Technologies of Integrated Sensing and Communication

vivo Communications Research Institute
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Introduction

From 2020 to 2022, vivo Communications Research Institute has released three white papers on the vision for 6G and the potential enabling technologies, including "Digital Life 2030+", "6G Vision, Requirements, and Challenges", and "6G Services, Capabilities, and Enabling Technologies" [1-3]. This white paper focuses on one of the key enablers, the Integrated Sensing and Communication (ISAC) technology. In particular, the paper elaborates on the definition, the feasibility, and the system framework, then followed by the introduction of several key technologies, e.g., waveform and signal design, multi-band collaborative sensing, and multi-antenna technologies. Along with our industry partners, we are continuously contributing to the technical development and the prototype verification of ISAC, towards constructing a freely connected digital and physical integrated world for 2030+.

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Definition of ISAC

Due to the existence of surrounding objects or the environment, the characteristics of wireless signals will be changed during propagation, such as amplitude and phase. Therefore, the receiver can not only obtain the information carried by the signals, but also extract the knowledge about the features of the objects or the environment. In other words, electromagnetic waves have an inherent sensing capability in addition to their ability to transmit information. Conventionally, communication and sensing systems were studied separately due to their different design objectives. However, both of them actually acquire and transmit information based on the transmitting and receiving electromagnetic waves. They share many similarities in the working principles, system architectures, and operating frequency bands. Hence, it is possible to reduce expenditure costs and improve spectrum utilization efficiency by integrating communication and sensing functions in the same system through shared spectrum, hardware, and signal, which is referred to as ISAC.

As one of the hot topics in 6G studies, ISAC has been widely recognized by organizations such as International Telecommunication Union--Radio communication Sector (ITU-R), China IMT-2030 (6G) Promotion Group, Next G Alliance, European Telecommunications Standards Institute (ETSI), Hexa-X, Institute of Electrical and Electronics Engineers (IEEE), and the 3rd Generation Partnership Project (3GPP). In the recommendation of "Framework and overall objectives of the future development of IMT for 2030 and beyond " [4] by ITU-R, ISAC is recognized as one of the typical usage scenarios of 6G. This scenario enables 6G systems to sense and acquire spatial information about both unconnected objects (such as human bodies) and connected devices (such as mobile phones), e.g., the movements and surroundings.

ISAC provides another promising opportunity for wireless networks and is expected to raise a wide range of diverse use cases for sensing. For example, in intelligent transportation, ISAC systems can identify emergencies by detecting vehicle position, velocity and pedestrian status from a global view. Vehicles can not only be the sensing targets, but also serve as dual-function communication and sensing nodes to work together with roadside ISAC base stations (BS) for simultaneously performing communication tasks and sensing the environment, thus achieving real-time obstacle avoidance, route selection, detection of emergencies, and compliance with traffic regulations. Besides, ISAC systems can conduct real-time traffic sensing in all-weather conditions and a wide coverage without additional deployment costs, which can effectively reduce safety hazards in road traffic scenarios.

ISAC can also play an important role in smart home, such as personal health monitoring and home security. Vital signs such as respiration and heart rate provide important clues for medical issues. Body symptoms such as rapid breathing or breathing difficulties during sleep and abnormal heart rate during activity reflect the non-healthy condition of the body. Monitoring vital signs is of great significance for personal medical care. Traditional contact-based detection is widely used in hospital monitoring, but it is not suitable for home use, because of the discomfort during sleep and the expensive specialized equipment. By using ISAC, characteristic information about respiration or heart rate can be obtained through wireless signals. In addition to vital signs, daily activities such as falls of the elderly or children can also be continuously monitored for home safety. Compared with traditional methods based on cameras or wearable devices, ISAC has great advantages, such as no need for physical contact, low cost, robust to line-of-sight conditions and lighting conditions, and high privacy preservation.

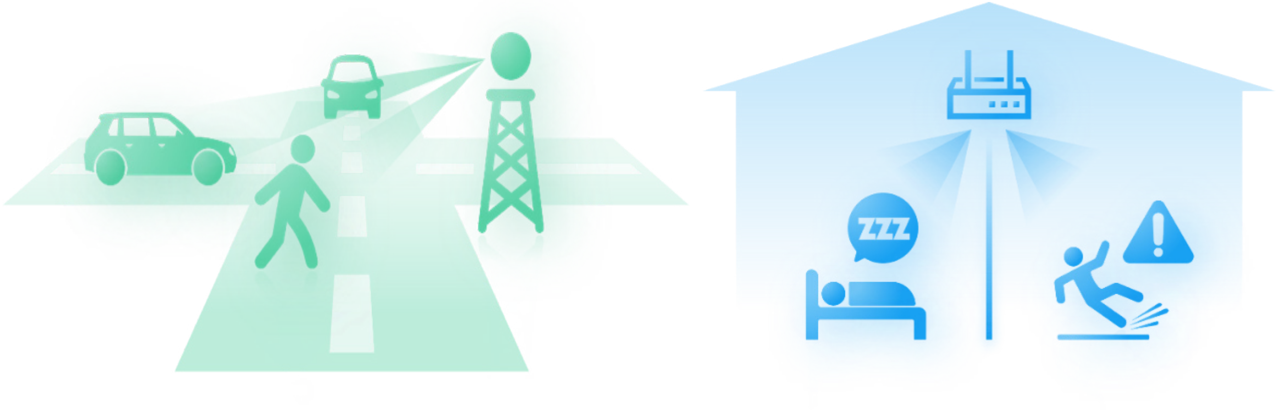


Fig. 2-1. The application of ISAC in intelligent transportation and smart home.

In addition to the scenarios of intelligent transportation and smart home, the application of ISAC will also cover other aspects of future social life, such as low-altitude unmanned aerial vehicles, industrial automation, medical health, warehousing logistics, security monitoring, agricultural meteorology, leisure and entertainment [5].

Furthermore, sensing-assisted communication is another important scenario [6-9]. Sensing can acquire the environmental information helpful to communications, such as the environment information and the communication node information. With this helpful information, the communication systems can achieve efficient beam management, improve channel estimation performance, reduce channel measurement feedback overhead, and adjust signal configuration and resource allocation strategies.

All-weather **Wide coverage** **High spectral efficiency**

03

Feasibility Analysis of ISAC

ISAC has the foundations in terms of demand, principles, and hardware conditions, and offers many benefits. However, there still exist differences in terms of the performance metrics and signal processing flow. Communication systems need to jointly transmit modulation symbols that carry information together with pilot symbols. The channel estimation algorithms only estimate the composite channel with a limited number of unknown parameters, with a focus on decoding performance, i.e., throughput and transmission reliability. In contrast, sensing systems do not need to consider information transmission issues, and typically use unmodulated transmit signals. Sensing systems focus on the changes that sensing targets bring to the transmit signals, with the optimization goal of improving parameter estimation accuracy.

3.1 Feasibility of ISAC Design

As mentioned earlier, ISAC can be achieved through shared spectrum, hardware, and signal. Typical radar systems work in frequency bands such as S (2-4 GHz), C (4-8 GHz), X (8-12 GHz), Ku (12-18 GHz), Ka (27-40 GHz), and millimeter wave (such as 70 GHz). With the continuous evolution of mobile communication systems, each new generation of mobile communication systems will be allocated new spectrum resources. The operating frequency bands used for communication and those for sensing are increasingly overlapped. Naturally, it is possible for communication and sensing to share spectrum resources, thus improving spectrum utilization.

From the perspective of the transmitter, communication and sensing can share modules such as baseband signal generation, digital/analog (D/A) conversion, RF front-end, and transmitting antenna array. From the perspective of the receiver, communication and sensing can share the receiving antenna array. To reduce the impact of self-interference, sensing systems can also use a separate receiving antenna array physically isolated from the transmitting antenna array to receive the echo signal. Additionally, the data preprocessing processes such as down-conversion, analog/digital (A/D) conversion, time-frequency synchronization, and time-frequency conversion at the receiving stage are usually the same for both communication and sensing. Communication systems use channel estimation to obtain channel information for subsequent equalization processing, completing the demodulation and decoding process. Sensing systems utilize channel information for parameter estimation to obtain corresponding sensing information. A typical scheme for sharing the transmitter and receiver modules between communication and sensing systems is shown in Fig. 3-1. The red box indicates sensing-specific processing modules, the blue box indicates communication-specific processing modules, and the black box indicates processing modules that can be shared by both.

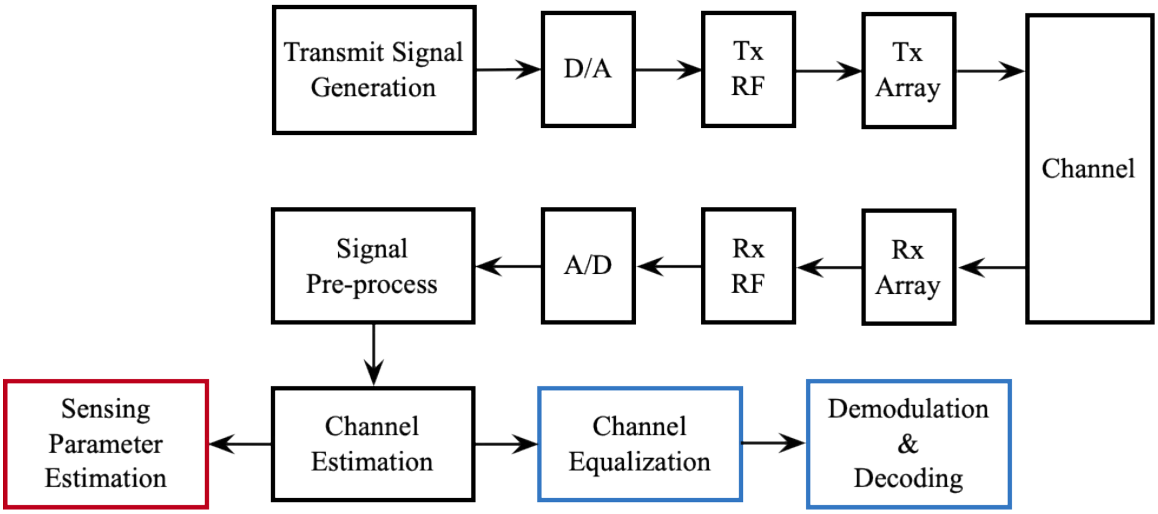


Fig. 3-1. Scheme for modules sharing of transmitter and receiver between communication and sensing systems.

Sensing systems can reuse existing signals in communication systems [10], including various reference signals used for channel measurement and channel estimation, synchronization signals, and communication data signals, etc. In addition, new dedicated sensing signals can be designed for different sensing scenarios and transmitted together with communication signals through time division multiplexing, frequency division multiplexing, spatial division multiplexing, etc.

3.2 Performance Analysis of ISAC

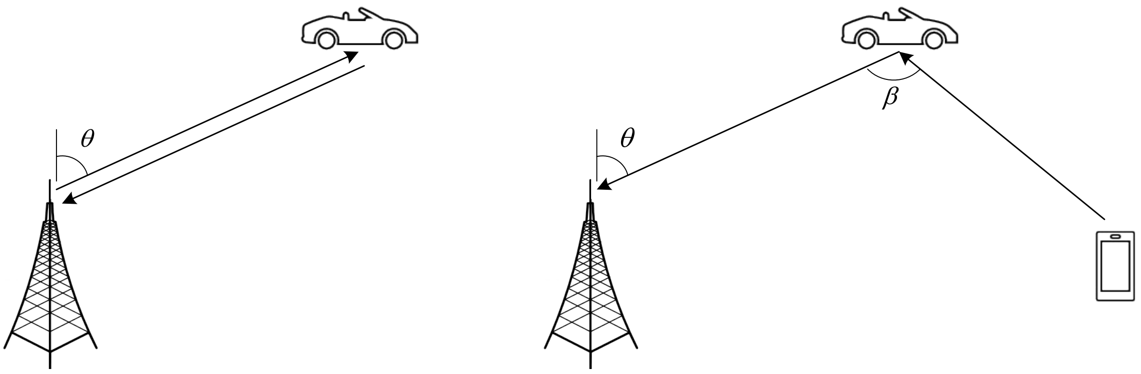
The performance metrics of ISAC can be categorized into communication performance metrics and sensing performance metrics. On one hand, communication performance metrics mainly contain bit error ratio, latency, data rate, connection density, spectrum efficiency, energy efficiency, and reliability. On the other hand, sensing performance metrics contain sensing accuracy, sensing resolution, sensing range, refresh rate, and service latency [3].

The sensing performance of ISAC systems is related to multiple factors, such as operating frequency bands, transmitting power, hardware architecture, receiving processing algorithms, and signal resource allocation. The relationship between sensing signal resource allocation and corresponding sensing performance is shown in Table 3-1 [11,12]. The time, frequency, and spatial resources of sensing signals determine the system's sensing performance in dimensions such as Doppler, delay, and angle, respectively. The bandwidth, coherent processing time, and antenna aperture of sensing signals determine the resolution of range, Doppler, and angle, while the sampling interval of sensing signals determines the maximum unambiguous sensing range. For bistatic sensing, the range and velocity measurement performance are also related to the geometric position of the receiving and transmitting equipment and the sensing target.

Table 3-1. Relationship between Sensing Signal Resources and Sensing Performance

Signal Resource Allocation	Sensing Performance
Signal Bandwidth B	Delay Resolution $\Delta\tau = 1/B$ Range Resolution (monostatic sensing) $\Delta R = c/2B$ Range Resolution (bistatic sensing) $\Delta R = c/2B\cos(\beta/2)$
Frequency Domain Sampling Interval Δf	Maximum Unambiguous Delay $\tau_{\max} = 1/\Delta f$ Maximum Unambiguous Range (monostatic sensing) $R_{\max} = c/2\Delta f$ Maximum Unambiguous Range (bistatic sensing) $R_{\max} = c/2\Delta f\cos(\beta/2)$
Coherent Processing Time T_f	Doppler Resolution $\Delta f_d = 1/T_f$ Velocity Resolution (monostatic sensing) $\Delta v = c/2f_cT_f$ Velocity Resolution (bistatic sensing) $\Delta v = c/2f_cT_f\cos(\beta/2)$
Time Domain Sampling Interval ΔT	Maximum Unambiguous Doppler $f_{d,\max} = 1/\eta\Delta T$ Maximum Unambiguous Velocity (monostatic sensing) $v_{\max} = c/2\eta f_c\Delta T$ Maximum Unambiguous Velocity (bistatic sensing) $v_{\max} = c/2\eta f_c\Delta T\cos(\beta/2)$
Antenna Aperture D	Angle Resolution $\Delta\theta = \lambda/Nd\cos\theta$
Antenna Element Spacing d	Maximum Unambiguous Angle $\theta_{\max} = \pm\sin^{-1}(\lambda/2d)$

Parameter Explanation:
β is the bistatic angle of bistatic sensing, as shown in Fig. 3-2;
η=1 when the target's motion direction is known, else η=2;
f_c is the carrier frequency, λ is the carrier wavelength,
N is the number of antenna elements, and θ is the beam direction.



