Parameter Estimation of Sensing Targets in OTFS-ISAC: Challenges and Applications

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***Abstract*—Orthogonal time frequency space-integrated sensing and communication (OTFS-ISAC) has recently emerged as a focal point of research within the development of sixth generation (6G) networks, due to its unique advantages in high mobility scenarios. In this article, we focus on the parameter estimation problem of sensing targets in the OTFS-ISAC system. Firstly, we introduce the system framework of OTFS-ISAC. Then, a review is conducted on the parameter estimation methods of sensing targets in OTFS-ISAC. Furthermore, technical challenges that OTFS-ISAC may face are outlined, as well as the future research directions. Finally, we provide several emerging applications for OTFS-ISAC and make statements on the parameter estimation of sensing targets in these scenarios.**

***Index Terms*—Integrated sensing and communication (ISAC), orthogonal orthogonal time frequency space (OTFS), parameter estimation, reconfigurable intelligent surface (RIS).**

I. Introduction

With the continuous development of wireless communication and sensing technologies, the issue of limited wireless spectrum resources has become increasingly prominent. To reduce the costs of hardware and spectrum resources, many studies have begun to focus on integrated sensing and communication (ISAC) [1]–[4]. ISAC integrates communication and sensing functionalities into one system. The communication subsystem and sensing subsystem can share hardware architecture, spectrum resources, and signal processing algorithms, thereby achieving "integration gain" and "reciprocal gain" [5]. The mainstream communication sensing integrated design solutions include reuse design and shared design. To achieve maximum utilization of system resources, more integrated shared design solutions are increasingly becoming a more favored research direction. The shared design scheme is prioritized and divided into three design concepts, i.e., sensor centric design, communication centric design and unified joint design [6]. For instance, in a communication-centric design, the communication function is prioritized over the sensing function, and the necessary adjustments can be made using the infrastructure and communication systems that are already in place to provide the desired sensing function. It is important to note that, from an application and financial standpoint, attaching sensing functions to communication systems, that is, communication centric design, seems to be a more mainstream trend. This is because base stations are ubiquitous as communication infrastructure. However, since standardized existing communication waveforms are not always dedicated to radar sensing, it is necessary to study complex processing techniques at the receiving end to improve sensing performance.

A multicarrier modulation technique called orthogonal frequency division multiplexing (OFDM) has been extensively employed in fourth generation (4G) and fifth generation (5G) communications [7]–[9], due to its effectiveness in overcoming interference between information symbols and fighting frequency selective fading. The research on OFDM-ISAC has proposed a detailed system model and provided parameters and corresponding performance analysis methods for quantifying radar sensing performance and communication performance, which effectively proves the effectiveness of of using the same RF hardware platform for both radar sensing and communication functions [10]. However, in the case of high Doppler frequency shift spread, the orthogonality between subcarriers of OFDM is likely to be significantly disrupted, which will have a serious impact on the reliability of communication and the effectiveness of sensing. Therefore, in 5G-Advanced and sixth generation (6G) networks, orthogonal time frequency space (OTFS) modulation schemes with strong robustness against Doppler spread hold significant research value and promising prospects [11], particularly in high mobility ISAC application situations like networks of unmanned aerial vehicles (UAVs) and vehicle to everything (V2X).

In the OTFS-ISAC system, the transmitter embeds the communication information symbols in the delay-Doppler (DD) domain rather than the conventional time-frequency (TF) domain. Meanwhile, the receiver performs channel estimation and target parameter sensing in the DD domain for signal processing. OTFS-ISAC is a synesthesia integrated system with communication as its main function, so research on channel estimation and symbol detection technology in communication can continue based on traditional OTFS communication systems. For OTFS-ISAC, although sensing is a secondary function, its main purpose, like traditional OTFS radar sensing, is still to obtain parameter information such as distance, speed, and angle of the sensing target. In some cases, this target parameter information can serve as sensing results to further assist communication, such as providing parameters for channel estimation or directly serving as the result of channel estimation. Specifically, when the system is a scattering multipath model, channel estimation is mainly completed by the communication subsystem based on uplink and downlink pilots, while the sensing subsystem can only provide some parameters for channel estimation [12]. When the downlink channel happens to be the line-of-sight (LoS) model, the sensing subsystem can fully estimate the downlink channel based on the radar echo. Therefore, as long as channel compensation is performed in advance at the sending end, the receiving end can directly obtain the transmission data without the need for channel estimation [13].

