Integrated Sensing and Communications: A Survey of Recent Progress Toward 5G-A and 6G

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Abstract. Integrated sensing and communications (ISAC) is one of the core innovations and important application scenarios of future wireless communication systems toward 5G-Advanced (5G-A) and 6G. This article summarizes the development status and analyzes the development trends from two perspectives: industry and academia. Then, this article analyzes the method to integrate sensing and communications and explains the intrinsic mechanism of ISAC. Next, the key technologies of ISAC are introduced. Among them, this article focuses on the analysis of novel waveforms of ISAC, such as orthogonal time frequency space (OTFS) and Affine Frequency Division Multiplexing (AFDM). Finally, prospect and conclusions are given.

Keywords: 5G-A and 6G · ISAC · OTFS · AFDM

1 Introduction

For a long time, wireless sensing has been a relatively independently developed technology, which has limited intersection with the development of mobile communication systems. While the integration of sensing functionality is emerging to embrace the new sensing functionality in the forthcoming 5G-Advanced (hereinafter referred to as 5G-A) and 6G eras. As an emerging technology, integrated sensing and communications (ISAC) has received great attention from the industry and academia due to its huge development potential.

1.1 The Industry Progress and Development Trends of ISAC

The rapid development of mobile communication has profoundly changed people's lifestyles. Currently, the construction of 5G networks is rapidly advancing, and 5G technology is deeply integrating with various new technologies, driving human society from the information age to the artificial intelligence age. In

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this process, sensing play an extremely important role. The integrated design of sensing and communication brings numerous advantages. Firstly, low cost and low power systems can optimize resource utilization, thus supporting new services and demands. Secondly, this integrated design can also enhance system performance, improving user experience and service quality. By incorporating various new technologies, ISAC is expected to play a crucial role in driving the development of future intelligent societies.

ISAC realizes the unified design of communication and sensing functions through signal joint design and/or hardware sharing. Sensing in ISAC is a wireless sensing technology based on mobile communication systems. The mobile communication system transmits wireless signals to target areas or objects and analyzes the received wireless signals to complete the sensing function. In addition, mobile communication systems can also aggregate and analyze measurement data from other sensing sources (such as cameras, sensors, radars, etc.) to jointly provide better sensing services.

