OTFS-based Delay–Doppler Detection Framework for Passive Coherent Location

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***Abstract*—This paper presents a target detection framework for passive coherent location (PCL) systems based on orthogonal time–frequency space (OTFS) modulation. While conventional PCL relies on cross-ambiguity function (CAF) detection, its performance degrades in rich multipath and with Doppler-sensitive OFDM-like illuminators. To address this limitation, we utilize the delay–Doppler (DD) domain structure of OTFS to transform the received signal into a sparse, interpretable 2D map and perform detection directly in this domain. Simulation results demonstrate accurate detection and parameter estimation for a low signal-to-clutter ratio (SCR) environment.**

***Index Terms*—PCL system, OTFS, delay-Doppler domain.**

I. Introduction

Passive coherent location (PCL) systems, also known as passive radar, have attracted significant attention for their ability to detect and track targets covertly by using existing non-cooperative transmitters, such as broadcast stations or communication signals [1]. This approach eliminates the need for dedicated transmitters, making PCL systems cost-effective [2-4].

The conventional signal processing technique for PCL suppresses substantial direct-path interference (DPI) and estimates target delay and Doppler using the cross-ambiguity function (CAF), which correlates the surveillance signal with time-delayed and frequency-shifted versions of a reference signal [2]. However, this approach breaks down in rich multipath environments, where the target echo becomes a distorted superposition of multiple reflections rather than a clean replica. The resulting blurred and ambiguous CAF output severely degrades detection and parameter estimation, especially for low- radar cross section (RCS) targets such as UAVs. This problem is further exacerbated by OFDM-like illuminators, which are inherently sensitive to Doppler shifts and contribute to peak spreading and estimation bias [5].

To address these limitations, this study employs orthogonal time–frequency space (OTFS) modulation instead of conventional OFDM-based illuminators, which are inherently vulnerable to Doppler spread [6]. OTFS constructs and transmits information directly in the delay–Doppler (DD) domain, offering enhanced robustness against multipath propagation and high mobility. Leveraging this structure, we transform the received signal into a sparse, stable two-dimensional representation in the DD domain and estimate the target in this domain. In this representation, each propagation path—including the primary target and its multipath components—is represented as a distinct, localized peak, enabling interpretable and reliable detection even in complex, time-varying channels. To further enhance detection robustness, we incorporate subspace projection–based clutter suppression [7] and a cell-averaging constant false alarm rate (CA-CFAR) detector [8] as auxiliary processing stages.

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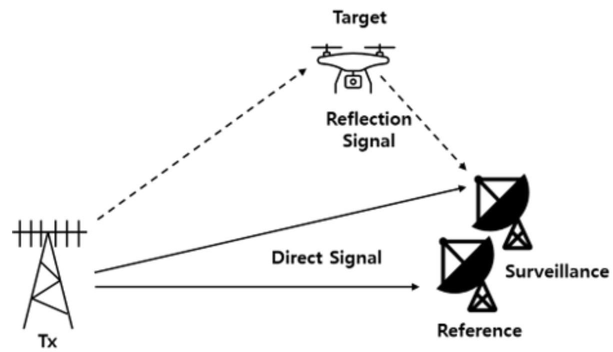

Fig. 1. The configuration of PCL system.

II. System Model and DD Domain Framework

A. System Model

The geometric configuration of the bistatic PCL system is illustrated in Fig. 1. The receiver employs a two-channel architecture to process signals from a non-cooperative transmitter. The reference channel is configured to capture a clean, direct-path signal. In contrast, the surveillance channel receives a mixed signal comprising the direct-path signal and the time-delayed, Doppler-shifted target echo.

B. Delay-Doppler Domain Framework

The proposed framework transforms the received signals from the time domain into the delay–Doppler (DD) domain,

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Carrier frequency (f_c)	77 GHz
Subcarrier spacing (ΔF)	400 kHz
Delay bins (M)	2048
Doppler bins (N)	128
Signal to clutter ratio (SCR)	-30 dB
Tx / Rx position	[-150, 0] / [0, 0] m
Target position	[80, 60] m
Target velocity	[-20, 15] m/s

drawing on principles of orthogonal time–frequency space (OTFS) modulation—a waveform paradigm tailored to high-mobility channels. Unlike conventional schemes that operate natively on the time–frequency (TF) plane, OTFS represents information on a DD grid whose coordinates correspond to the channel's physical parameters: propagation delay and Doppler shift [6]. In a standard OTFS modem, symbols are placed on the DD grid and mapped to the time-domain transmit signal via the inverse symplectic finite Fourier transform (ISFFT) followed by the Heisenberg synthesis; under typical channel conditions, TF-domain distortions manifest as localized, nearly time-invariant features in DD.