Usually, sensing at the OTFS-ISAC receiver can be divided into two types, active sensing, joint passive sensing and data detection [14]. The difference between active sensing and passive sensing is whether the OTFS-ISAC base station actively emits integrated electromagnetic wave signals for target sensing. Specifically, active sensing involves the OTFS-ISAC base stations estimating the channel delay and Doppler frequency shift based on the transmitted and received signal vectors in the DD domain. Joint passive sensing and data detection is an OTFS-ISAC base station that estimates channel parameters including complex channel coefficients , channel delay, and channel Doppler frequency shift, and restores the transmission data vector when the transmission pilot vector and received signal vector are known. Furthermore, active sensing can generally be divided into single station sensing and multi station sensing, with sensing targets being either single or multiple. Different OTFS-ISAC sensing modes and scenarios have their own characteristics, and appropriate sensing parameter estimation methods need to be adopted. Some preliminary progress has been made in exploring OTFS-ISAC sensing parameter estimation techniques, although there are still many challenges to be addressed. Some initial progress has been made in advancing the OTFS-ISAC sensing target parameter estimation techniques, although there are still many challenges to be solved.

In this article, we give an overview of the sensing target parameter estimation problem in the OTFS-ISAC system. Firstly, we introduce the transmission and reception framework of a typical OTFS-ISAC system in Section II. Then, we discuss the representative parameter estimation methods for OTFS-ISAC in Section III. Section IV outlines several technical difficulties and potential avenues for further study on this subject. Furthermore, we describe emerging application scenarios of OTFS-ISAC sensing in Section V. Finally, Section VI concludes the article.

II. System Architecture of OTFS-ISAC

In this section, we introduce the operating principles of the OTFS-ISAC system architecture and discuss the performance metrics and its advantages based on the transmission and reception structure diagram of a typical monostatic sensing OTFS-ISAC system.

A. *OTFS-ISAC Transmission and Reception Principle*

As illustrated in Fig. 1, an OTFS-ISAC system architecture for monostatic sensing includes transmitters, channels, and receivers. In order to achieve communication and sensing,

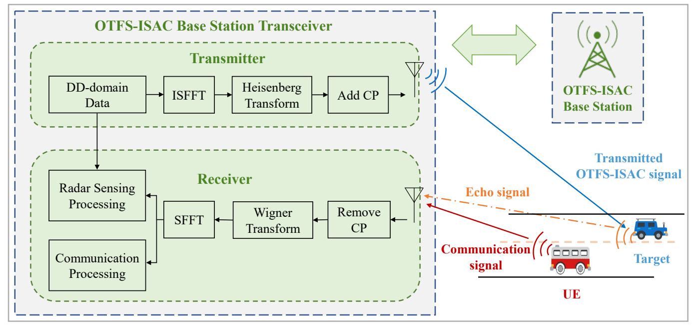

Fig. 1. Transceiver architecture of a typical monostatic sensing OTFS-ISAC system.

the transmitter sends OTFS-ISAC waveforms, actively sensing physical information such as distance and speed of the target while communicating with the user in the downlink. The uplink communication signal from the user and the echo of the perceived target can be received at the receiver. It is worth noting that communication users can also simultaneously serve as sensing targets for the ISAC system. The following will specifically describe the transmission and reception process of OTFS-ISAC base stations.

1) Transmitter: Firstly, the random data stream is mapped through a constellation to form data symbols in the delay-Doppler domain, and then undergoes inverse symplectic finite Fourier transform (ISFFT) to form a two-dimensional discrete signal in the time frequency domain. Next, Heisenberg transform the time-frequency domain signal, which aims to convert the discrete time-frequency domain signal obtained in the previous step into a continuous time-domain signal that the transmitter can transmit. We can simply consider the Heisenberg transform as a joint operation of inverse discrete Fourier transform (IFFT) and emission shaping pulse. Usually, to be compatible with OFDM modulation, we use rectangular transmit and receive pulses. In addition, a cyclic prefix (CP) needs to be inserted before each data frame in the time-domain signal and transmitted through the antenna.