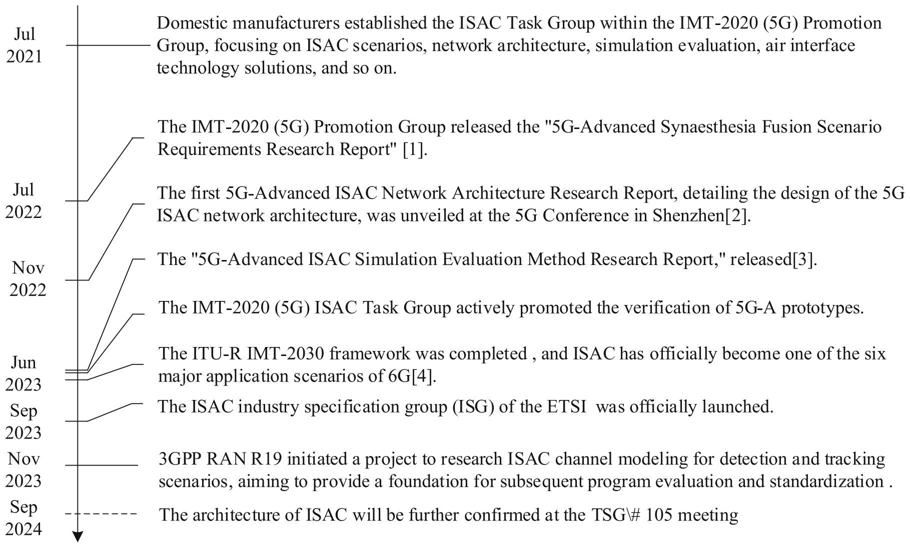


Fig. 1. The industry process of the ISAC in recent years

ISAC in 5G is still in its early stages, despite the introduction of large bandwidth, millimeter wave, and massive MIMO technologies, which equip the 5G system with considerable sensing potential. Exploring enhanced sensing functions in 5G-A, especially solutions that make minor changes to the air interface and appropriately enhance network capabilities, will help the application of sensing in 5G-A networks. In July 2021, domestic manufacturers jointly established the ISAC Task Group in the IMT-2020 (5G) Promotion Group, which is committed to promoting ISAC application scenarios and requirements, network architecture, simulation evaluation methods, air interface technology solution research and prototypes verifications based on 5G technology and other work. At the end of July 2022, the IMT-2020 (5G) Promotion Group released the "5G-Advanced Synaesthesia Fusion Scenario Requirements Research Report" [1], which enhanced the industry's understanding of sensing scenarios and requirements. The first 5G-Advanced ISAC Network Architecture Research Report including the design of 5G ISAC network architecture was released at the 5G Conference held in Shenzhen in November 2022 [2]. Moreover, the "5G-Advanced ISAC Simulation Evaluation Method Research Report" was released in June 2023, which brought together the industry's latest 5G ISAC channel model modeling methods and simulation evaluation results [3]. At the same time, the IMT-2020 (5G) ISAC Task Group is also actively promoting the verification of 5G-A prototypes. Further, 3GPP RAN R19 has initiated a project to conduct research on ISAC channel modeling for detection and tracking scenarios, which will provide a research basis for subsequent program evaluation and standardization since 2023. And the architecture of ISAC will be further confirmed at the TSG# 105 meeting in September 2024.

The ISAC is also one of the key innovations of the sixth generation (6G) of mobile communications. With the completion of the ITU-R IMT-2030 framework in June 2023, ISAC has officially become one of the six major use scenarios of 6G [4]. Relevant standardization work is underway. Moreover, in September 2023, the ISAC industry specification group (ISG) of the european telecommunications standards institute (ETSI) was officially launched. In the first phase, ETSI ISG ISAC will prepare systematic outputs on 6G use cases, channel models, architecture and deployment considerations, KPIs, and evaluation assumptions.

1.2 The Academic Progress and Development Trends in ISAC

As a new and rapidly developing research field, ISAC is currently receiving significant attention from both academia and industry. From radar communication (RadCom), joint communication and radar (JCR), joint radar and communication (JRC), to dual-function radar communication (DFRC), and now to ISAC, the terminology of integrated communication and radar has continually evolved, and its technology has undergone years of research and development.

The concept of ISAC dates back to the 1960 s when researchers began embedding communication information into radar pulses. Although the information rate was low, it initially achieved the compatible use of radar and communication [5]. Building on this, in 1975, researchers used variations in the pulse repetition frequency to represent communication signals, modulating information by switching the pulse generator [6]. Since 1980, the United States gradually applied ISAC in military equipment, proposing the "Sapphire Column" project [7] and the advanced multifunction radio frequency (AMRFC) project, integrating radar and communication systems on a unified platform [8]. Military requirements began to gradually propel the development of research on integrated communication and radar. In 2003, researchers first proposed the combination of linear frequency modulation (LFM) radar signals with communication, using chirps with positive and negative frequency sweeps to transmit radar and communication signals separately [9], which gradually became a development direction. Subsequent research introduced combinations of chirps with MSK, CPM, MPSK, and MQAM [10–12]. At this point, the primary development focus was embedding communication information into radar signals.

Entering the 21st century, with continuous development in mobile communications, orthogonal frequency division multiplexing (OFDM) has been widely applied in communication systems due to its strong anti-fading capability, high bandwidth efficiency, and support for high speed data transmission. The authors in [13] explored the application of OFDM modulation technology in the radar field, proposing the multicarrier complementary phase code (MCPC) radar signal. In [14], OFDM radar signals are analyzed to indicate its significant advantages compared to LFM signals, including high robustness to Doppler shifts and capability to process unambiguous distance and Doppler independently. Due to the significant advantages of OFDM signals in radar and communication systems, a large number of scholars have begun researching integrated radar communication systems based on OFDM signals. With the continuous development of communication waveforms, aside from the classical OFDM mentioned above, some emerging waveforms can also be used to achieve dual functionality. Representative waveforms include index modulation (IM) techniques that embed information into waveform parameters [15–17], orthogonal chirp division multiplexing (OCDM) [18,19] or AFDM [20,21] for information transmission using orthogonal chirps, and orthogonal time frequency space (OTFS) [22–25] which performs information modulation in the delay Doppler domain.