（a） monostatic sensing （b） bistatic sensing

Fig. 3-2. The geometry of monostatic and bistatic sensing systems

The sensing accuracy generally depends on the sensing resolution and the signal-to-noise ratio (SNR) or signal-to-interference-plus-noise ratio (SINR) of the received signal [13]. Fig. 3-3 shows the simulation results of the sensing SINR for monostatic sensing, i.e., the base station sends and receives sensing signals, and bistatic sensing, i.e., the base station sends sensing signals and the user equipment (UE) receives sensing signals, in the urban micro (UMi) scenario. The sensing SINR represents the ratio of the signal power of the path(s) or cluster(s) reflected by the sensed target to the interference and noise, and the simulation considers co-channel interference from other cells except for the three strongest interfering cells. The radar cross-section (RCS) of vehicles and pedestrians as sensing targets is assumed to be 1 m^2 and 0.1 m^2, respectively. For bistatic sensing, it is assumed that the distance between the sensing target and the UE is not larger than 10 meters. The frequency-domain subcarrier spacing of the sensing signal is 120 kHz, with a frequency of 6 GHz and a bandwidth of 400 MHz. For high-speed targets such as vehicles, the signal transmission period is 0.125 ms with a coherent processing time of 10 ms; for low-speed targets such as pedestrians, the signal transmission period is 1.25 ms with a coherent processing time of 100 ms. Under the two typical signal resource configurations mentioned above, using two-dimensional Fourier transform for sensing signal processing can achieve a processing gain of approximately 54 dB. Processing gain is considered in the sensing SINR. Simulation results show that due to the shorter distance between the sensing receiving node and the sensing target, bistatic sensing can achieve better sensing coverage performance than monostatic sensing in mobile cellular network.

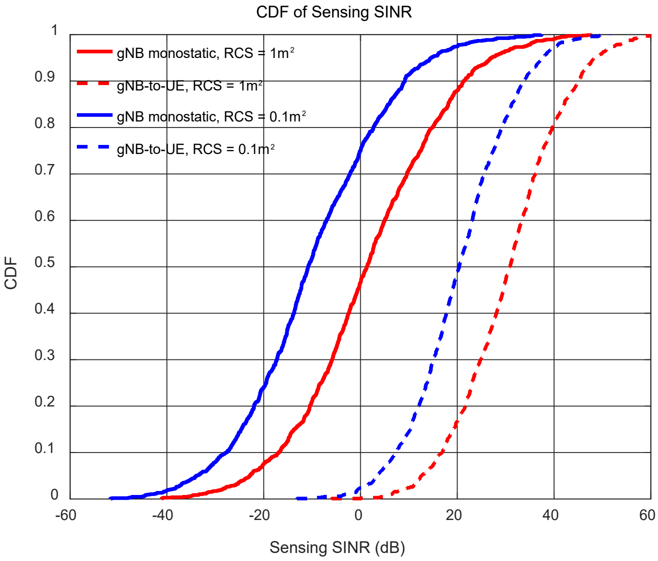


Fig. 3-3. Sensing performance simulation results in the Umi scenario.

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Framework and Key Technologies of ISAC Systems

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In this chapter, we first introduce the system framework of ISAC systems, and then analyze several key technologies of ISAC systems.

4.1 The Logical Framework of ISAC System

The system logical framework of ISAC system is shown in Fig. 4-1. The functional devices related to the sensing service in the 6G network include the sensing control device, the sensing data processing device, and the sensing transmitting and receiving device. The sensing control device is used for signaling and strategy control related to the sensing service, including sensing flow control such as sensing QoS guarantee, sensing privacy and security, and configuration of sensing signals and sensing measurements. The sensing transmitting and receiving devices are used to perform the reception and transmission of sensing signals, measurements, and obtaining information about the environment or target objects. It can be either a base station or UE, or other similar devices.

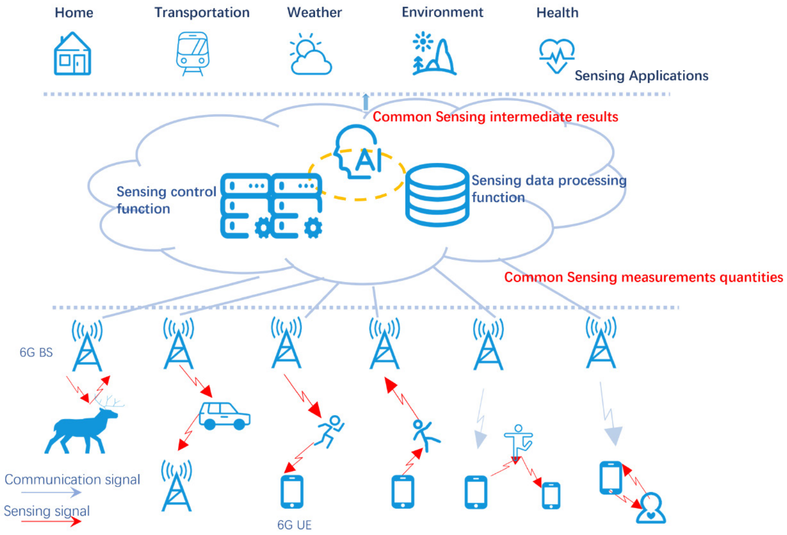


Fig. 4-1. The logical framework of ISAC system

Based on Fig. 4-1, an exemplified flow of a sensing service is depicted as follows.

Sensing service triggering:

When a consumer requests sensing services from the network, the sensing control device first triggers the sensing authorization and security verification process to confirm that the consumer can obtain relevant information about the sensing target. In addition, the sensing control device applies corresponding sensing service PCC (policy and charging control) strategies, and provides differentiated sensing service guarantees for consumers.

Selection of sensing transmitting and receiving devices:

Based on the service requirements, the sensing control device determines the appropriate sensing mode and selects the appropriate sensing transmitting and receiving devices. The appropriate sensing mode can be a mixture of multiple sensing modes.

Execution of sensing measurements:

The sensing control device triggers the sensing transmitting and receiving devices to perform signal reception, transmission, and measurement according to the corresponding sensing mode(s). Multiple sensing transmitting and receiving devices can perform multiple sensing modes, and the PCC strategy not only needs to ensure the coordination between different sensing transmitting and receiving devices, but also between communication services and sensing services.

Generation of sensing results:

The sensing transmitting and receiving devices report the general sensing data to the sensing data processing device in the network. The sensing data processing device analyzes the sensing data to obtain the general sensing intermediate results, and AI capabilities can be considered during the process. The sensing data processing device feeds back the sensing intermediate results to consumers, and business consumers process them according to their own business logic to generate the final sensing results.

From the perspective of reception and transmission of sensing signals, the ISAC system is classified into six basic sensing modes:

six basic sensing modes

- **1.Base station simultaneously transmits and receives sensing signals.**
- **2.Base station A transmits and base station B receives sensing signals.**
- **3.Base station transmits and UE receives sensing signals.**
- **4.UE transmits and base station receives sensing signals.**
- **5.UE simultaneously transmits and receives sensing signals.**
- **6.UE A transmits and UE B receives sensing signals.**

Among them, sensing mode (1) and (5) belong to monostatic sensing, and the other modes belong to bistatic sensing. The advantages and disadvantages of different sensing modes are summarized in Table 4-1. In addition to the six basic sensing modes mentioned above, the ISAC system framework will also adapt to non-3GPP sensing. Non-3GPP sensing refers to the use of sensors, cameras, radar devices, and other devices existing in the communication network to obtain sensing data.

Table 4-1. The advantages and disadvantages of different sensing modes

Sensing modes	Advantages	Disadvantages
Base station simultaneously transmits and receives sensing signals	No synchronization issues between transmission and reception	The base station needs to have full-duplex capability
Base station A transmits and base station B receives sensing signals	No full-duplex capability is required	Synchronization errors between transmission and reception will affect sensing performance
Base station transmits and UE receives sensing signals	It can reuse or enhance existing signals, does not require full-duplex capability, and by selecting suitable UE, the sensing coverage performance can be improved	Estimation errors in UE position, orientation, and velocity, as well as synchronization errors between transmission and reception, will affect sensing performance
UE transmits and base station receives sensing signals	It can reuse or enhance existing signals, does not require full-duplex capability, and by selecting suitable UE, the sensing coverage performance can be improved	Estimation errors in terminal position, orientation, and velocity, as well as synchronization errors between transmission and reception, will affect sensing performance
UE simultaneously transmits and receives sensing signals sensing signals	No synchronization issues between transmission and reception, and supports sensing in areas without network coverage	The UE needs to have full-duplex capability
UE A transmits and UE B receives sensing signals	It can reuse or enhance existing reference signals, does not require full-duplex capability, and supports sensing in areas without network coverage.	Estimation errors in terminal position, orientation, and velocity, as well as synchronization errors between transmission and reception, can affect sensing performance

The sensing use cases for ISAC are diverse and numerous, and different use cases may have different requirements for sensing measurement quantity. On one hand, it is necessary to sort and classify the sensing measurement quantity to form a unified framework, paving the way for future standardization work. On the other hand, for some use cases, the transmission overhead of sensing measurement quantity may be too large. In the process of reporting sensing measurements, data compression is required, and the data compression should not cause significant loss in sensing quality. The definition of different levels of sensing information is shown in Table 4-2, where the received signal or raw channel information is the most basic sensing information, with a large amount of data that needs to be further processed and analyzed to obtain sensing measurement quantity and sensing results.

Table 4-2. Different levels of sensing information

Sensing information	Contents of sensing information
Received signal or raw channel information	Complex results of the received signal or channel response
Sensing measurement quantity	Delay, Doppler, angle, strength, and their multi-dimensional combined representation
Sensing results/ sensing intermediate results	Presence or absence of target, distance, velocity, orientation, acceleration, position, trajectory, movement, expression, respiration rate/heart rate, imaging results, weather, air quality, material and composition, etc.

4.2 ISAC waveform and signal design

(1) ISAC Waveform Design

Waveform design in ISAC is a critical research aspect, due to its characteristics impacting sensing performance. ISAC waveform can be designed based on either communication waveforms or sensing waveforms; namely, either the enabled communication waveforms support sensing functions or the enabled sensing waveforms support communication functions. However, this approach has lower resource utilization efficiency. Alternatively, a new waveform design can be used to integrate communication and sensing functions into a single waveform, achieving an integrated design. Several potential ISAC waveforms are given below.

Communication waveforms

The design based on communication waveforms aims to achieve sensing functions while ensuring efficient communication transmission. Common communication waveforms include Orthogonal Frequency Division Multiplexing (OFDM), Discrete Fourier Transform Spread-OFDM (DFT-s-OFDM), Single Carrier Frequency Domain Equalization (SC-FDE), and Filter Bank Multi-Carrier (FBMC). OFDM is a typical multicarrier modulation technology widely used in 4G/5G mobile communication systems, with high spectral efficiency and flexible bandwidth resource allocation. OFDM waveform is used in parameter estimation without range-Doppler coupling effect, and the detection algorithm based on Fourier transform at the receiver is simple and efficient. Moreover, the transmitter mechanisms of radar and communication systems based on OFDM waveforms are almost the same, making it easier to achieve ISAC design. However, OFDM waveform has problems such as high peak-to-average power ratio (PAPR) and sensitivity to Doppler and phase noise, which require related optimization. The use of CE-OFDM (Constant Envelope-Orthogonal Frequency Division Multiplexing) design can alleviate the problem of nonlinear distortion in high-power amplifiers caused by the PAPR of traditional OFDM waveforms [14]. DFT-s-OFDM waveform uses DFT extension to provide single-carrier characteristics, thereby reducing PAPR. Some studies have applied frequency domain spectrum shaping (FDSS) to DFT-s-OFDM waveform to further reduce out-of-band (OOB) emission and inter-symbol interference (ISI) [15]. For the IEEE 802.11ad system that uses SC-FDE waveform, the short training field (STF) and channel estimation field (CEF) in the wireless frame are composed of complementary Golay sequences, which are used for communication system frame synchronization, frequency offset estimation, channel estimation, and can also be used for radar system target detection, range measurement, and velocity measurement [16]. Additionally, FBMC can be used as an ISAC waveform with good spectral characteristics and usually does not require a cyclic prefix. However, it has the same problem of high PAPR as OFDM and usually uses offset quadrature amplitude modulation (OQAM) to avoid inter-carrier interference (ICI), which makes the calculation of the sensing information more complicated at the receiver [17].

Radar waveforms

Frequency Modulated Continuous Wave (FMCW) is the widely used radar waveform. FMCW radar transmits a sequence of chirps and detects the echo signals. The chirp signal is also known as Linear Frequency Modulation (LFM) signal, whose frequency linearly changes with time. LFM signal has the advantages such as large time-bandwidth product, constant envelope, and good autocorrelation properties. The signal detection of LFM signals can be directly completed by mixing, which simplifies transceiver architecture and signal processing flow. To enable communication capabilities with FMCW, data can be embedded into FMCW waveforms. For example, communication information can be carried by changing the frequency slopes or initial frequencies. Furthermore, ISAC design based on radar waveforms can also be combined with spatial modulation or generalized spatial modulation, such as carrying communication information by selecting different transmitting antennas, which can avoid changing the characteristics of the sensing signal and minimize the impact on sensing performance. The above schemes that implement communication functions based on FMCW typically suffer from low communication efficiency.