2) Channel: Due to the high real-time requirements of OTFS-ISAC systems, the data frame duration of time-domain signals must remain short.The probability of fractional Doppler, in which the Doppler frequency shift is not an integer multiple of the Doppler resolution, is increased by the fact that the Doppler resolution is inversely related to the frame time. Therefore, modeling the delay-Doppler channel as a continuous delay and Doppler frequency shift (CDDS) channel is more reasonable, as in [14], rather than a discrete channel model.

3) Receiver: Since the receiver and transmitter of the OTFS-ISAC base station are in the same position, the receiver can receive echo signals from sensing targets and communication signals from users. The receiver antenna must function in in-band full duplex (IBFD) mode in order to accomplish simultaneous communication and sensing. Self-interference between the transmitting and receiving antennas can be mitigated using self-interference cancellation technology, ensuring that the echo signal and communication signal received by the receiver remain intact [15]. It is worth noting that by adopting successive interference cancellation (SIC) technology, non-orthogonal multiple access (NOMA) systems can distinguish multiple user signals at the receiving end within the same time and frequency resources through power division. Due to the rapid development of this technology, it is entirely feasible to assume that the radar sensing echo signals and communication signals in the base station's received signals can be effectively separated using SIC technology in the OTFS-ISAC system. Based on this assumption, radar sensing and communication processing can be conducted in the DD domain after removing CP, Wigner transform, and symplectic finite Fourier transform (SFFT), which reverse the operations performed at the transmitter and receiver ends.

In addition to the two-step OTFS modulation based on the ISFFT and Heisenberg transform, the inverse discrete Zak transform (IDZT) can also be used for OTFS modulation. This method directly converts DD domain signals into time-domain signals at the transmitter of the OTFS-ISAC base station, with the corresponding discrete Zak transform (DZT) employed for OTFS demodulation at the receiver. The two OTFS modulation methods are mathematically equivalent in essence.

B. OTFS-ISAC Performance Metrics

The performance metrics related to OTFS-ISAC can be divided into radar sensing performance metrics, communication performance metrics, and integrated performance metrics.

1) Radar Sensing Performance Metrics: Generally, radar sensing encompasses target detection and target parameter estimation. Among them, radar detection involves determining the existence of a target, while target parameter estimation focuses on extracting physical information including the distance and velocity of the target. Detection performance metrics primarily consider the ambiguity function and detection probability, whereas the metrics for target parameter estimation include the maximum unambiguous distance and velocity, distance and velocity resolution, and the root mean square error (RMSE) of the estimates. Compared to OFDM, OTFS exhibits lower sidelobes in the range ambiguity function, leading to enhanced radar detection performance. Additionally, OTFS outperforms OFDM in parameter estimation for targets with high-speed mobility.

2) Communication Performance Metrics: Like traditional OTFS communication systems, the two widely used metrics are throughput and bit error rate (BER). Shannon's theorem states that when the channel bandwidth is constant, the channel capacity is the theoretical maximum rate of data transmission, while throughput is the actual rate of transmission on the channel. The error rate is used to measure the reliability of a system, which refers to the percentage of received error message bits to all information bits. For multipath fading channels, OTFS achieves a lower BER compared to OFDM.

3) Integrated Performance Metrics: Integrated performance metrics refer to metrics applicable to both communication and sensing subsystems, such as peak to average power ratio (PAPR). Due to the limited dynamic range of the power amplifier, it is easy for the power amplifier to enter the nonlinear region when the peak to average ratio of the signal is large, resulting in nonlinear distortion of the signal and serious degradation of the entire system performance. Time-varying multipath channels are converted into the DD domain by OTFS technology, resulting in sparse channels that are nearly identical and change slowly for every symbol in the transmission unit. The PAPR of the OTFS signal is lower than that of OFDM because of the uniform expansion of all modulation symbols in the time-frequency domain within the OTFS system and the high peaks of various subcarrier signals in the OFDM system following IFFT operation [11].

III. Sensing Parameter Estimation in OTFS-ISAC

In OTFS-ISAC transceiver processing, various algorithms are available for estimating target parameters at the radar sensing receiver. For instance, maximum likelihood (ML) algorithms are primarily suited for single target parameter estimation, whereas matched filtering (MF) algorithms are effective for multiple target scenarios. Additionally, within OTFS radar reception processing, correlation reception methods are also employed. Under specific conditions, correlation reception and MF reception can be considered equivalent. This section mainly introduces ML-based and MF-based estimation methods.