In recent years, MIMO technology has continuously developed, with massive MIMO (mMIMO) [26] becoming a core technology of 5G. Based on MIMO technology, MIMO radar was proposed for the first time by introducing the spatial diversity of MIMO communications into radar [27], which has better spatial resolution, anti-jamming capabilities, parameter estimation, and target tracking and recognition performance compared to traditional phased array radars. Literature [28] proposed a MIMO radar communication integration method, which embeds PSK communication information into MIMO radar, while the communication rate is limited by the number of orthogonal waveforms. Literature [29] explored radar detection using mMIMO. Additionally, the combination of MIMO and new waveforms for ISAC, such as combining MIMO with OTFS or AFDM, has also become a current research hotspot [30–32].

With the further development of communication and radar technologies, there is a trend towards deeper integration of these fields. The demand for more spectrum and spatial resources is driving both communication and radar towards higher frequency bands and large-scale antenna arrays. Operating frequencies have now reached the millimeter wave band. Millimeter wave communication channels are sparse and primarily line of sight (LoS), allowing channel models to align better with physical geometries, and beam domain signal processing is continually advancing. To some extent, communication on the beam domian mimics the traditional radar signal processing, where beam training and tracking can be analogized to target search and tracking [33,34]. Consequently, the boundaries between radar and communication are becoming blurred, and sensing functions are not necessarily limited to radar infrastructure.

2 Integrated Sensing and Communications Methods

The goal of ISAC is to achieve resource sharing by integrating communication and sensing functions into a unified system, thereby enhancing the overall performance and efficiency of the system. How to allocate resources and how to integrate sensing and communications are crucial aspects of ISAC design. As shown in Fig. 1, the existing methods for integrating communications and sensing can be categorized into five main types: time division multiplexing (TDM), frequency division multiplexing (FDM), space division multiplexing (SDM), code division multiplexing(CDM), and unified waveforms (Fig. 2).

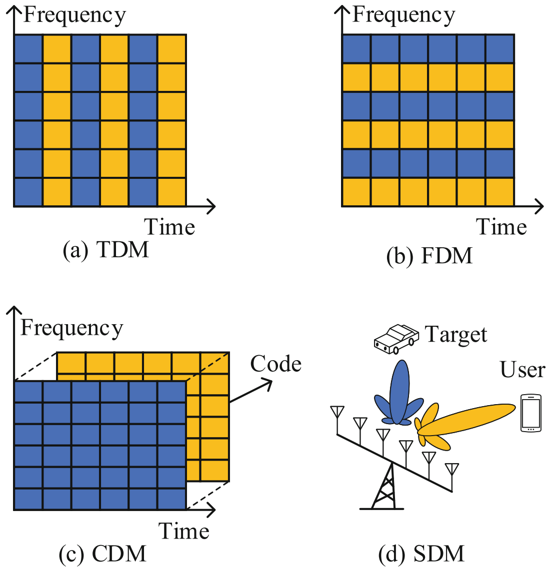


Fig. 2. Schematic diagram of the multiplexed waveforms (blue: sensing, yellow: communications) (Color figure online)

2.1 TDM

TDM refers to the operation of radar waveforms and communication waveforms at different time intervals. This method avoids mutual interference between radar and communication functions through temporal separation and allows the two to use the entire available spectrum simultaneously, thereby eliminating spectrum conflicts. In TDM systems, sensing and communication functions can design specific waveforms according to their respective needs with minimal mutual interference [35–40].

TDM technology has advantages such as simplicity, low complexity, and flexibility of the system configuration. Since radar and communication signals are completely orthogonal in the time domain, they do not interfere with each other and can use the entire frequency band resources. However, the drawback of TDM is that radar and communication functions cannot be realized simultaneously, which may lead to low time resource utilization. Additionally, the accuracy of time synchronization can impact the system performance.