New waveforms for ISAC

Orthogonal Time Frequency Space (OTFS) is a new candidate of the 6G ISAC waveform. OTFS technology defines a transformation between the delay-Doppler domain and the time-frequency domain and maps communication data and pilot signals to the delay-Doppler domain for processing. Existing research has shown that OTFS is comparable to OFDM waveforms in terms of sensing parameter estimation performance, and its cyclic prefix overhead is smaller than that of OFDM, which means OTFS achieves higher spectral efficiency at the cost of higher complexity [18]. Some studies have also designed new ISAC waveforms by combining chirp and OFDM. Chirp signals are used instead of single-frequency signals as subcarriers in OFDM systems, which reduces PAPR compared to traditional OFDM waveforms without increasing the complexity of the receiving end [19].

(2) ISAC Signal Design

ISAC signal design includes sequence design and resource mapping design. The design principle is to pursue the optimal measurement performance of basic sensing measurement quantities such as delay, Doppler, and angle while satisfying certain signal resource costs.

Sequence design

Sequences with good auto-correlation properties such as Barker codes, Gold sequences, Kasami sequences, and Zadoff-Chu sequences, are usually used in the design of phase-coded radar signals and communication pilot signals. In addition to autocorrelation characteristics, cross-correlation characteristics, envelope characteristics, and sequence length are also important in sequence design. In OFDM communication systems, a cyclic prefix is generally added to each symbol, and least square (LS) channel estimation is used to obtain channel information for sensing, such as range and Doppler. The autocorrelation characteristics of the transmitted sequence generally do not affect the channel information acquisition. However, other characteristics of the sequence will affect the performance of interference resistance and noise resistance, hence sequence design is still an important aspect to be considered in sensing signal design.

Sequence design in communication systems usually only considers sequence characteristics in the time domain or frequency domain, while sensing data processing usually requires combining multiple symbols or multiple time slots, and both time and frequency domain dimensional characteristics of the sequence need to be considered. For example, for communication reference signals generated and mapped in the frequency domain, the time-domain autocorrelation sidelobes of multiple OFDM symbols are relatively high. To improve their time-domain autocorrelation characteristics, time-domain scrambling can be used. Assuming that each coherent processing time for sensing contains M OFDM symbols, and each symbol carries a reference signal sequence of length N, i.e., , a sequence with good autocorrelation and cross-correlation characteristics is used to phase-modulate the reference signal sequences carried by different symbols, resulting in . The new signal design improves the time-domain sequence characteristics by phase-modulating the reference signal sequences with different symbols, without affecting the frequency-domain sequence characteristics. Regarding the multi-target perception, this design can reduce interference and improve sensing performance when compared with communication reference signal designs where only frequency-domain sequence characteristics are considered.

In order to further make full use of the signal resources in the ISAC system and improve the sensing performance, communication data can also be used to assist sensing measurement. For the bistatic sensing mode, since the transmitted data are unknown to the receiver, data demodulation and decoding are required to recover the transmitted data before calculating the sensing results. In communication systems, communication data typically require more resource allocation. Using communication data signals to assist sensing measurement can improve processing gain. Due to the increased time-frequency domain resource density, the maximum unambiguity measurement range can be increased. However, the sensing performance may be compromised by the decoding errors at the receiver and the misalignment of the beam directions between the data signals and the sensing signals.

Signal resource mapping design

The mapping of sensing signal resources needs to consider meeting performance requirements such as sensing resolution and sensing measurement range. Larger signal bandwidth and longer signal duration can provide higher range resolution and velocity (Doppler) resolution, respectively. Increasing signal frequency-domain density and time-domain density can provide a larger unambiguous range and unambiguous velocity (Doppler), respectively. In traditional radar sensing, signals with long duration and large bandwidth are typically sent with continuous resources. However, in ISAC systems, the impact on communication data rate also needs to be considered, which limits the resource allocation for sensing to some extent. The design of signal resource mapping patterns needs to be based on the different requirements for the aforementioned sensing performance in sensing applications. For example, in low-speed target detection scenarios with a high velocity resolution requirement, a signal pattern with a longer duration, lower time-domain density, smaller bandwidth, and lower frequency-domain density can be used. Another option is to abandon some time-frequency resource elements while ensuring sensing resolution, that is, not using a regular rectangular resource pattern. At the same time, the maximum bandwidth in the irregular resource pattern needs to meet the ranging resolution requirements or the maximum time-domain resource length needs to meet the velocity (Doppler) resolution requirements. Alternatively, a resource pattern design with non-uniform sampling intervals can be used to balance the contradiction between sensing measurement range and resource allocation.

Stepped-frequency radar with high-range resolution is widely used. Drawing on the idea of using narrow instantaneous bandwidth to achieve large system bandwidth in stepped-frequency radar, frequency hopping is used to map sensing signal resources to obtain high sensing resolution. Using Costas codes with an approximate "thumbtack" ambiguity function to replace stepped-frequency codes can alleviate the range-Doppler coupling problem in stepped-frequency radar and improve radar detection performance [20]. In the design of ISAC systems, the frequency hopping idea of Costas codes can also be used for signal resource mapping. Fig. 4-2 shows the resource mapping relationship of two Costas arrays in an OFDM system with orders of 6 and 12, respectively.

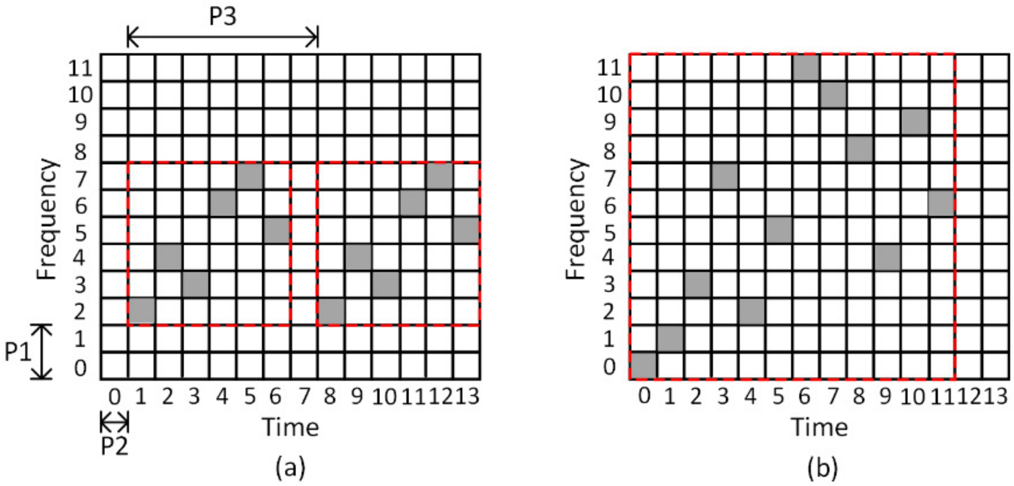


Fig. 4-2. Resource mapping relationship of Costas arrays in an OFDM system

In order to reduce the resource overhead of sensing signals in time, frequency, and spatial dimensions, sub-Nyquist sampling method can be employed to design sensing signals based on compressive sensing theory, as shown in Fig. 4-3. When sensing signal is designed based on sub-Nyquist sampling method, the sampling position of sensing signal should satisfy the restricted isometry property (RIP) [21]. In general, random sampling position could satisfy the RIP, which leads to much convenience to sensing signal design based on sub-Nyquist sampling. Besides, the sampling number cannot be arbitrarily small, and the relationship of should be satisfied, where M is the sampling number of sub-Nyquist sampling, N is the corresponding sampling number of full sampling, K is the number of sensing targets and α is a constant. Therefore, if the number of sensing targets is smaller in the environment, the sampling number of sub-Nyquist sampling can be configured smaller, which leads to less resource overhead. It is worth noting that, sensing signal design based on sub-Nyquist sampling requires higher signal processing capability at the sensing receiver and the overhead of signal configuration is higher, compared to the traditional sensing signal design based on full sampling.

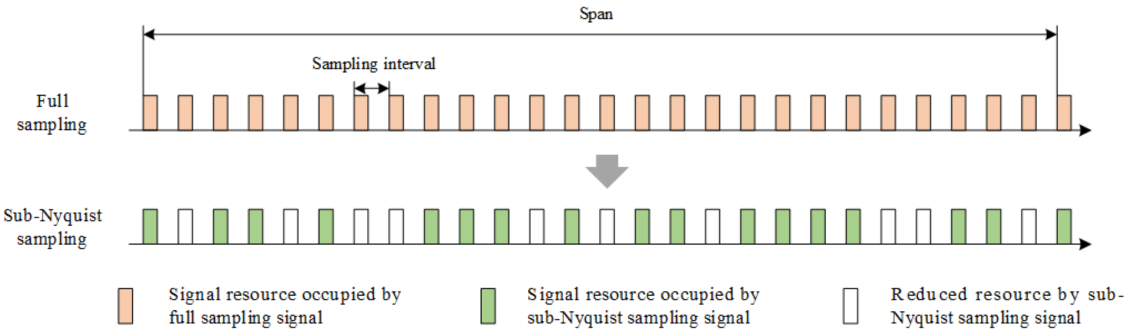


Fig. 4-3. Sensing signal based on sub-Nyquist sampling

4.3 Multi-Band Collaborative Sensing

Multi-band collaborative sensing can fully utilize spectrum resources and thus improve spectrum utilization efficiency. On one hand, multi-band collaborative sensing expands the bandwidth resources, benefiting high-resolution sensing. Moreover, the signal wavelengths in different frequency bands are different, and their channel response characteristics are different. Making full use of different frequency bands for sensing can obtain more comprehensive sensing information. On the other hand, various types of communication networks, such as 6G, 5G, Wi-Fi coexist, and multi-band collaborative sensing technology can enable different types of communication networks to collaborate in sensing, thereby improving the stability of ISAC systems and expanding their application scope. Multi-band collaborative sensing can be divided into multi-band independent measurement and multi-band joint measurement, depending on how sensing data are processed.

Multi-band independent measurement refers to obtaining sensing measurements on different frequency bands separately, and then fusing the sensing results for different frequency bands. On one hand, different sensing measurement quantities can be assigned to different frequency bands for measurement based on the characteristics of each frequency band. On the other hand, the same sensing measurement quantity can also be assigned to different frequency bands, and then the results obtained from each band can be non-coherently combined. In addition, different frequency bands can also work together in a cooperative manner during the measurement process. For example, coarse-grained measurements can be based on low-frequency bands first, and after that, fine-grained measurements can be based on high-frequency bands to obtain the final measurement results. The advantage of multi-band independent measurement for collaborative sensing is that it brings simplicity for implement. However, it may lead to redundant information and inconsistent sensing results, and cannot fully utilize the advantages of increased bandwidth resources brought by multi-band collaborative sensing.

Multi-band joint measurement refers to the joint acquisition and fusion of sensing data on different frequency bands, which can obtain more comprehensive and accurate sensing results. The sensing range resolution is inversely proportional to the signal bandwidth. In practical systems, due to resource overhead limitations, different user resource scheduling and allocation strategies, hardware performance and other factors, it may not be possible to use continuous large-bandwidth signals for sensing measurements. Using multiple discontinuous frequency bands for range measurement can improve the range resolution. Compared with the sensing based on a single continuous band with bandwidth of (B1+B2), two discontinuous frequency bands with bandwidth B1 and B2 for sensing measurement and coherent processing can obtain a higher range resolution, due to a larger span of discontinuous frequency bands. The larger the interval between the two discontinuous bands, the higher the range resolution.

However, compared to the continuous frequency band, measurement based on discontinuous frequency bands may introduce additional interference due to the lack of sampling information. Therefore, its performance in low SNR region is not as good as that of sensing under continuous frequency band. The challenge of multi-band joint measurement also lies in the fact that there may be random initial phase problems in different frequency bands, which can have a serious impact on the use of coherent processing. It requires special receiver processing and transmitter signal design to solve the phase distortion problem between the bands, leading to a high level of implementation complexity.

4.4 Multi-antenna Technologies

In wireless communications, with the help of multi-antenna technologies, spatial diversity and spatial multiplexing can be achieved, which can respectively improve communication reliability and communication capacity. Multi-antenna technologies are also vital for wireless sensing as they expand the sensing dimension, that is, enable the system to have the ability to sense the azimuth and elevation of the target. It also can enhance the sensing performance, and improve sensing reliability and energy efficiency.

Through digital/analog beamforming, the ISAC system equipped with multiple antennas can form high-gain narrow beams, which concentrate most of the energy of the sensing signal in the sensing area or sensing target, improving the SNR of the reflected signal. When the angle range of the sensing area is large, or there are multiple targets/areas to be sensed, beam sweeping may be required. However, beam sweeping takes longer time than single-shot measurement, making it unsuitable for real-time sensing. If a wider beam is used to cover the target/area, it sacrifices the sensing accuracy or sensing SNR, under the assumption that the total transmission power is the same.

Future multi-antenna ISAC systems are likely to have both MIMO communication and MIMO radar functions [22], and can utilize the virtual array (VA), which is proposed in the field of MIMO radar, to improve the angle sensing accuracy. Based on the VA principle, by deploying the transmitting and receiving antennas in a reasonable manner, an angle resolution corresponding to MN-element array can be obtained using only M+N antenna elements. When the number of antennas on one side of the MIMO system is limited (such as the UE side), high-resolution sensing can be achieved by increasing the number of antenna elements used on the other side. In addition, this technology can effectively suppress clutter interference through array signal processing methods such as spatial filtering.