A. ML-Based Estimation Method

Radar sensing in OTFS-ISAC is used to estimate target parameters, such as time delay and Doppler frequency shift, which are then used to determine the velocity and distance of the target. The ML-based parameter estimation method is achieved by constructing and minimizing likelihood functions. In the OTFS-ISAC scenario of monostatic sensing, the integrated transmission signal and radar echo signal are known, which allows us to derive the likelihood function of the sensing target parameters through a channel matrix containing parameter dependencies.

When there is a single objective in the system, the minimization problem in the ML estimator can be transformed into a maximization problem. The objective function of the maximization problem includes the transmitted DD domain signal vector, the received DD domain echo signal vector, and a high-dimensional channel matrix that depends on the sensing channel parameters. For the case of integer Doppler, the estimated parameters for the maximization estimation problem are the delay of sensing the target and Doppler tap. At this point, the method to solve the maximization estimation problem is to perform peak search on the delay-Doppler grid. The delay and Doppler tap index values at the peak are multiplied by the corresponding resolution to obtain the estimation results of delay and Doppler. Based on the estimation results with integer multiple resolutions, further off-grid search can be conducted to achieve fractional Doppler estimation, which can further improve the accuracy of parameter estimation. At this point, the maximization estimation only needs to be searched near the estimation of the integer delay and Doppler tap index. For example, a two-dimensional golden section method can be used to iteratively reduce the interval of uncertainty at the golden section ratio until final convergence [14].

When there are multiple sensing targets in the OTFS-ISAC scenario, considering the interference between multiple targets and the high computational complexity that cannot be ignored, the ML estimation method needs to estimate multiple targets step by step. In addition, an interference cancellation mechanism is required to eliminate interference signals from the previously estimated (i-1) targets when estimating the parameters of the i-th target. However, when the positions and velocities of two targets are relatively close, the performance of ML in estimating parameters for multiple targets may significantly decrease.

B. MF-Based Estimation Method

Matched filtering was initially applied in radar technology through linear frequency modulation (LFM) pulse compression radar. In this radar system, a matched filter compresses the pulse width during reception, enabling the separation of echo signals from multiple targets in the time domain. Consequently, MF is highly effective for multi-target range estimation. Inspired by this approach, the MF concept could be extended to estimate both distance and velocity of multiple targets in OTFS-ISAC systems.

The fundamental concept of the MF method in OTFS radar sensing is to effectively separate multiple target echoes within the DD domain. In particular, the OTFS-ISAC sensing subsystem employs the MF algorithm to estimate the positions of channel complex gains corresponding to targets distributed across the discrete DD grid. With knowledge of the transmitted signals and received target echoes, the algorithm estimates the delays and Doppler shifts of multiple targets, ultimately enabling the calculation of their distances and velocities. It should be noted that the delay and Doppler tap index values determine where the target's channel complex gain is located in the DD grid. The integrated signal transmitted determines the specific design of the MF filter at the OTFS-ISAC system's sensing and receiving end. After the echo signal is output with a high-dimensional MF, the discrete delay tap index and Doppler tap index related to a single or multiple targets can be determined by detecting peak values.

At present, the OTFS sensing algorithm based on MF mainly solves the estimation of single target and multiple target parameters in high-dimensional DD grids, without considering the fractional Doppler problem, which is limited by the demand for high delay and Doppler resolution and high computational complexity [16].

IV. Potential Challenges of OTFS-ISAC Sensing

In OTFS-ISAC-based sensing, estimating target parameters presents a range of technical challenges. These challenges arise from the necessity to seamlessly integrate sensing and communication functionalities, along with the requirement to maintain accurate estimation in dynamic and complex environments. This section lists a few of these possible difficulties and offers ideas for future lines of research to deal with them.

A. Potential Technical Challenges

1) Accuracy and Complexity of Target Parameter Estimation for Sensing: Estimating target parameters for sensing requires differentiating various parameters such as distance, speed, and angle of different targets. In high-dynamic environments, Doppler effects and time-varying channel characteristics increase the complexity of estimation.