2.2 FDM

Through FDM, communications and sensing functions can be custom designed within their respective frequency bands. This method mainly utilizes notch filtering to superimpose useful communication signals onto radar signals. For example, useful communication signals can be embedded in ultra wideband radar signals or by adding notch filtered communication signals to each array element's radar transmission signal in a MIMO multi-antenna system to form an integrated signal [41,42].

In general, while FDM systems avoid interference between radar and communication functions and allow for the custom design of communication and sensing functions in different frequency bands according to their specific needs, providing high flexibility, this method means that no single function can fully utilize the entire spectrum resources, leading to lower spectrum utilization efficiency. Moreover, FDM also divides the transmission power, affecting the radar's detection capability, such as the decrease in distance resolution. In summary, although FDM offers design flexibility, its spectrum utilization efficiency is low because it requires consuming more bandwidth resources.

2.3 CDM

CDM refers to the modulation of sensing and communication signals using different pseudorandom (orthogonal) codes for sensing and communication, respectively, and then synthesizing the modulated signals to achieve both communication and sensing functions simultaneously. Common methods include using different codes for communication and sensing multiplexing, such as Direct Sequence Spread Spectrum (DSSS) [43,44], chirp sequence spread spectrum [45], polyphase sequence sets [46,47], and complete complementary codes [48,49], and so on.

CDM leverages the orthogonality in the code domain, allowing radar and communication functions to share system time, space, and frequency resources. This design employs pseudorandom codes, resulting in lower signal power spectral density and low probability of interception. Due to the good orthogonality between different pseudorandom codes, interference between sensing and communication functions is minimal. However, the design of orthogonal code sets for code division multiplexing is challenging, and the isolation between radar and communication functions is determined by the orthogonality of the code sequences, which results in limited isolation and incomplete separation. The autocorrelation and cross-correlation performance of the code sequences are constrained by each other, meaning that code division multiplexing can lead to transmission power splitting, affecting the radar's detection performance. Moreover, the use of pseudorandom codes requires spectrum spreading of the signals, reducing spectrum utilization efficiency.

2.4 SDM

SDM, which utilizes related technologies such as beamforming, leverages the degrees of freedom in the spatial domain of arrays. Communication and sensing beams are emitted in different directions to achieve the functions of communication and sensing. SDM in ISAC also uses different orthogonal spatial degrees of freedom, including main and side lobes [50,51], antenna arrays [52,53], or waveforms [54–57] to conduct radar sensing or communication.

Using SDM, the waveform design for sensing and communication has extremely high flexibility, and the communication rate is high. However, the sensing and communication functions cannot be realized in the same direction, and when the communication beam and the radar beam are directed in similar directions, there will be mutual interference between the beams. Therefore, this integration method is only suitable for scenarios where the communication targets and sensing targets are located in different directions. Additionally, effective beam power allocation strategies and related measures are needed to reduce the impact of mutual interference between beams (Fig. 3).

2.5 The Unified Waveform Mode

In the unified waveform mode, communication and sensing share the same waveform, which means that the radio frequency equipment achieves communication and sensing functions in the same direction, time, frequency band, and code domain by transmitting the same signal waveform [58]. Furthermore, the unified waveform can be divided into three modes: sensing-centric waveform, communication-centric waveform, and joint waveform.

The sensing-centric waveform aims to design a shared waveform by embedding or modulating communication information into an existing radar waveform. It can be roughly divided into two approaches: 1) The first method involves modifying the radar waveform to achieve communication information transmission. For example, attaching communication information based on LFM or chirp signal modulation [9–12,59]. 2) The second method is index modulation (IM). It embeds communication information by controlling radar waveform parameters such as the selection of different antennas, frequencies, and coding choices. For example, an MIMO sensing-communication shared system based on frequency hopping codes [15] or an integrated MIMO vehicular radar communication system based on multicarrier frequency modulated continuous waveform