In multi-antenna ISAC system, it is reasonable to use both beamforming and VA technology. In this combination, the beamforming process can refer to the beam management of the existing 5G system. The optimal sensing beam can be determined based on the measured values of the sensing measurement quantities (such as Doppler, range, and angle) or the sensing performance indicators (such as sensing SNR). Fig. 4-4 is a schematic diagram of multi-antenna ISAC system for illustration, which consists of base station and UE. In this scenario, the UE sends an ISAC signal, and the BS receives the signal to sense the positions of the vehicles in the environment, while communication is also carried out between the UE and the BS. The BS is equipped with multiple digital channels, each of which is connected to an antenna subarray. Assuming that the BS has 6 antenna ports (i.e., 6 digital channels) and the UE has 2 antenna ports (i.e., 2 digital channels), the BS and UE can construct a VA with a maximum of 12 antenna ports. The system can obtain measured values of communication measurement quantities and sensing measurement quantities, through two independent beam sweeping processes which correspond to communication and sensing respectively, or a joint beam sweeping process, to determine the communication beams and sensing beams. As shown in Fig. 4-4, the sensing beams point to the sensing target, while the communication beams point to the BS and UE. It should be pointed out that, the design of hybrid analog/digital large-scale MIMO architecture with low cost and flexibility, as well as high-precision phase control scheme, are the prerequisites for the practical implementation of the aforementioned multi-antenna ISAC technologies. In addition, flexible and low-complexity ISAC beamforming and precoding schemes are not yet mature requiring further research in the future.

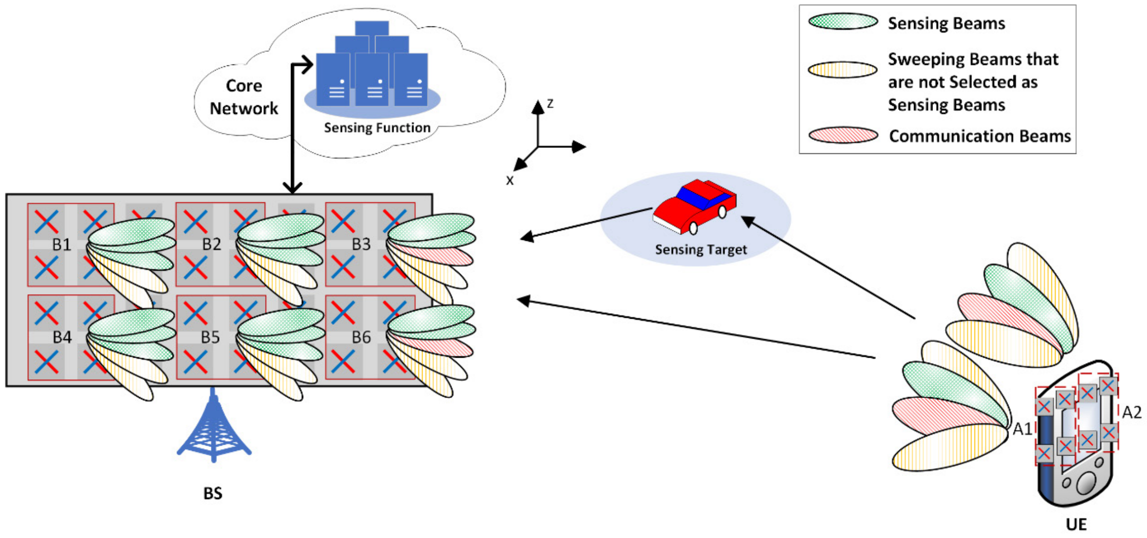


Fig. 4-4. Illustration of beam management for multi-antenna ISAC system

4.5 Coordinated Multiple Points (CoMP) for Sensing

One benefit of monostatic sensing is that there are no synchronization issues between the receiving and transmitting nodes. One of its drawbacks, however, is that the sensing node needs to have full-duplex capability to avoid self-interference. Another drawback is that the sensing node can only "see" one side of the sensing target that is facing towards the node, and cannot "see" the other sides of the target. This is because the radar cross-section (RCS) of most sensing targets varies at different angles, while the angles having a smaller RCS will affect the sensing performance.

To address the drawbacks of monostatic sensing, it is possible to consider introducing Coordinated Multiple Points (CoMP) for sensing. Bistatic sensing is the simplest form of CoMP for sensing, which includes BS-to-BS bistatic sensing, as well as BS-to-UE bistatic sensing and UE to BS bistatic sensing. In BS-to-BS bistatic sensing, BS locations are generally fixed, thus there may be situations where the base station is far from the sensing target, resulting in difficulty in meeting the sensing requirements for certain target locations.

BS to UE bistatic sensing and UE to BS bistatic sensing can reuse existing frame structures and existing signals. By selecting suitable UE (such as those closer to the sensing target) to participate in the sensing process, the sensing coverage performance can be improved. However, the drawback is the estimation error of UE position, orientation, and velocity, as well as synchronization errors between BS and UE, which can affect the sensing performance. A feasible solution is to introduce a special type of UE, that is, assisting UE for sensing. Assisting UE for sensing can be placed to the locations closer to the sensing target, and kept relatively stationary. Their position and orientation are known to avoid the impact of estimation errors of UE position, orientation, and velocity on sensing performance. Please refer to Table 4-3 for more differences between assisting UE for sensing and regular UE.

Table 4-3. The differences between assisting UE for sensing and regular UE

Attributes	Assisting UE for sensing	Regular UE
Owner	Operators or industry users or consumers	Consumers
Whether it is mobile or not	Relatively stationary	Mobile
Power supply method	Battery, or through wired or wireless charging	Battery
Uplink and downlink capabilities	Both uplink and downlink capabilities, or only downlink, or only uplink	Both uplink and downlink
The hardware capabilities, size, and number of antennas	Higher, larger, and more numerous than those of regular terminals	-
Synchronization capability between the terminal and the base station	Synchronize with the base station through wired connection, GNSS, or air interface.	Synchronize with the base station through air interface

Furthermore, on the basis of bistatic sensing, more complicated forms, i.e., CoMP for sensing can be considered, as illustrated in Fig. 4-5. CoMP for sensing contains sensing with more nodes (e.g., more than two), CoMP sensing with different sensing modes, CoMP sensing with different frequency bands, and CoMP sensing with integrated RF sensing and non-RF sensing.

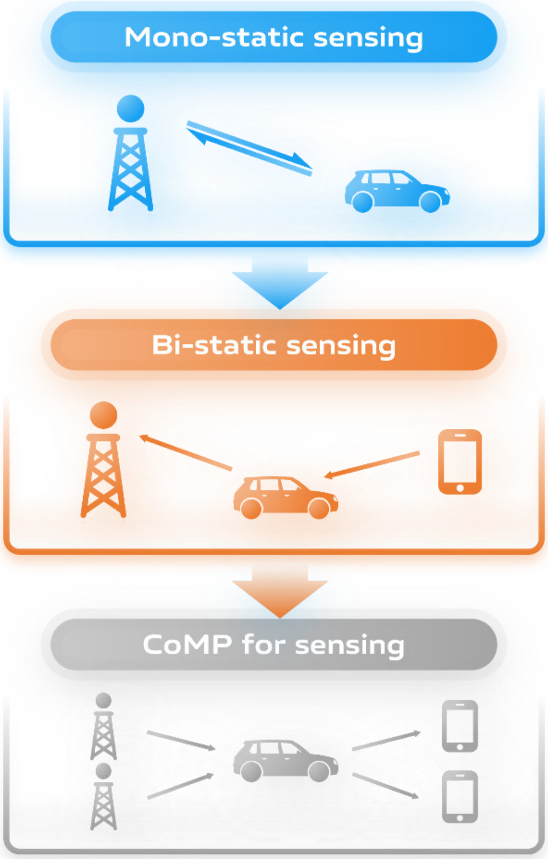


Fig. 4-5. Development path from monostatic sensing to bistatic sensing to CoMP sensing

Compared with monostatic sensing, CoMP sensing can improve sensing coverage range, enhance sensing performance, and improve system robustness and interference resistance ability. In particular, CoMP sensing can solve problems including the blind speed problem caused by the special motion direction of the sensing target in monostatic sensing or bistatic sensing, the blind spot for distance detection caused by the sensing target located near the line connecting two nodes of bistatic sensing, as well as the angle measurement ambiguity caused by the sensing target being in the same plane as the receiving antenna panel. In CoMP sensing, it is necessary to collect and process sensing information from multiple nodes to generate the final sensing results, and it is necessary to consider the trade-off between the volume of the sensing information data and the cooperative gain of CoMP.

The challenges of CoMP sensing include synchronization issues between the participating receiving and transmitting nodes, hardware inconsistency issues, and the various types of interference including intra-cell/inter-cell co-frequency interference, cross-link interference, etc.

4.6 Link Adaptation Technology

To achieve optimal allocation of signal resources while meeting the sensing performance requirements of sensing use cases, the network needs to adaptively adjust the resource allocation of sensing signals, which is known as link adaptation technology of ISAC. It helps to improve the overall efficiency of ISAC system.

The basic procedure of the link adaptation technology for sensing is shown in Fig. 4-6. The sensing receiver receives the sensing signal sent by the sensing transmitter and obtains the sensing measurement quantities. After that, the sensing receiver provides specified sensing measurement quantities to the network. Based on the sensing measurement quantities and in consideration of other factors, the network determines whether it needs to update the resource allocation of the sensing signal. If necessary, the network notifies the sensing transmitter of the updated sensing signal resource configuration.

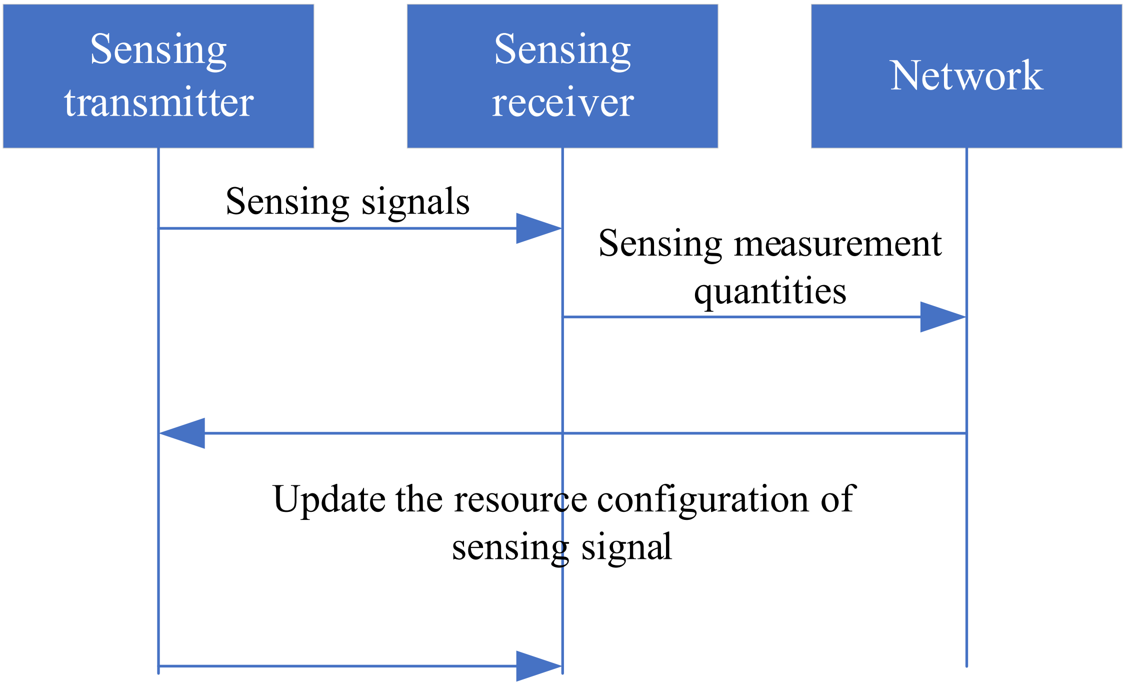


Fig. 4-6. Procedure of link adaptation technology for ISAC

To perform the link adaptation for sensing, the network needs to collect the sensing measurement quantifies and then to execute the adaptive adjustment of resource allocation in power, time, frequency and spatial domain.

Adaptive adjustment in power domain

The sensing receiver shall feedback the sensing signal power and the sensing SNR to the network, with which the network makes the decision and execute the adaptive adjustment of transmitted power of sensing signal. The sensing signal power represents the signal power of the certain rays or clusters which are reflected through the sensing target, and the sensing SNR is the ratio of the sensing signal power to the noise.

Adaptive adjustment in time domain

The sensing measurement quantities that sensing receiver need to feedback include Doppler or target velocity, the variance of Doppler or target velocity, the variance of delay or target range, and the variance of target angle. In these measurements, variance of Doppler or target velocity, variance of delay or target range, and the variance of target angle, can express the variation of the target velocity. In the adaptive adjustment of time resource, the precondition is that the requirements of the measurement resolution and the maximum unambiguous scope of Doppler or target velocity should be satisfied. Smaller time sampling interval helps to improve the sensing signal power and sensing SNR, and smaller sensing update period helps to maintain the stable tracking for the sensing target. However, larger sensing frame interval results in the problems of range migration. Therein, the sensing update period should be chosen between two shots of sensing signal processing.

Adaptive adjustment in frequency domain

The sensing receiver need to feedback the target delay or range to the network. In the premise of satisfying the requirements of the measurement resolution and maximum unambiguous scope of delay or target range, smaller sampling interval in frequency domain, which means more subcarriers allocated to sensing signal, will help to improve the coherent processing gain of the sensing signal, and finally results in higher sensing signal power and sensing SNR.

Adaptive adjustment in spatial domain

The sensing receiver need to feedback the target angle to the network. In the premise of satisfying the requirements of the measurement resolution and maximum unambiguous scope of target angle, fewer antenna elements and larger antenna interval can help to reduce the resource overhead of sensing signal.

According to the above discussion, in the adaptive adjustment of sensing signal, the adjusting parameters and the corresponding sensing measurement quantities are as listed in Table 4-4.

Table 4-4. Adjusting parameters and sensing measurement quantities in adaptive adjustment of sensing signal

Domain	Adjusting parameters	Sensing measurement quantities
Power	EPRE	Sensing signal power, sensing SNR
Time	Temporal sampling interval, sensing frame interval, sensing update period	Doppler/velocity,variance of Doppler/velocity,varianceof delay/range, variance of angle
Frequency	Frequency sampling interval, bandwidth	Delay/range
Spatial	Number of antenna elements, interval of antenna elements	Angle

4.7 Mobility Management

The mobility management for ISAC aims to ensure service continuity, which includes two aspects: the continuity of communication service and the continuity of sensing service. The changes of the states (including spatial position, spatial orientation, velocity, etc.) of the sensing target and the sensing nodes, or the changes of the environment may affect the sensing performance of the ISAC system. In addition to the aforementioned beam management for ISAC which ensures the Quality of Service (QoS), the network may need to carry out the mobility management.