Leveraging this property, our framework converts the complex, time-varying propagation effects into a sparse, stable two-dimensional map, in which each path—whether clutter or target—appears as a distinct, localized peak in the DD domain. This channel-mapping paradigm directly addresses the limitations of the conventional technique, whose performance degrades when the target echo is smeared by multipath. By transforming the received signal into an interpretable map of discrete peaks, the proposed framework treats clutter and target responses as separable entities, enabling robust, high-precision target detection.

III. SIMULATION RESULTS

In this section, we evaluate the proposed DD-domain target-estimation framework in a bistatic PCL scenario. Table 1 summarizes the waveform parameters, power levels, and geometry used in the simulations.

For clutter suppression, we employed a subspace projection method based on singular value decomposition (SVD) [7]. The algorithm was configured to nullify the three largest singular values, which correspond to the dominant clutter components. The subsequent 2D CA-CFAR detector [8] was implemented with a stringent false-alarm probability P_{fa} of 10^{-6} to ensure reliable detection and minimize false positives.

Fig. 2 shows the Delay-Doppler (DD) channel response after the subspace projection stage for clutter suppression. The substantial interference, concentrated near the zero-Doppler axis, is markedly attenuated, revealing the target echo as a localized, high-magnitude region that coincides with the ground-truth value (red "×"). This alignment confirms that an accurate estimation is now possible. However, numerous other spurious peaks in the noise floor exhibit similar magnitudes,

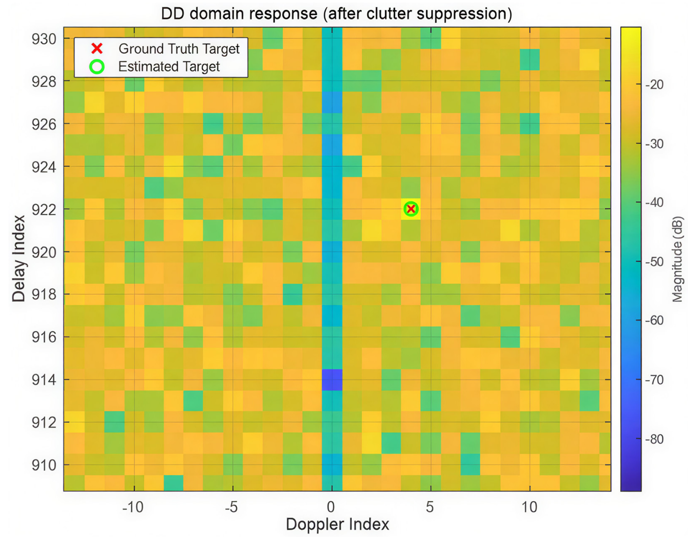

Fig. 2. Delay-Doppler channel response after clutter suppression.

creating a high risk of false alarms for a simple peak detector. This result validates the need for a robust statistical method, such as 2D CA-CFAR, to reliably identify the actual target.

Fig. 3 shows the binary detection map produced by the 2D CA-CFAR applied to the data in Fig. 2. The algorithm successfully rejects the entire noise floor, resolving the ambiguity issue and producing a clean detection map with a single, unambiguous peak. This detected peak, indicated by the green circle, shows a precise alignment with the ground truth target location. The result validates that the adaptive thresholding of the CA-CFAR detector is highly effective in this DD-domain application, achieving a high probability of detection while maintaining the stringent false alarm rate $P_{fa} = 10^{-6}$ set in our experiment.