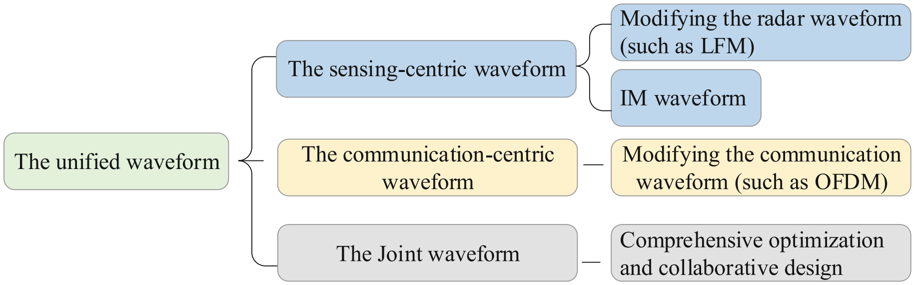


Fig. 3. The classification of ISAC waveform design

(FMCW) [16,17]. In the sensing-centric waveform mode, communication and sensing functions can share time, frequency, space, and hardware resources, effectively enhancing the utilization of network and system resources without requiring significant modifications to traditional radar processing methods. However, this mode is limited by factors such as the signal modulation waveform, frequency, and bandwidth of the radar system, making it difficult to achieve higher communication rates.

In the communication-centric waveform mode, the radio frequency equipment transmits communication waveforms, enabling sensing functions through their direct use or modification. The most representative example is orthogonal frequency division multiplexing (OFDM) ISAC [60–64]. In this mode, communication and sensing functions can share time, frequency, and spatial resources. Compared to the method of sensing-centric waveform, this approach imposes fewer restrictions on the communication function, thereby achieving higher communication rates. However, adopting this method requires the development of new radar processing algorithms, which could potentially degrade sensing performance to some extent.

Joint waveform (JW) aim to optimize ISAC waveforms through the comprehensive optimization of various performance metrics and the collaborative design across multiple domains, thereby providing a better trade off between sensing and communication functions. JW breaks free from the limitations of existing waveforms, demonstrating more flexibility and degrees of freedom to simultaneously balance the needs of sensing and communication, and can even enhance overall performance. Common methods include designing waveforms by optimizing certain metrics, such as using Signal to Interference plus Noise Ratio (SINR) for optimization [65–67]; minimizing optimization under constraints based on the Cramér-Rao Bound (CRB) [68,69]; or optimizing by maximizing the mutual information (MI) of the communication and radar waveforms [70,71].

3 The Novel ISAC Waveforms

With the rapid advancement of wireless communication technology, 5G-A and 6G systems are encountering challenges related to the diversification of user demands and the enhancement of performance. Users expect wireless systems to provide efficient ISAC functionalities and support a wide range of applications and scenarios, such as the internet of things (IoT), edge computing, smart cities, Vehicle to Everything (V2X), high-speed rail, and non-terrestrial networks (NTN). These complex requirements present significant challenges for researchers.

To address these challenges, several studies have proposed innovative waveforms, including orthogonal time frequency space (OTFS) waveforms in the delay Doppler (DD) domain and the recently introduced affine frequency division multiplexing (AFDM) in the Chirp domain, which show great potential. These waveforms are capable of maintaining symbol orthogonality under doubly dispersive conditions, thus proving robust to high mobility and advantageous for ISAC, as they inherently facilitate the estimation of environmental parameters, such as the distance and speed of scatterers (corresponding to the delay and Doppler shift parameters in the channel estimation).

This section will focus on discussing these two promising novel waveforms and exploring their applications and advantages in future wireless communication systems.

3.1 OTFS

OTFS technology was initially designed as a new communication waveform for high mobility scenarios [72]. Unlike the traditional time domain and frequency domain modulation methods, OTFS is a two-dimensional modulation scheme in the DD domain. By modulating information in the delay Doppler (DD) domain, OTFS transforms the fading and time varying wireless channels into time invariant sparse DD channels [73]. Under time varying channels, it can achieve higher diversity gain to combat time varying fading, thereby improving the transmission performance of the communication system.