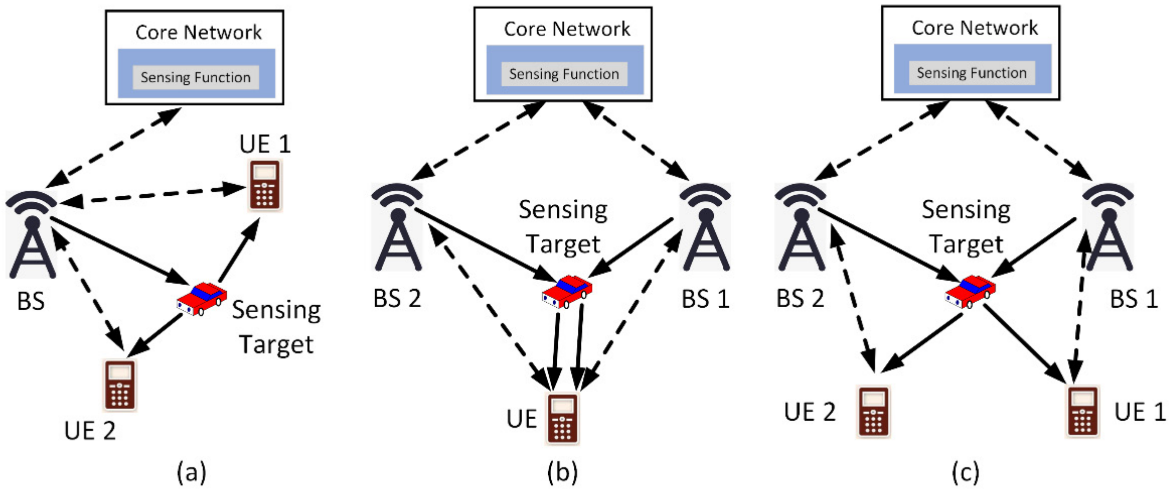


Fig. 4-7. Illustrations of sensing node handover with bistatic sensing mode

In what follows, we make a brief discussion of several typical sensing handover scenarios. It is assumed that the sensing signal or ISAC signal is transmitted from the BS and received by the UE, and the UE can perform range measurement and velocity measurement for the mobile vehicle in the sensing area.

Fig. 4-7 (a) shows the scenarios where the UEs perform handover. When the target moves from near UE 1 to near UE 2, the quality of the sensing signal or ISAC signal reflected by the target may significantly decrease, due to the increase of the propagation distance between UE 1 and the target, or the changes of the target's Radar Cross-Section (RCS). It results in a performance decrease or interruption of the sensing service. BSs or sensing function in the core network can schedule UE 2 as the new sensing node after handover, based on the UE information they acquire for the local area.

Fig. 4-7 (b) shows the scenario where the BSs perform handover. Similarly, the sensing service is performed seamlessly, through the BS 1 (i.e., the source node) or the sensing function schedules BS 2 (i.e., the target node) as the new sensing node. Fig. 4-7 (c) shows the scenario where both the BSs and UEs carry out handover. Before the handover, BS 1 and UE 1 perform the range and velocity measurements for the target, and after the handover, BS 2 and UE 2 perform the range and velocity measurements for the target.

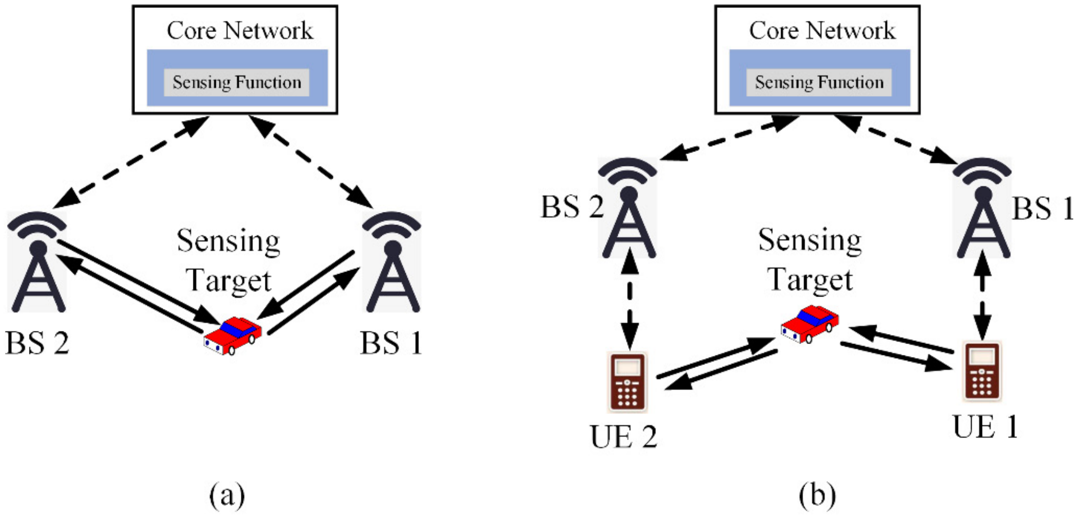


Fig. 4-8. Illustrations of sensing node handover with monostatic sensing mode

For the monostatic sensing mode, it is also necessary to perform handover between different sensing nodes, including BSs and UEs, to ensure the continuity of sensing service, as shown in Fig. 4-8 (a). The BS 1 or the sensing function can schedule BS 2 as the new sensing node after handover based on the information of other BSs in the area, and perform monostatic sensing. This situation is similar to UE monostatic sensing, as shown in Fig. 4-8 (b).

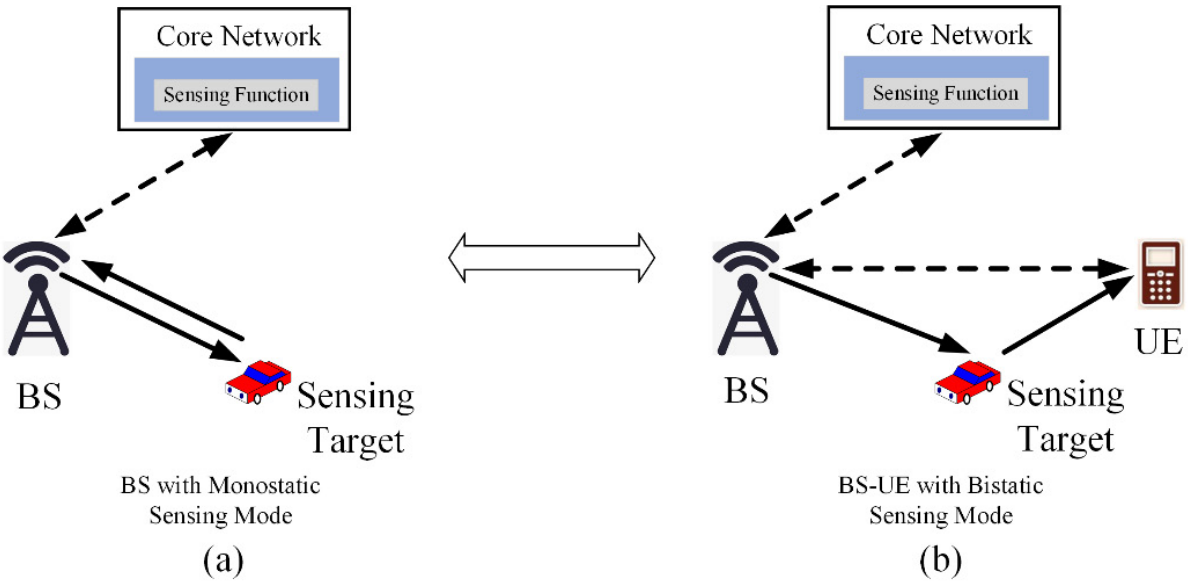


Fig. 4-9. Illustration of sensing mode switchover

Considering the differences in sensing capabilities among different sensing nodes (including BSs and UEs), and the irregular distribution of sensing nodes, handover between sensing nodes may also be accompanied by the switching of different sensing modes. Again, we take the range measurement and velocity measurement of mobile vehicle as example. Fig. 4-9 shows a schematic diagram of sensing mode switching. Assuming that before switching, the BS performs range and velocity measurements to the vehicle with monostatic sensing mode. The BS transmits the sensing signal or ISAC signal and receive the echo. When the target gradually moves away from the BS, a performance degradation or interruption of the sensing service may occur due to the increase of the round-trip propagation distance, or the changes of the target's RCS. At this point, the BS or sensing function can schedule a UE and a BS near the target based on information of all the BSs and UEs in the vicinity of the target. The range and velocity measurements to the target can be continuously performed with BS-UE bistatic sensing mode. It is noted that in this scenario, the BS participating in sensing after the sensing mode switching can be different from the source BS.

4.8 Solution to Sensing Non-ideal Factors

In the ISAC application, the sensing non-ideal factors which are caused by the non-ideal nature of devices can lead to serious measurement errors, which in turn affects the accuracy of sensing. [10, 23]. The sensing non-ideal factors mainly include timing offset (TO), local frequency offset (LFO), channel inconsistency, and temporal random phase. These sensing non-ideal factors may not have significant impact on communication performance, but can significantly impact the sensing performance. Sharing the clock between the transmitter and receiver of the sensing signal is the most direct method for solving the problem of TO and LFO [24]. Besides, following are other solutions of sensing non-ideal factors.

(1) CSI ratio or CSI conjugate multiplication

◉ The division operation or conjugate multiplication for the received signals from multiple receiving antennas sharing common clock source, can be used to suppress the influence of the LFO and temporal random phase between the transmitter and receiver, and extract the Doppler frequency of the sensing target.

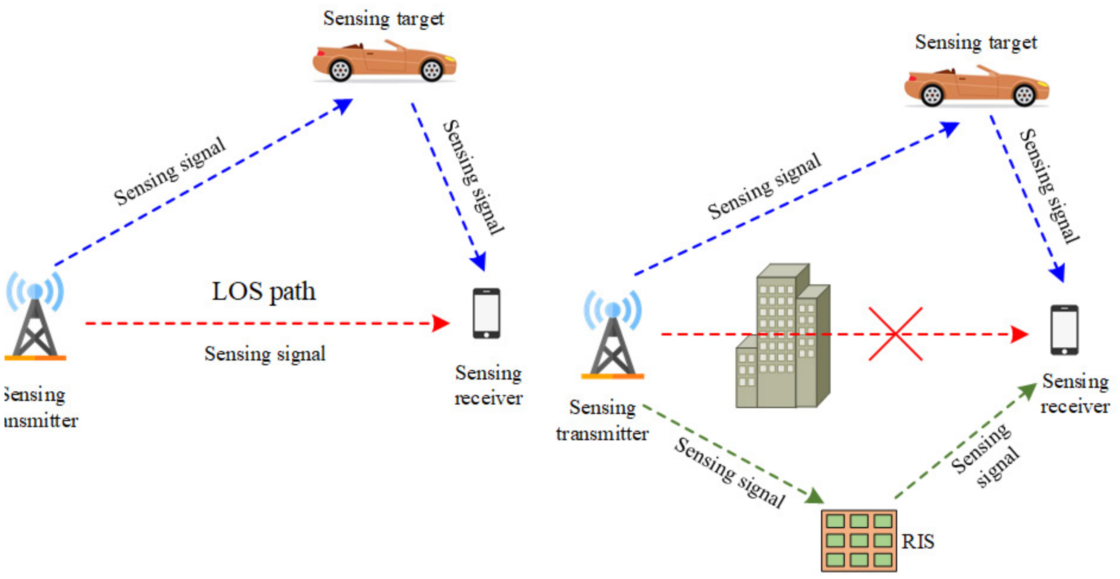
◉ The basic principle of CSI ratio or conjugate multiplication is that the LFO and temporal random phase on the received signals of two antennas are the same if the two antennas are connected to the same RF (Radio Frequency) and baseband module. Thus, the LFO can be easily removed after division operation or conjugate multiplication. Furthermore, when the power of the static path is dominant, the CSI ratio method can extract the Doppler frequency of the sensing target which is not affected by the image frequency of the Doppler frequency shift.

◉ The CSI ratio or conjugate multiplication has some limitations. Firstly, only the Doppler frequency of the sensing target can be extracted, while the delay ambiguity caused by TO cannot be solved. Secondly, this method requires that only the dynamic path (with Doppler shift) corresponding to the sensing target dominates in the sensing environment, and all other paths should be the static paths. This means that there should be no other moving targets in the environment. Lastly, the Doppler frequency extracted with conjugate multiplication suffers from the problem of ambiguity, which comes from the image frequency in the results of conjugate multiplication.

(2) Reference path

◉ A reference path is a path whose parameters can be determined in advance based on the prior information in a sensing measurement environment. The core idea is to estimate the additional delay and Doppler frequency (i.e., TO and LFO) superimposed on this path through the known signal propagation delay and Doppler frequency of the reference path. As shown in Fig. 4-10(a), the most typical reference path is the line of sight (LOS) path [25].

- When there is no LOS path between the transmitter and receiver of sensing signal due to shadowing or some other reasons, the Reconfigurable Intelligent Surface (RIS) can be used for relay to obtain the reference path [26], as shown in Fig. 4-10(b). Given the position of the RIS, the real delay and Doppler frequency can be calculated according to the position relationship of the transmitter, the RIS and the receiver. Similar to the case of LOS path, the TO and LFO can be obtained by comparing the measured delay and measured frequency of the reference path reflected by RIS with the real delay and Doppler frequency. Furthermore, RIS can modulate the sensing signal, and the receiver of the sensing signal can identify the reference path reflected by RIS through the modulation information of RIS [27].



