing over sensing-assisted communication are highly dependent on the specific scenarios. In multistatic scenarios or at BSs with a priori information, such as networked sensing, ubiquitous sensing, and CKM-assisted sensing, which are particularly relevant to mmWave and intelligent transportation technologies, sensing typically derives greater benefits. Conversely, in environments characterized by high-mobility and high-frequency communication, the advantages predominantly favor communication.

Communication-assisted sensing offers significant benefits, particularly when the target is part of the surrounding environment. When BSs are connected via fronthaul links and participate in downlink bi-static sensing in a PMN framework, one BS's data payload can be directly acknowledged by another BS through coordination, which can be utilized for sensing functions. The high-capacity and low-latency optical fiber fronthaul also eliminates the need for complex phase noise compensation and synchronization methods.

On the other hand, sensing-assisted communication benefits more when the S&C channels are closely correlated and there are more wireless resources available for management. In general, sensing-assisted communication systems take advantage of the correlation between S&C channels to lower communication overheads and improve efficiency. Sensing-assisted V2X beam training, tracking, and prediction techniques, for example, rely on the fact that a vehicle serves as both a radar target and a communication receiver, meaning that the S&C channels are highly linked. Sensing can be helpful in a high-mobility network not only for beam resources but also for allocating and managing more general wireless resources like power and bandwidth.

Given the existing communication networks and ubiquitous communication signals, communication-assisted sensing, with its broad coverage and capabilities for multi-node cooperative sensing, generally excels in more array of application scenarios. In the future, ISAC should progress from a monostatic to a multi-domain cooperative model. The exploration of methods to integrate as much sensory information as possible with minimal complexity to maximize cooperative gains remains a critical area of future research.

4 An Example: CKM-Assisted Multipath Beam Tracking

We provide an example of communication-assisted sensing in this section. In our example, tracking can be considered a sensing task, which aims to obtain the location of a moving target based on the angle and position measurements. Communication nodes record channel state information in a database known as the CKM, which can enhance sensing accuracy.

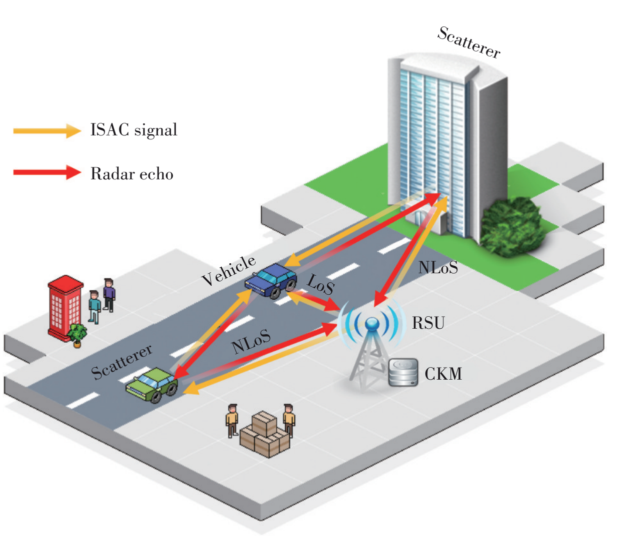
4.1 System Model

Robust beam tracking schemes are required due to the dynamic properties of vehicle motion and communication environments, as well as the high path loss and sensitivity to shadowing in mmWave communications[42]. In the conventional beam tracking process, the receiver estimates the angle based on the received signal from the transmitter's pilot and returns it back to the transmitter. A tradeoff between the pilot overhead and the estimation accuracy is therefore needed[20, 43–47]. In high-mobility communications, to achieve higher estimation accuracy, it is necessary to transmit more pilot signals, which incurs higher delay. A discrete Markov process has been proposed as a model for the temporal angle variations in a fast beam tracking strategy for mobile mmWave systems[17].

We consider an mmWave MIMO system that includes an ISAC BS within an RSU. The RSU provides downlink communication services to user vehicles. Each user vehicle is equipped with a uniform linear array (ULA) for receiving signals from the RSU. The RSU itself functions both as a receiver and a transmitter, each end equipped with its own ULA.