The model of OTFS-ISAC system is shown in Fig. 4. First, at the transmitter, it maps the communication data onto the delay Doppler (DD) domain grid. Then, the data information in each DD domain is distributed to the time frequency (TF) domain through an inverse symplectic finite Fourier transform (ISFFT). Finally, multicarrier modulation is applied using the Heisenberg transform, thereby generating the time domain transmitted signal:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} X[n,m] e^{j2\pi m \Delta f (t-nT)} g_{\text{tx}}(t-nT), \tag{1}$$

where g_{tx} represents the transmitted rectangular pulse, N is the number of subcarriers, M is the number of symbols, Δf is the subcarrier frequency, and T is the duration of one complete symbol period. $X[n,m]$ represents the time frequency domain data information obtained by the ISFFT of the delay Doppler domain data information, indicating the communication information on the n-th subcarrier of the m-th OTFS symbol.

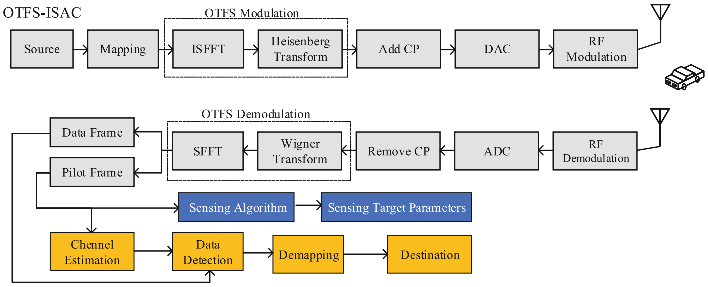


Fig. 4. The system model of OTFS-ISAC.

The transmitted signal reaches the receiver after being reflected:

$$y(t) = \int h(\tau,\nu)s(t-\tau)\mathrm{e}^{j2\pi\nu(t-\tau)}\mathrm{d}\tau\mathrm{d}\nu, \tag{2}$$

where τ and ν represent the delay and Doppler shift respectively, while $h(\tau,\nu)$ is the delay Doppler channel impulse response.

The receiver performs a Wigner transform on the echo signal, followed by a Symplectic Finite Fourier Transform (SFFT) to restore the data to DD domain information. Then, based on the channel estimation from the pilot, it demodulates the signal to obtain the sensing target parameters and the final communication data.

Radar parameters, specifically the effective distance r and the relative linear velocity v of a target, directly correspond to the path delay τ and the Doppler shift ν of the target's reflected signal. These relationships are given by $\tau = \frac{r}{c}$ and $\nu = \frac{2vf_c}{c}$, where c is the speed of light and f_c is the carrier frequency. Assuming there are P targets, the time domain channel impulse response can be expressed as

$$h(\tau,\nu) = \sum_{i=1}^{P} h_i\delta\left(\tau-\tau_i\right)\delta\left(\nu-\nu_i\right), \tag{3}$$

where h_i, τ_i, and ν_i represent the complex gain, delay, and Doppler shift caused by the i-th target, respectively, and $\delta(\cdot)$ denotes the Dirac delta function.

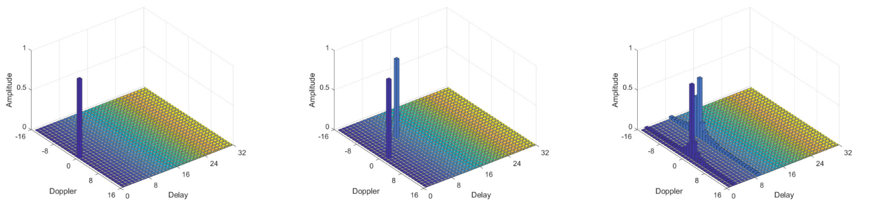
After OTFS modulation and demodulation, the TV time domain channel is equivalently transformed into a DD domain channel by OTFS, and the delay Doppler parameters of the channel are discretized on the grid of the DD domain. Let l_i and k_i represent the delay and Doppler taps of the i-th path (relative to the delay Doppler grid), then the actual path delay and Doppler can be expressed as $\tau_i = \frac{l_i}{M\Delta f}, \quad \nu_i = \frac{k_i+\kappa_i}{NT}$, where $-\frac{1}{2} < \kappa_i \le \frac{1}{2}$ denotes the fractional Doppler shift. Based on the channel input-output relationship under integer Doppler and fractional Doppler:

$$\mathrm{Y}[m,n] = \sum_{i=1}^{P} h_i e^{\frac{j2\pi(m-l_i)}{MN}} X\left[[m-l_i]_M, [n-k_i]_N\right] \tag{4}$$

$$Y[m,n] = \sum_{i=1}^{P} h_i e^{\frac{j2\pi(k_i+\kappa_i)(m-l_i)}{MN}} \sum_{k=0}^{N-1} \zeta_N\left(k_i+\kappa_i-k\right) \mathrm{X}\left[[m-l_i]_M, [n-k]_N\right] \tag{5}$$

with $\zeta_N(x) = \frac{1}{N}\sum_{k=0}^{N-1} \mathrm{e}^{\frac{j2\pi xk}{N}} = \frac{1}{N}\frac{\sin(\pi x)}{\sin(\pi x/N)}\mathrm{e}^{\frac{j\pi x(N-1)}{N}}$.

Effectively obtaining the DD channel parameters allows for simultaneous estimation of the channel parameters and perception of the target parameters (Fig. 5).



(a) The DD domain pulse signal at the transmitter (b) The impulse response under integer Doppler (c) The impulse response under fractional Doppler

Fig. 5. The OTFS input-output relationship in the DD domain

Based on this direct and specific correspondence, the sensing algorithm based on approximate maximum likelihood estimation proposed in [23] allows the sensing accuracy of OTFS to rival that of dedicated sensing waveforms such as FMCW. To further enhance the performance of OTFS-ISAC, the authors in [74] investigated schemes for the allocation of frequency and power resources between communication and sensing within integrated OTFS systems. Reference [75] proposed an integrated OTFS waveform based on weighted fractional Fourier transform, optimizing the performance of both communication and sensing by flexibly adjusting parameters. Current research on the use of OTFS in the ISAC field is still in its early stages, and the combination of OTFS with MIMO for ISAC in the spatial and DD domains [76] also holds great potential.

3.2 AFDM

Compared to OTFS, AFDM is also a newly proposed next generation candidate waveform. AFDM multiplexes information symbols in the discrete affine Fourier transform (DAFT) domain, with each subcarrier carrying information in the form of orthogonal chirp waveforms [77]. The AFDM waveform can be adapted to the channel profile by optimizing its parameters, enabling the separation of all paths in the DAFT domain and achieving full diversity in doubly selective channels to improve communication performance [78]. Compared to OTFS, AFDM offers comparable communication performance in terms of bit error rate (BER) but has lower complexity and reduced channel estimation overhead [79]. Additionally, since it inherently uses orthogonal chirps with the same bandwidth and orthogonality, and has a large time bandwidth product, it is well-suited for radar sensing applications. Therefore, AFDM is considered a potential candidate waveform for ISAC systems [20,80].

The AFDM-ISAC system structure is similar to OTFS-ISAC. However, the difference is that data and pilot information are replaced from the DD domain to the discrete affine Fourier transform domain. After the affine Fourier transform, the obtained time domain information is:

$$\mathbf{s}[n] = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} \mathbf{x}[m] e^{j2\pi\left(c_1 n^2 + \frac{1}{N} mn + c_2 m^2\right)}, \tag{6}$$

where c_1 and c_2 are the parameters that control the chirp rate in AFDM. When $c_1 = c_2 = \frac{1}{2N}$, AFDM degenerates into OCDM. By considering the time frequency dispersion characteristics of the time varying channel, flexibly adjusting c_1 and c_2 allows AFDM to achieve better system performance.