(a) LOS Path as Reference Path

(b) Reference Path After RIS Reflection

Fig. 4-10. Reference Path Method

(3) Round-trip measurement

Similar to the Round-Trip Time (RTT) method [28] in NR (New Radio) positioning, in ISAC system, the TO and LFO between transmitter and receiver of sensing signal can be estimated through round-trip measurement. The basic assumption is that, in a short period (for example, few milliseconds to tens of milliseconds), the movement state (position and velocity) of the sensing target does not change. Towards the same sensing target, when the sensing signal is transmitted and received in a round-trip mode between the transmitter and receiver, signal propagation delays or Doppler frequencies in the round-trip are the same, while the TO or LFO have the same absolute value and opposite signs in the round-trip. Therefore, the TO and LFO can be extracted or suppressed.

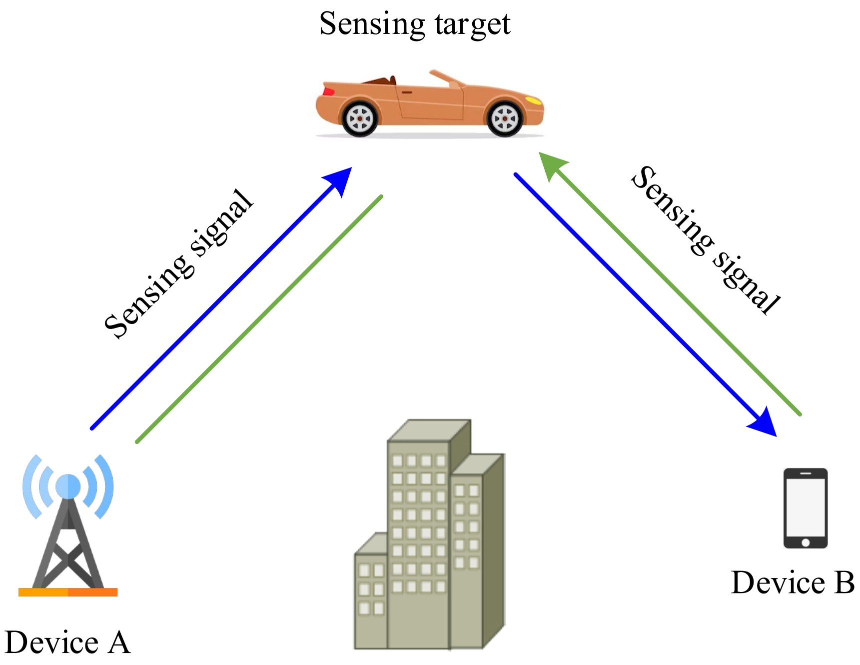


Fig. 4-11. RTT Measurement Method

4.9 Sensing Security and Privacy Protection Schemes

The introduction of sensing provides new business capabilities for wireless communication systems, but it also brings new security and privacy issues. Some of the information obtained from sensing may be private in nature, and there is a risk of information leakage, such as the location or behavior of the target, the monitoring data of vital signs, and the imaging results of a specific area. Therefore, corresponding regulatory rules and means are needed to regulate sensing applications, as well as effective technical means to protect sensed information to prevent privacy leakage and other security incidents. Some potential sensing security and privacy protection schemes are described below.

(1) Sensing signal encryption

In view of the characteristics of sensing signals of OFDM waveforms, the privacy problem of sensing results can be solved by starting from the wireless sensing signal transmitting and measuring process. The transmitting or receiving devices of sensing signals encrypt the sensing signals according to the demand of sensing encryption, i.e., encrypting the sensing information such as delay (range) and Doppler (velocity) by means of time and frequency domain scrambling. Therefore, only specific devices can acquire the correct sensing measurement results. The transmitting data with the number of subcarriers N and the number of symbols M is represented in matrix form as

$$X = \begin{pmatrix} c_{0,0} & \cdots & c_{0,M-1} \\ c_{1,0} & \cdots & c_{1,M-1} \\ \vdots & \ddots & \vdots \\ c_{N-1,0} & \cdots & c_{N-1,M-1} \end{pmatrix}$$

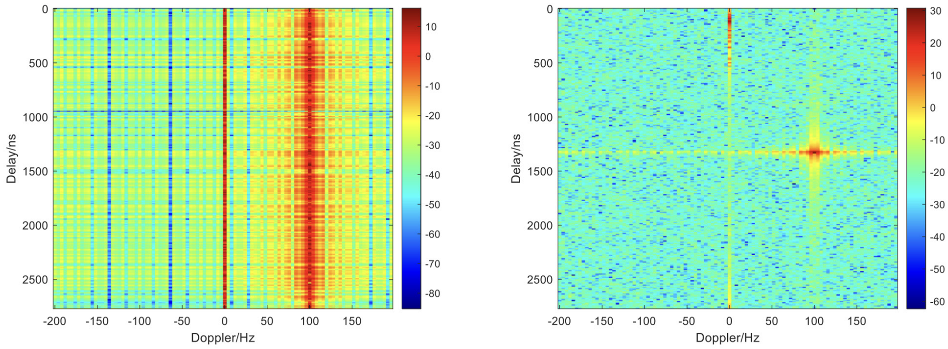
Where $c_{k,l}$ represents the modulation data carried on the k-th subcarrier and l-th symbol. Taking delay (range) encryption as an example, based on the scrambling sequence , $\{e^{-j\alpha_k}, k = 0,1,\ldots,N-1\}$ the transmitting data matrix is scrambled along the frequency domain dimension. The received signal can be represented as:

$$Y'_{k,l} = c_{k,l}H'_{k,l} + W_{k,l} = c_{k,l}A_{k,l}\sum_{q=0}^{Q-1} e^{j2\pi T_O f_{D,q} l} e^{-j\left(2\pi k\tau_q \Delta f + \alpha_k\right)} e^{j\varphi_q} + W_{k,l}$$

where τ_q represents the delay caused by the q-th target, $f_{D,q}$ represents the Doppler shift caused by the relative velocity of the q-th target, T_O is the OFDM symbol duration, $A_{k,l}$ represents the channel amplitude attenuation factor, and $W_{k,l}$ represents the noise. Based on the original sending signal X, the channel information obtained by LS channel estimation can be represented as:

$$D'_{k,l} = \frac{Y'_{k,l}}{X_{k,l}} = A_{k,l}\sum_{q=0}^{Q-1} e^{j2\pi T_O f_{D,q} l} e^{-j\left(2\pi k\tau_q \Delta f + \alpha_k\right)} e^{j\varphi_q} + \frac{W_{k,l}}{X_{k,l}}$$

Directly using $\boldsymbol{D'}$ for delay-Doppler detection cannot obtain accurate delay information. The scrambling sequence is needed to recover the detection results to obtain the true detection results, as shown in Fig. 4-12.



(a) Direct detection result

(b) Recovered detection result

Fig. 4-12. Encryption and recovery of sensing information based on sequence scrambling

(2) Enabling/Disabling of sensing functions

With the development of sensing technology, more wireless sensing functions will emerge, and the privacy requirements will become more diverse and complex. It may be necessary to enable or disable some of the sensing functions of specified devices under certain conditions based on security and privacy requirements or policies. For example, in some situations, it may be necessary to disable the sensing capabilities of some base stations to prevent those base stations from being used to track user location information. It is also possible to enable or disable specific sensing functions of the device according to the actual situation. For example, some sensing functions with low privacy requirements, such as weather conditions and air quality detection, are not restricted. However, sensing functions with high privacy requirements, such as vital signs and location information, are disabled.

(3) Sensing authorization and authentication

In order to protect the privacy of sensing areas and sensing targets, as well as the security of sensing devices, the network needs to judge whether a sensing request is allowed or not based on authorization information. 6G mobile networks need to address multiple dimensions of sensing authorization and authentication, including: 1) authorization and authentication of the sensing area; 2) authorization and authentication of the sensing target; 3) authorization and authentication of UEs, base stations and network functions as sensing devices.

The sensing area is the area where the network performs sensing, such as the no-fly area in the UAV regulatory application scenario. The sensing target is the object sensed by the mobile network, such as the person in the gesture and action recognition application scenario. The authorization information of the sensing region and the sensing target may be provided by the corresponding region and target owner or manager, and may include information such as whether sensing is allowed, what is allowed to be sensed (e.g., range, velocity, respiration, etc.), permitted requesting party for sensing, permitted recipient of sensing results, and permitted accuracy of sensing. The authorization of sensing areas and sensing targets is maintained by a network function, which may be maintained and used by multiple network function instances according to sensing geographic location or sensing business attributes, etc.

4.10 Other Key Technologies

(1) Integration of 3GPP sensing and non-3GPP sensing

In this discussion, the sensing based on 5G or 6G ISAC system is defined as 3GPP sensing. In addition to 3GPP sensing, all the other sensing methods are defined as non-3GPP sensing. The typical non-3GPP sensing module includes millimeter-wave radar, camera, accelerometer and gyroscope, etc. 3GPP sensing and non-3GPP sensing complement each other and can be efficiently integrated, providing an important way for the more convenient, efficient, and accurate digital construction of the physical world.

The integration of 3GPP sensing and non-3GPP sensing, mainly contains the following aspects:

The non-3GPP sensing module (GPS/accelerometer/gyroscope) equipped on UE or BS can provide the state information of UE or BS, including the position, velocity and direction of UE or BS. On one hand, solution to sensing non-ideal factors depend on the UE or BS state information. On the other hand, conversion from the sensing measurement quantities to the sensing results also rely on the UE or BS state information. Therefore, the precision of UE or BS state information determines the precision of sensing results.

After obtaining distance/velocity/angle or point cloud information of sensing targets through 3GPP sensing, it is sometimes difficult to accurately match them with the real sensing targets in the physical world. Non-3GPP sensing can help to solve this problem. For example, the amount and category of sensing target obtained with camera can be provided to the 3GPP sensing module. Then the amount and category of sensing target can be associated with the information of range/velocity/angle/point cloud.

Integration of the measurement quantities obtained from 3GPP sensing and non-3GPP sensing can have the following effects: Integration of the same type of sensing measurement quantities can improve the sensing accuracy, while integration of different types of sensing measurement quantities can enrich the types of sensing measurement quantities, making the sensing results more multidimensional.

Collaboration between 3GPP sensing and non-3GPP sensing can improve sensing efficiency. For example, the information provided by non-3GPP sensing can be used as prior information for sensing, thereby reducing the search load of 3GPP sensing or improving the efficiency of signal processing of 3GPP sensing.

To achieve efficient integration between 3GPP sensing and non-3GPP sensing, it is necessary to standardize the measurement quantities of non-3GPP sensing and require network such as core network to support unified control of non-3GPP sensing and 3GPP sensing.

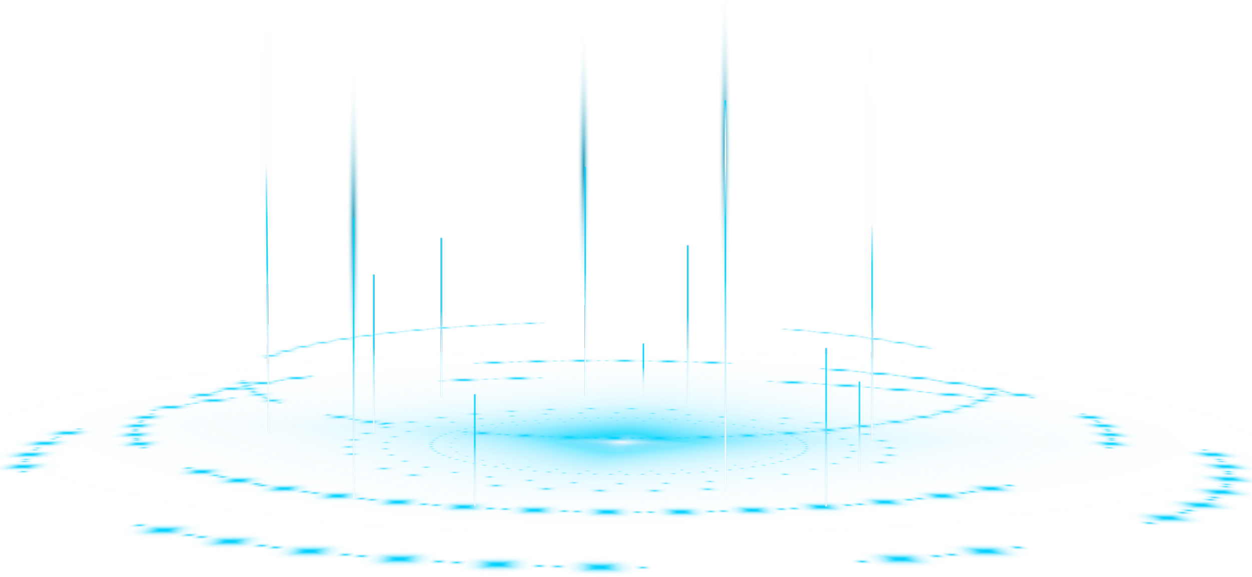
(2) RIS-assisted ISAC technology

RIS-assisted positioning systems can improve positioning accuracy by optimizing the phase adjustment parameters of RIS. Reference [29] analyzes the CRB of the positioning system and points out that maximizing the signal strength of the virtual LOS path (The path of the signal from the transmitter to the receiver through RIS reflection) can lead to the optimal CRB. Therefore, the beam alignment of RIS is a key operation in the RIS-assisted positioning process, which directly affecting the positioning accuracy. Meanwhile, the forwarding beam angle of RIS can also be used as auxiliary information in the positioning estimation process, to determine the position of the terminal relative to the RIS. When sensing device-free objects in the environment, the receiver needs to separate the reflection path of the sensing object from the multipath signal through signal processing, and estimate the characteristics of the sensing object based on the reflection path information of the sensing object. Currently, algorithms for sensing device-free objects mainly focus on the design of the transmitter and receiver. RIS-assisted sensing technology provides a new signal processing dimension for obtaining the reflection path of the sensing object. RIS reflection beams can form a mirror of the base station, expanding the observation angle of the sensing object [30]. The RIS reflection signal can be used to suppress the interference paths, increasing the energy ratio of the signal corresponding to the reflection path of the sensing object [31].

(3) Backscatter-assisted ISAC technology

Backscatter Communication is one of the most representative technologies to realize ultra-low-power communication. Backscatter devices, such as Radio Frequency Identification (RFID) tags, have the advantages of low cost, low power consumption, and easy large-scale deployment. Backscatter-assisted ISAC, by installing tag devices on specific sensing targets or deploying them in specific sensing areas, compared to device-free ISAC, can not only achieve basic sensing functions, but also obtain additional sensing target information, thereby further enhancing the performance of ISAC.