Time is divided into slots, with each slot further divided into sub-slots. Within each slot, channel parameters remain constant. The transmitted ISAC signals are reflected back to the RSU after encountering scatterers, resulting in the RSU receiving a sum of paths, including reflections from various elements, such as buildings or other vehicles. The RSU exploits the echo signals and a priori information of CKM to align and track the beams accurately. The power of the reflected signal is not only determined by the round-trip path-loss but also by the radar cross-section (RCS) of the target. In order to examine the RCS channel properties and environmental data, ZHANG et al.[48] created an ISAC channel measurement platform. By approximating Maxwell's equations, extracting parameters through measurements, and estimating physical optics (PO), one can obtain the RCS. In target localization and tracking scenarios, the vehicle is usually modeled as a point, ignoring its volume and shape[9]. The RCS of the vehicle is assumed to be constant within a short period of time while the RCS of buildings is considered to be known, attributed to the CKM[9, 16–17]. The same assumptions as proposed in other articles are used in this paper, i.e. the RCS of structures is known and the RCS of vehicles is assumed to be constant throughout a short period of time.

From the view of the RSU, the radar sensing channel is both time and frequency selective, which is given by: $\boldsymbol{H}(t,\tau)=\sum_{i=1}^{P}\beta_i\,\boldsymbol{b}(\theta_i)\,\boldsymbol{a}^H(\theta_i)\,\delta(\tau-\tau_i)\,e^{j2\pi\mu_i t}$, where β_i, τ_i and μ_i denote the channel path gain, the round-trip delay, and the round-trip Doppler spread corresponding to the i-th path, respectively. We denote θ_i as the angle of the i-th path relative to the RSU. Tracking NLoS paths improves communication performance in wireless networks, despite their lower path gain compared with LoS paths. While NLoS pathways experience many reflections, resulting in lower signal strength, they, like LoS paths, contribute considerably to overall multipath propagation. To solve the difficulty of low NLoS path gain, we use angular a priori knowledge from the CKM and temporal correlation to track NLoS path directions more reliably.



CKM: channel knowledge map
ISAC: integrated sensing and communication
LoS: line-of-sight
NLoS: non-line-of-sight
RSU: roadside unit

▲Figure 3. Considered scenario of CKM-assisted ISAC beam tracking system

4.2 Dual Domain Beam Tracking Framework

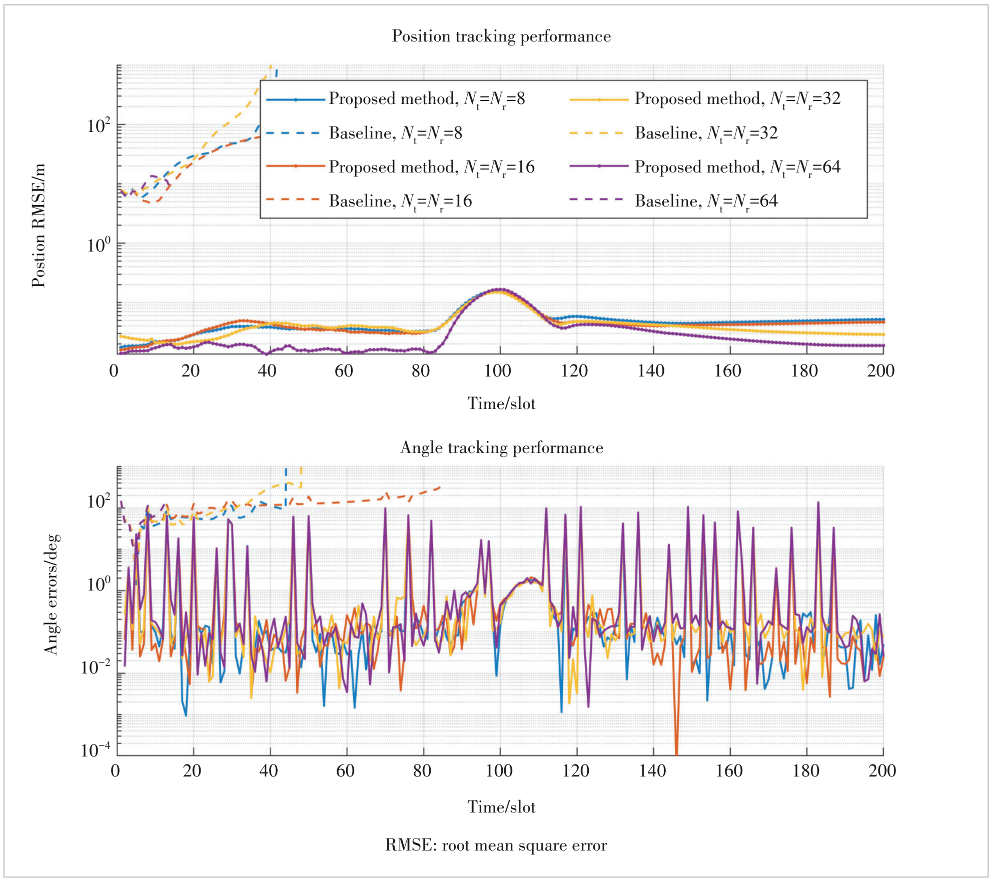
We have developed a robust multipath beam tracking method based on CKM. This method leverages prior information from CKM, which maps location to CSI, including parameters such as channel gains, angles, delays, and Doppler frequency shifts. By integrating this information, we propose an EKF-based tracking technique that is suitable for scenarios where the LoS path may disappear, allowing for precise continuous tracking.