Through channel, the received AFDM signal is received through DAFT demodulation. The time domain channel is converted to the discrete affine Fourier domain. Similar to OTFS, the input-output relationship of AFDM under integer Doppler and fractional Doppler can be expressed as:

$$\mathbf{y}[n] = \sum_{i=0}^{P} h_i \alpha_{l_i} \mathbf{x}\left[[n - loc_i]_N\right] \tag{7}$$

$$\mathbf{y}\left[n\right] = \sum_{i=0}^{P} h_i {\alpha'}_{l_i} \sum_{k=0}^{N-1} \zeta_N\left(\kappa_i - k\right) \mathbf{x}\left[[n - loc_i - k]_N\right] \tag{8}$$

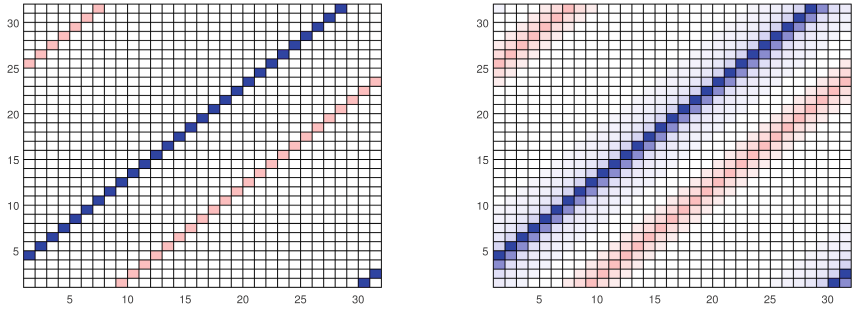
with $\alpha_{l_i} = \exp\left(-j2\pi c_1 l_i^2\right)$ and $loc_i = \left(k_i + 2Nc_1 l_i\right)_N$.

As shown in the Fig. 6, the channel and target parameters also exhibit a explicit correspondence in the discrete affine Fourier domain. Based on the response of the received signal, channel estimation and target detection can be performed.

Currently, the research on the combination of AFDM and ISAC is still in its infancy. However, compared to OTFS-ISAC or OCDM-ISAC, the AFDM-ISAC described in the literature [81] has simpler self interference cancellation (SIC), avoiding the expensive full-duplex operation, thus reducing the overall implementation complexity.

4 The Other Key Technologies

We discuss the novel ISAC waveforms, including the ISAC waveform design and the corresponding signal processing. Besides, sensing-enabled communications, communications-enabled sensing, collaborative sensing, recognition, environment reconstruction, mobilitymanagement,interference suppression, etc. are also the key technologies to make ISAC play an important role in the future. Moreover, by integrating ISAC with AI, AI technology can be utilized to enhance



(a) Target Parameter:(l,k)=(1,-1),(2,3) (b) Target Parameter:(l,k)=(1,-1.2),(2,3.2)

Fig. 6. The input-output relationship in equivalent discrete affine Fourier domain under different target parameters (l denotes the normalized time delay, and k denotes the normalized Doppler)

target recognition and trajectory tracking performance, infer and predict communication channel information, thereby reducing the feedback overhead of the communication process while simultaneously enhancing sensing performance [82,83]. Using RIS technology can achieve non line of sight (NLOS) sensing, effectively utilizing paths that are typically unavailable. Even when line of sight (LOS) paths are available, RIS can provide NLOS paths to further improve sensing accuracy and reliability [84]. In terms of environmental reconstruction, communication information can be used to achieve high precision and high resolution reconstruction of the surrounding environment, thereby enhancing sensing performance. Sensing assisted communication can leverage radar sensing to reduce communication overhead and improve communication reliability, among other benefits.

5 Prospect and Conclusion

In the 5G system, with the introduction of large bandwidth, millimeter wave, and massive MIMO technology, the 5G system already has the potential to sense objects in the area to complete the perceptual exploration of the physical world, including detection, ranging, angle measurement, speed measurement, positioning, identification, tracking, gesture recognition and other functions. As an important evolution direction of 5G-A and 6G, ISAC can serve typical applications such as smart low altitude, smart transportation, smart life, and smart factories, which can promote more convenient and efficient industry and user terminal applications, and broaden the boundaries of communication system applications.

Research on ISAC waveforms, multi-antenna sensing technologies, interference suppression, mobility management, and combined applications with AI, RIS, etc. in ISAC is intensively carrying out. With the evolution and development of related technologies, ISAC is becoming more practical and will surely promote the implementation of intelligent connectivity of all things.

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