Existing research shows that backscatter-assisted ISAC has the following advantages: assisting and enhancing sensing performance, improving sensing SNR, achieving sensing of weak signals, and expanding the sensing range [32-36]. In addition, high-speed long-distance backscatter technology [37] lays the foundation for achieving cellular-based and backscatter-based ISAC. However, there are still some technical challenges that need to be addressed for backscatter-assisted ISAC, including the elimination of non-ideal factors such as synchronization error, improvement of sensing reliability, and further improvement of sensing accuracy and range.



05

Channel Modelling and Prototype Implementation for ISAC

Channel measurement and modelling are the foundation of simulation evaluation. Simulation evaluation and prototype verification are crucial to identify the potential problems raised in principle verification, system design, hardware implementation, and algorithm design, to find the corresponding solutions, as well as to promote the future commercial implementation. This chapter analyzes channel measurement and modelling, as well as prototype verification for ISAC.

5.1 Channel Measurement and Modelling

ISAC channel modelling provides a foundation for research and simulation evaluation of various key technologies. Channel measurement further enables a better understanding of the characteristics and variation rules of sensing channels in different scenarios, providing a reference basis for channel modelling. vivo Communications Research Institute, in collaboration with Beijing Jiaotong University, conducted channel measurement and Ray tracing-based simulation generalization for ISAC channels in indoor scenarios such as human respiration and falls [38, 39]. Analysis of simulated and measured channel parameters reveals that there are certain similarities and regularities in the statistical characteristics of communication and sensing channels. Therefore, it is reasonable and feasible to build up ISAC channel modelling based on existing communication channel models.

Currently, 3GPP TR 38.901 has supported communication channel modelling in the 0.5~100GHz frequency band [40], which is mainly used for communication system performance evaluation without considering the sensing system function. The ISAC channel modelling can be based on the geometry based stochastic model (GBSM) method in 3GPP TR 38.901 with the addition of the modelling of sensing targets, and it can also be modelled deterministically using methods such as ray tracing (RT).

Channel clusters associated with sensing targets and channel clusters associated with non-sensing targets need to be considered for ISAC channel modelling. In particular, when modelling based on 3GPP TR 38.901, two modelling approaches, segmented modelling or non-segmented modelling, can be used to model the sensing target [39]. The segmented modelling scheme is to model the channel from the sensing transmitter to the sensing target and the channel from the sensing target to the sensing receiver as two cascaded segments. In each segment, both LOS and NLOS clusters can be modelled to carve out the channel characteristics of the clusters of single-reflection and multiple-reflection channels associated with the sensing target. The cluster delay, power, angle and other parameters of each channel segment are generated by following the 3GPP TR38.901 small-scale modelling process. The channel coefficients from the sensing transmitter to the sensing receiver can be generated as a whole based on the channel characteristics of the sensing transmitter, the sensing receiver, and the phase change due to the sensing target movement. The channel coefficients from the sensing transmitter to the sensing target and from the sensing target to the sensing receiver can also be generated separately, and then the two channel coefficients are convolved to generate the final channel coefficients. Unsegmented modelling, on the other hand, models the channel from the sensing transmitter to the sensing target and the channel from the sensing target to the sensing receiver as a joint segment of the channel, models the sensing target as single or multiple sensing clusters, with the delay and angle information of the sensing clusters being deterministically generated based on the position of the sensing target. Unsegmented modelling only considers the channel characteristics of the single reflective channel cluster associated with the sensing target (multiple reflective channel clusters associated with the sensing target are not considered for the time being or are generated randomly), which can also be considered as a simplified version of the segmented modelling approach.

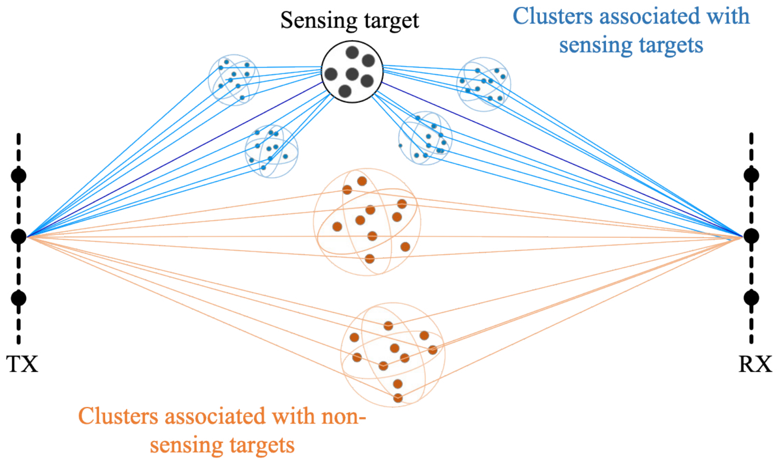


Fig. 5-1. Schematic diagram for modelling the ISAC channel

The channel clusters associated with non-sensing targets (e.g., environment clutter) can be statistically modelled for non-sensing targets and randomly generated according to the 3GPP TR 38.901 channel model, or a number of non-sensing targets can be randomly sprinkled in the environment and associated channel clusters can be generated based on their 3D positions (the generation method can be referred to the method of sensing targets). The channel clusters associated with sensing targets and the channel clusters associated with non-sensing targets are merged and superimposed with large-scale fading to obtain the final channel coefficients. The path loss modelling in the large-scale modelling is associated with the positions of the sensing target, sensing transmitter and receiver, as well as the sensing target RCS features. The RCS features of the sensing target can also be reflected in the small-scale modelling on the channel cluster power.

5.2 ISAC Prototype Implementation

(1) Monostatic ISAC prototype for range and velocity measurement

A typical ISAC use case is to achieve range and velocity measurements of pedestrians or other moving objects in a wireless signal propagation environment while performing communication. In order to verify the feasibility of this issue, we have developed a OFDM based monostatic ISAC prototype for range and velocity measurement. The hardware of the prototype consists of two universal software radio peripherals (USRP), as shown in Fig. 5-2. Among them, USRP 1 is the communication transmitter, USRP 2 is the communication receiver, and USRP 1 also serves as the sensing transmitter and receiver.

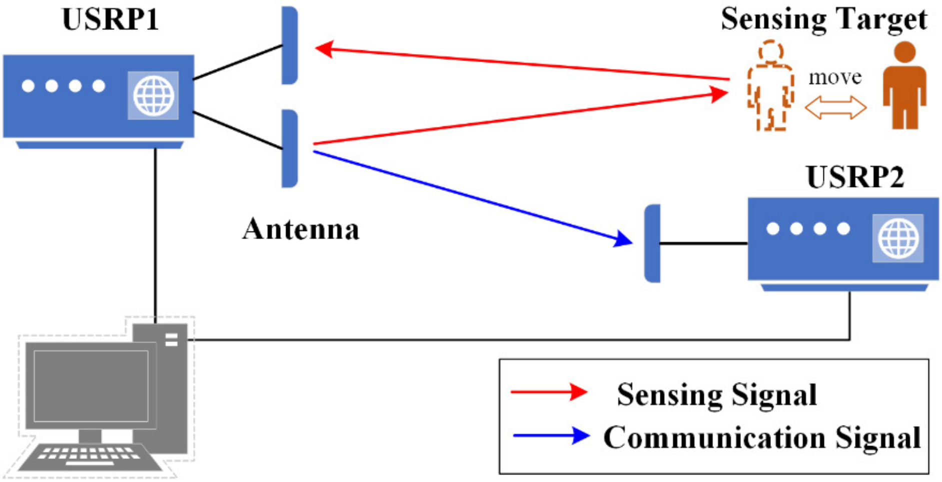


Fig. 5-2. Layout of monostatic range and velocity measurement ISAC prototype

The post-processing of communication and sensing signals is completed by a general computing unit. Due to the fact that the transmitter and receiver of the sensing signal share the same RF module and baseband module, the sensing mode of this prototype is similar to that of a monostatic radar. To suppress self-interference of the direct path, the transmitting antenna and receiving antenna for sensing are separated by an appropriate distance (i.e., 0.8 meter in the test). Pedestrians and corner reflectors act as the sensing targets during the test. The corner reflector is placed on the platform of a mechanical guide rail.

The motion velocity of the platform on the guide rail can be set according to the test requirements, and can be regarded as the true value. Fig. 5-3 shows the photos of the prototype.

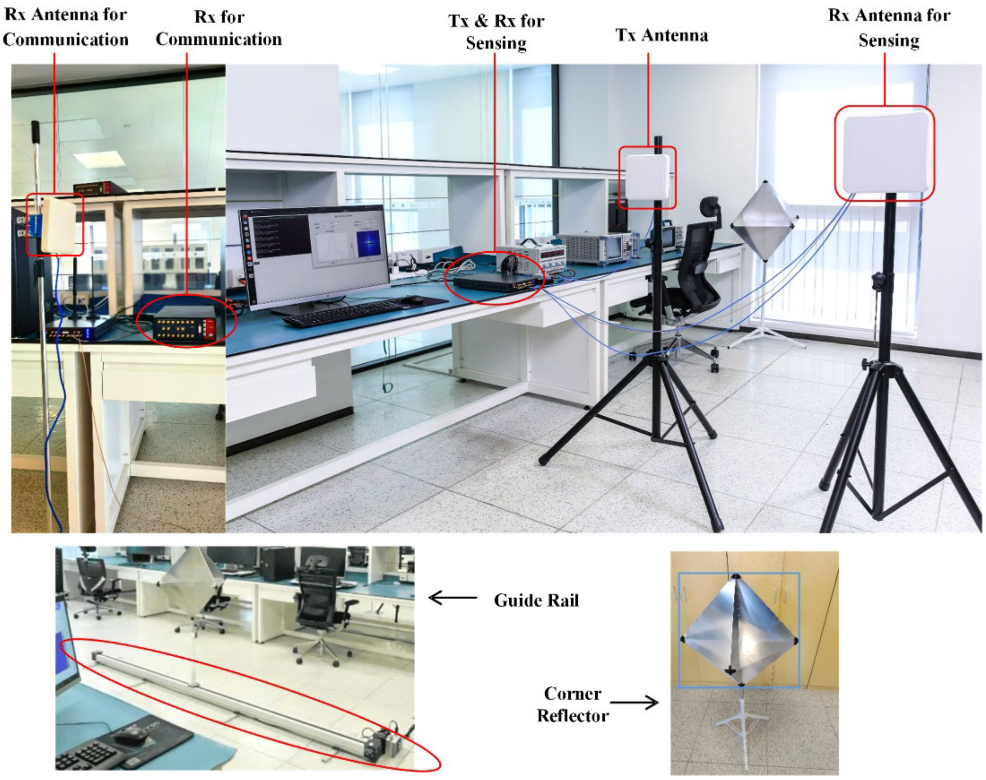
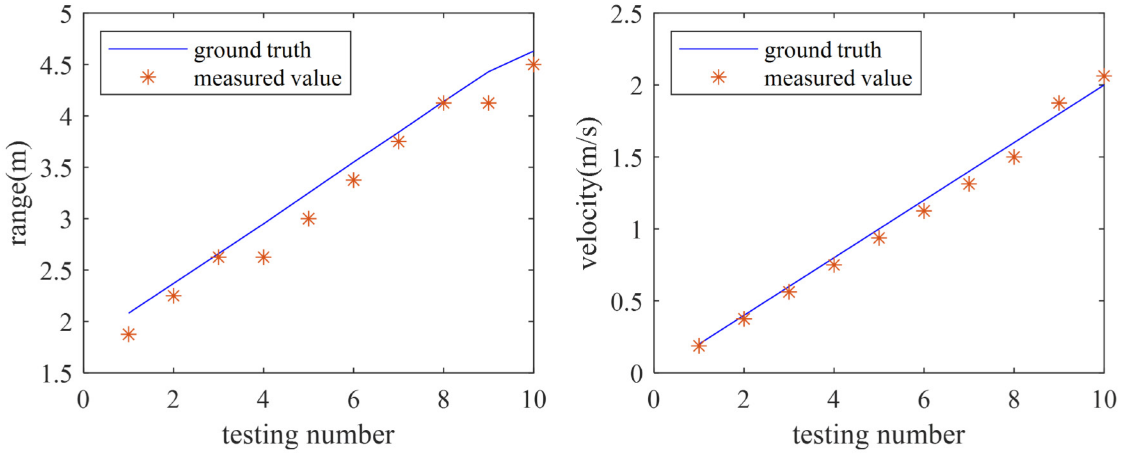
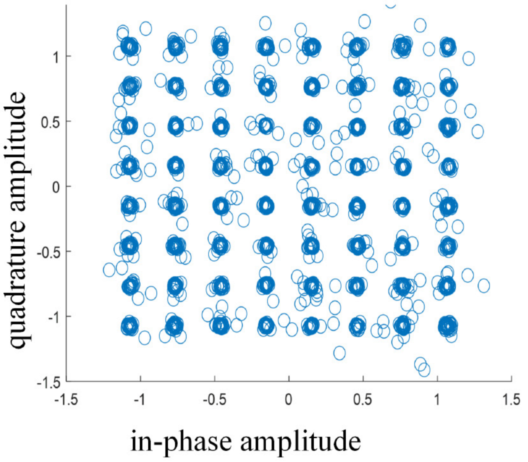


Fig. 5-3. Photos of monostatic range and velocity measurement ISAC prototype

The center frequency is 4 GHz, and the bandwidth is 400 MHz in the test. The prototype works in the monostatic sensing mode with proper isolation for transmitting and receiving antenna, and can achieve real-time range and velocity measurements of the target in the area. We use the physical downlink shared channel demodulation reference signal (PDSCH-DMRS) as the sensing signal. In order to achieve static target detection, clutter suppression is needed. The environmental clutter signals are recorded before the test. The range and velocity measurement results are obtained through the commonly used two-dimensional fast fourier transform (2D-FFT) [41]. Before performing sensing, the system records the environmental clutter, and then subtracts its impacts from the range-velocity spectrum during sensing measurement. To reduce the interference of noise, multiple measurements of static clutter can be taken and averaged. In addition, by placing objects with precise known distances in the environment as references, the fixed delay offsets caused by non-ideal factors of the equipment are eliminated. A detailed signal processing process including algorithm design can be found in reference [42].