2) Sensing Resolution and Resource Constraints: Enhancing the resolution of sensing under resource constraints is a significant challenge. Communication and sensing may share resources, which could result in a performance trade-off and lower sensing resolution.

3) Real-time Nature of Target Parameter Estimation for Sensing: As target dynamics increase, real-time updating of parameter estimation becomes crucial. However, processing algorithms with high complexity and limited computational resources impact the realization of real-time capabilities.

4) Multi-target and Occlusions: In multi-target scenarios, mutual occlusion among targets and crossing of different signals cause interference in parameter estimation, reducing the accuracy of the estimation.

B. Future Research Directions

To address the aforementioned challenges, it is necessary to explore a variety of solutions that may represent the future research directions for target parameter estimation in OTFS-ISAC sensing.

1) Deep Learning-based Parameter Estimation: Utilizing deep learning for feature extraction and sensing parameter estimation can improve the accuracy of estimation. Future research may focus on developing intelligent algorithms adapted to dynamic environments to achieve faster and more accurate target detection and tracking.

2) Cooperative Sensing Techniques: Improved accuracy in estimating the parameters of sensing targets can be achieved through multi-node collaboration. Future research may concentrate on how to effectively coordinate information sharing and processing between multiple OTFS-ISAC nodes, as well as how to exploit cooperative gains to enhance sensing performance.

3) High-Resolution Signal Processing Methods: Researching high-resolution signal processing techniques, such as compressive sensing and sparse representation, can help improve parameter estimation performance in multi-target situations. Future work may focus on integrating these methods with OTFS modulation techniques to enhance sensing precision.

4) Resource Optimization Algorithms: Resource Optimization Algorithms: A better balance between sensing and communication can be achieved through intelligent resource allocation. Future research directions could involve developing advanced beamforming strategies and spectrum allocation

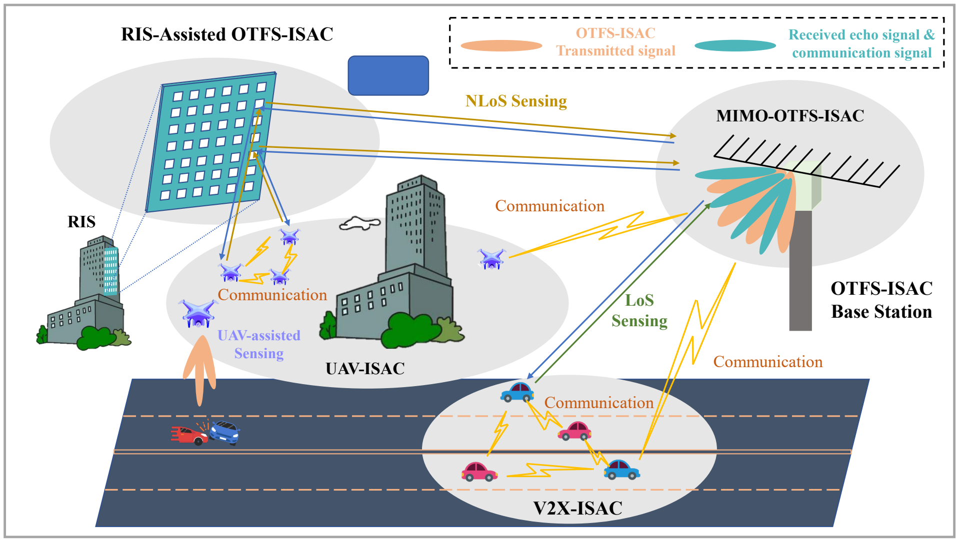

Fig. 2. Emerging application scenarios of OTFS-ISAC.

methods to enhance the resolution and accuracy of parameter estimation.

5) Development of Low-Complexity Algorithms: For real-time requirements, the development of low-complexity target detection and parameter estimation algorithms is particularly important. Future research directions may involve simplifying existing algorithms or inventing new computational reduction techniques to decrease the computational burden while maintaining estimation performance.

6) Occlusion-Resistant Sensing Mechanisms: For multi-target and occlusion issues, research on how to use spatial diversity and temporal diversity to design occlusion-resistant sensing mechanisms is possible. This may include developing more complex signal processing algorithms, such as multiple-input multiple-output (MIMO) and beamforming, which can increase the system's tolerance to occlusions by providing multiple independent observation angles.