The framework utilizes EKF to predict and track the state of vehicles, with state evolution and measurement models defined for both LoS-present and LoS-absent conditions. Under LoS-absent conditions, the measurement variables are time delays, Doppler shifts, and angle measurements for multiple reflectors, while the state variables are the vehicle's position and velocity. Essentially, the measurement model makes use of CKM, which records the channel parameters for each location. The proposed algorithmic framework bridges coordinate domain and beam domain information, effectively incorporating environmental awareness into the tracking process. The EKF measurement equations can maintain continuous beam tracking even when the LoS path is obscured, enabling robust multipath beam tracking.

4.3 Simulation Results

In this section, we present the numerical results to verify the performance of our proposed algorithm. The method described in Ref. [15], which does not utilize CKM's prior information to enhance angle estimation, is used as the baseline algorithm.

Fig. 4 demonstrates that our algorithm achieves the best sensing performance under different antenna configurations. In the scenario under consideration, the vehicle approaches the RSU from one side and then moves in front of it to the other. It is evident that as time goes on, the position tracking errors initially rise and subsequently fall. This pattern arises because as the vehicle approaches the BS, its relative angular velocity increases, heightening the likelihood of losing track of the vehicle. Notably, compared with the baseline, our algorithm's superior performance stems from utilizing prior information provided by CKM, which significantly reduces angle estimation errors in multipath low signal-to-noise ratio (SNR) environments.



▲Figure 4. Performance of vehicle tracking

5 Conclusions and Outlook

ISAC is proposed to revolutionize the landscape of wireless communication and sensing systems. This paper offers a comprehensive overview of ISAC, detailing its foundational principles, system models, use cases, and main challenges. We began by elucidating the basic concepts of ISAC. Through various use cases, such as V2X applications, smart homes, and military scenarios, we demonstrated ISAC's vast potential and versatility. Our analysis delved into the significant performance gains from both sensing-assisted communication and communication-assisted sensing. Sensing-assisted communication enhances beamforming and channel estimation, especially crucial in high-frequency and high-mobility environments. Conversely, communication-assisted sensing leverages the expansive cellular infrastructure to create a cooperative sensor network, markedly improving environmental perception accuracy and coverage. We presented a practical example illustrating the benefits of ISAC integration. This example underscored the enhanced sensing accuracy, affirming its transformative impact on future wireless networks. In conclusion, while ISAC technology presents immense opportunities, several critical challenges still need to be addressed to fully realize the promise of ISAC in shaping the next generation of intelligent and interconnected systems.

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