(a) range measurement (b) velocity measurement



(c) Constellation diagram of communication

Fig. 5-4. Examples of test results of monostatic range and velocity measurement ISAC prototype

The prototype has undergone certification testing by the IMT-2030 (6G) Promotion Group. The range measurement results are shown in Fig. 5-4 (a). The Root Mean Square Error (RMSE) of the measured range is approximately 0.1935 meter. In velocity measurement, the velocity of the moving target towards the receiving antenna of the sensing receiver varies between 0.2 m/s and 2 m/s. The velocity measurement results are shown in Fig. 5-4 (b), with an RMSE of approximately 0.0643 m/s. Communication is simultaneous during the sensing. Fig. 5-4 (c) shows the measured 64 quadrature amplitude modulation (QAM) constellation, with a measured communication throughput of approximately 1.213 Gbps, which is consistent with the theoretical prediction based on communication configurations.

(2) Bistatic ISAC prototype for respiratory monitoring

Health monitoring is an important application scenario of ISAC, and one of the most common use cases in health monitoring is respiratory monitoring. vivo Communications Research Institute has developed a respiratory monitoring prototype based on commercial 5G small base station and their own developed 5G UE. This prototype can achieve human respiration rate monitoring while performing communication service.

Due to the periodical movement of the human chest when breathing, the phase of the downlink channel state information (CSI) obtained by the receiver periodically changes. By extracting this phase change, respiration rate can be obtained. In practice, due to the difference in the clocks of transmitter and receiver, there exists some non-ideal factors such as carrier frequency offset (CFO) and phase noise (PN), which can significantly affect the performance of respiratory monitoring based on CSI. We can use CSI ratio or CSI conjugate multiplication to eliminate these non-ideal factors [43].

The respiratory monitoring prototype based on 5G system is shown in Fig. 5-5. The carrier frequency is 3.6 GHz, and the bandwidth is 100 MHz. During the sensing procedure, the UE receives the sensing signal transmitted by the BS. The antenna resources for sensing in this prototype are 1 transmitting antenna and 4 receiving antennas. The channel state information-reference signal (CSI-RS) is used as the sensing signal, with a transmission period of 20 ms and a frequency domain density of 1, i.e., there is one resource element (RE) for CSI-RS in one physical resource block (PRB). Since the downlink reference signal of 5G system is used for sensing without additional sensing resource overhead, it has no impacts on the communication data rate and normal uplink and downlink communication services can be carried out.

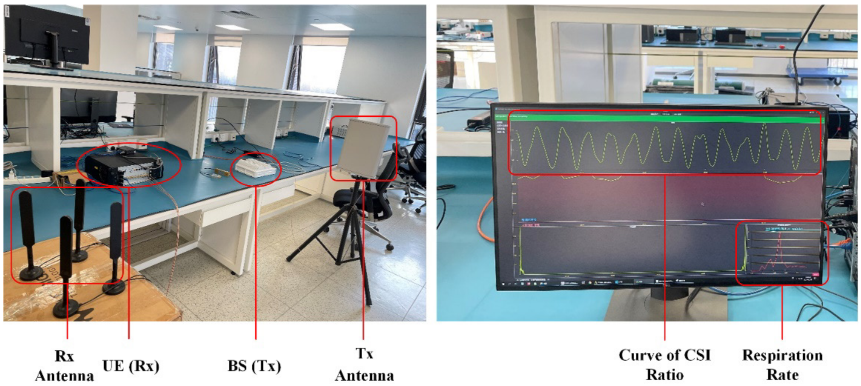
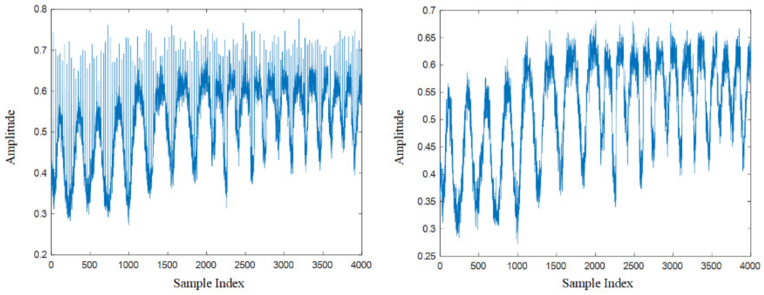


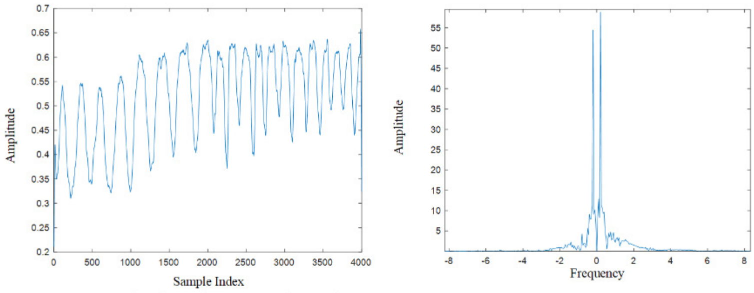
Fig. 5-5. Photos of bistatic respiratory monitoring ISAC prototype

After obtaining the frequency channel response, the UE performs preprocessing such as noise suppression, outlier removal, and smoothing. After that, the data in antenna and frequency domain is filtered and merged. Finally, the Doppler domain information is extracted, and the human respiration rate result is obtained, as shown in Fig. 5-6.



(a) CSI ratio before preprocessing

(b) CSI ratio after noise suppression



(c) CSI ratio after noise suppression and smoothing

(d) Frequency spectrum based on (c)

Fig. 5-6. Examples of data processing results of bistatic respiratory monitoring ISAC prototype

（3）Bistatic CoMP based ISAC prototype for trajectory tracking

The positioning and trajectory tracking of moving targets is another typical ISAC use case. The network can achieve trajectory tracking of the sensing target such as pedestrian, vehicle, and drone, through CoMP sensing. In order to verify the feasibility of CoMP sensing with bistatic sensing mode, we have built a trajectory tracking ISAC prototype based on our own developed 5G platform.

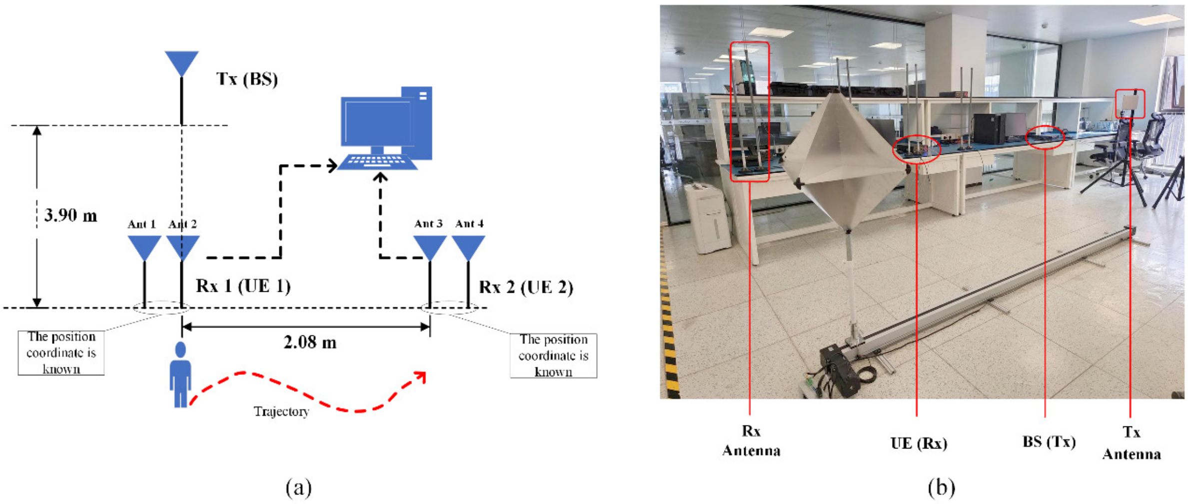
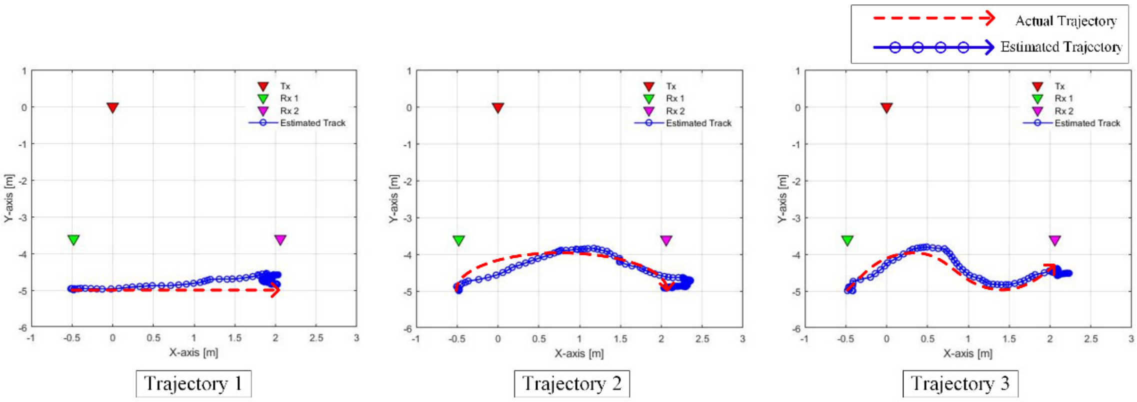


Fig. 5-7. Bistatic CoMP based ISAC Prototype for Trajectory Tracking: (a) Layout of the prototype; (b) Photo of the prototype

The prototype uses an 8-channel USRP to simulate the BS. The BS transmits the sensing signal (i.e., the CSI-RS) with one antenna port. The carrier frequency is 4 GHz, and the bandwidth is 100 MHz. Meanwhile, another 8-port USRP is used to simulate 2-4 UEs, with 2-4 receiving antenna ports for each UE. In the test, at least two UEs continuously obtain downlink CSI. Based on the downlink CSIs, the Doppler frequency of the dynamic path reflected by the sensing target (i.e., human body or corner reflector) to the UE can be obtained. The measured Doppler frequencies are reported to a computer. The computer can calculate the velocity and moving direction of the target and further estimate the trajectory, based on the reported Doppler frequencies and the position coordinates of the UEs and BS. It should be pointed out that, to realize the trajectory tracking, at least 2 UEs are needed. Fig. 5-7 (a) shows the system layout (i.e., using two receiving UEs as example), and Fig. 5-7 (b) shows the photos of the prototype.



Trajectory 1 Trajectory 2 Trajectory 3

Fig. 5-8. Illustration of the tracking results for different trajectories

In signal processing, the multiple signal classification (MUSIC) algorithm is used to estimate the Doppler frequency of the dynamic path. We use 50 consecutive CSI samples in the time domain for each estimation, and the period of CSI-RS is 10 ms. The target can be considered to move at a constant speed within 500 ms. Fig. 5-8 shows the test results of different target trajectories for examples. The red curve represents the actual pedestrian movement trajectory and the blue curve represents the estimated one. It is shown that the two trajectories are well matched with each other.

Due to the independent clock at transmitter and receiver, there exists local frequency offset, which causes CFO. The superposition of CFO and Doppler frequency offset results in trajectory estimation error. In our prototype, two frequency offset cancellation methods, CSI ratio and calibration based on reference path (e.g., the LOS path), were evaluated. The results showed that both methods could obtain accurate Doppler estimations. In the future, the communication function of the prototype will be improved. Moreover, we will continue to improve the accuracy and reliability of trajectory tracking. The goal is to achieve real-time and high-precision positioning and tracking of moving targets in the environment, while performing communication.

06

Conclusions

Compared to the previous generations of mobile communication systems, the 6G system is expected to operate at higher frequencies, require larger bandwidths, and feature larger scale antennas and denser network deployment. Through ISAC, 6G can provide high-precision sensing services in addition to super communication capabilities. The 6G system will natively support the integrated design of communication and sensing, and will utilize key technologies such as ISAC waveform and signal design, multi-band collaborative sensing, multi-antenna technologies, CoMP, link adaptation, mobility management, solution to sensing non-ideal factors, and sensing security and privacy protection schemes, in conjunction with the improvement for the performance of both communication and sensing, reduce the resource consumption, and support richer sensing functions and scenarios.

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Abbreviations

2D-FFT	Two-Dimensional Fast Fourier Transformation
3GPP	3rd Generation Partnership Project
5G	The fifth generation mobile communication systems
6G	The sixth generation mobile communication systems
CEF	Channel Estimation Field
CE-OFDM	Constant Envelope-OFDM
CSI	Channel State Information
CSI-RS	Channel State Information-Reference Signal
DFT-s-OFDM	Discrete Fourier Transform Spread-OFDM
ETSI	European Telecommunications Standards Institute
FBMC	Filter-Bank Multi-Carrier
FDSS	Frequency Domain Spectrum Shaping
FMCW	Frequency Modulated Continuous Wave
GBSM	Geometry Based Stochastic Model
GPS	Global Positioning System
ICI	Inter-Carrier Interference
IEEE	Institute of Electrical and Electronics Engineers
ISI	Inter-Symbol Interference
ITU-R	International Telecommunication Union-Radio communication Sector

LFM	Linear Frequency Modulation
LOS	Line Of Sight
LS	Least-square
MIMO	Multiple Input Multiple Output
MUSIC	Multiple Signal Classification
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out-Of-Band
OQAM	Offset Quadrature Amplitude Modulation
OTFS	Orthogonal Time Frequency Space
PAPR	Peak to Average Power Ratio
PCC	Policy and Charging Control
PDSCH-DMRS	Physical Downlink Shared Channel-Demodulation Reference Signal
PRB	Physical Resource Block
RE	Resource Elements
SC-FDE	Single Carrier Frequency Domain Equalization
SINR	Signal to Interference plus Noise Ratio
SNR	Signal to Noise Ratio
STF	Short Training Field
UE	User Equipment
Umi	Urban Micro
VA	Virtual Array