Through the continuous exploration and innovation of these research directions, the sensing capabilities of OTFS-ISAC will be significantly enhanced. These advancements will not only be theoretical but will also be integrated into practical systems and applications within the entire OTFS-ISAC field.

V. Emerging Applications of OTFS-ISAC Sensing

The OTFS-ISAC framework mentioned earlier was introduced in the scenario of single-input single-output (SISO) system. In this section, we present several more complicated and challenging OTFS-ISAC application scenarios, as shown in Fig. 2. Then, we will also provide a brief explanation of the sensing sub-mission in these scenarios.

A. MIMO-OTFS-ISAC Sensing

V2X, as an emerging application in future wireless communication and sensor networks, has been widely studied [17]. However, vehicles are usually moving at high speeds, which causes the Doppler effect, severely degrading the performance of the communication link. Therefore, OTFS holds great promise in the integration of V2X communication and sensing. To serve numerous user equipments (UEs), which are fast-moving vehicles, at once, the MIMO-OTFS-ISAC base station is outfitted with a uniform linear array (ULA) with multiple antennas. This antenna array serves dual purposes, one for MIMO radar sensing and the other for uplink communication. Consequently, the design of a hybrid digital-analog beamformer for both radar sensing and communication is essential.

In the V2X scenario, the antenna height of the OTFS-ISAC base station is typically higher than that of the sensing targets, e.g., moving vehicles. This means that the transmission path between the OTFS-ISAC base station and the sensing targets is predominantly LoS. As previously noted, in a LoS channel, once the estimation results for the sensing target are obtained, downstream channel estimation can be bypassed and only preemptive channel compensation is required at the transmitter. Therefore, MIMO-OTFS-ISAC sensing can significantly enhance channel estimation in V2X scenarios. Furthermore, MIMO-OTFS wireless channels show sparsity in the angular domain with only a few non-negligible angles of arrival (AoAs) and angles of departure (AoDs) [18]. Communication and sensing both benefit from such sparsity in the delay-Doppler-angle (DDA) domain [19].

B. RIS-Assisted OTFS-ISAC Sensing

In 6G wireless networks, ISAC based on UAVs has attracted increasing research interest, with drones envisioned as aerial wireless base stations to offer enhanced coverage and improved sensing and communication performance [20]. For sensing targets such as drones that move at high speeds in the air, there may be a non-line-of-sight (NLoS) path between the OTFS-ISAC base station and sensing targets due to the possibility of being obstructed by higher buildings.

To mitigate this issue, reconfigurable intelligent surfaces (RIS) [21]–[24] can be deployed at elevated positions to act as sensing relays. In this configuration, the sensing model involves OTFS-ISAC base station to RIS, RIS to target, and then from the target back to RIS and the base station. The integrated sensing signal undergoes a total of four hops from transmission to reception. To improve target estimation, we assume the synchronization of information between the OTFS-ISAC base station and the RIS. The ISAC base station can then analyze the variation in the signal as it passes through the RIS and recalculate the sensing signal accordingly. This requires modifications or a complete reestablishment of the original sensing theory. A comprehensive summary of the RIS-assisted sensing model is available in [25]. Given its ability to address sensing and parameter estimation for high-mobility targets in NLoS scenarios, RIS-assisted OTFS-ISAC provides an advantageous approach for future developments.

VI. Conclusions

The OTFS-ISAC system, with its unique capabilities and technical feasibility, is poised to become a cornerstone of future communication and sensing technologies. In this article, we introduced the OTFS-ISAC system architecture, including the principles of transmission and reception, as well as the performance metrics. After that, two methods for estimating sensing target parameters within the OTFS-ISAC framework were presented. Subsequently, we identified several technical challenges that OTFS-ISAC sensing may encounter and outlined future research directions. Finally, in conjunction with emerging ISAC application scenarios, we conducted a preliminary review of sensing technologies relevant to these contexts. By enabling the seamless integration of high-speed data transmission with precise sensing capabilities, OTFS-ISAC is anticipated to foster the innovative applications and enhanced network intelligence in the upcoming 6G era.

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