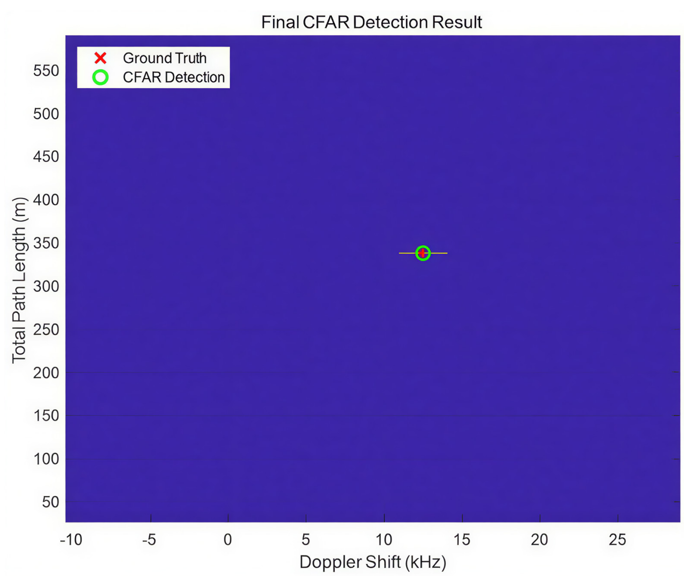

Fig. 3. CA-CFAR detection result.

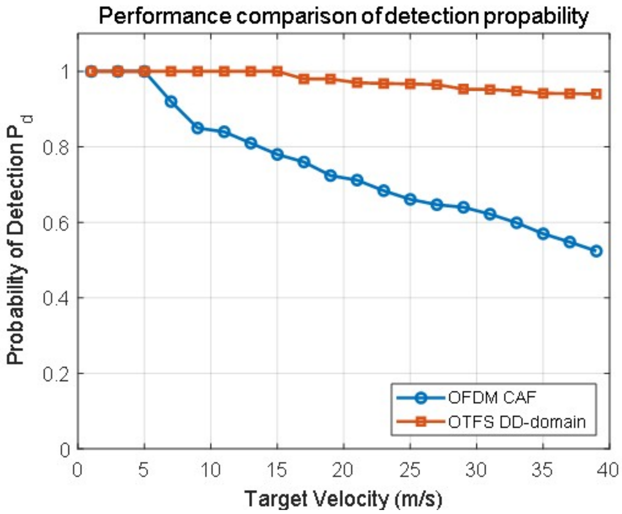

Fig. 4. Performance comparison of detection probability.

These results collectively validate that the proposed two-stage DD-domain framework can reliably solve the challenges of PCL. The subspace projection stage effectively removes dominant clutter to reveal the target, and the subsequent CA-CFAR stage successfully resolves the remaining ambiguity to isolate the actual target from the noise floor.

To further evaluate the robustness of the proposed framework under varying target dynamics, Fig. 4 presents the detection probability P_d as a function of target velocity. In this experiment, the conventional OFDM-based PCL system employs the standard CAF-based processing, whereas the proposed method performs detection directly on the OTFS delay–Doppler domain grid using the same CA-CFAR criterion. As the target velocity increases, the detection performance of the conventional OFDM–CAF approach gradually degrades due to Doppler-induced peak spreading and increased ambiguity, which are inherent limitations of CAF-based processing with Doppler-sensitive waveforms. In contrast, the proposed OTFS DD-domain method maintains a consistently high detection probability over the entire velocity range. This behavior indicates that representing the received signal in the delay–Doppler domain effectively mitigates the adverse impact of Doppler spread, leading to more stable and reliable target detection.

Overall, these results validate that the proposed two-stage DD-domain framework provides a practical and robust alternative to conventional CAF-based processing for PCL systems operating in rich multipath and Doppler-challenging environments, and offers a solid basis for subsequent system-level evaluation.

IV. Conclusion

We proposed a target detection framework for passive coherent location (PCL) systems that leverages the inherent delay-Doppler (DD) structure of OTFS modulation. By directly operating on the DD-domain representation of the received OTFS signal, the proposed method overcomes the limitations of conventional CAF-based approaches in rich multipath and Doppler-dispersive environments. A two-stage pipeline—consisting of subspace projection and 2D CA-CFAR—was included as auxiliary processing to improve detection robustness. Simulation results demonstrated accurate delay and Doppler estimation for a low-RCS target at an SCR of -30 dB, confirming the effectiveness of the OTFS-based DD-domain detection approach. Future work will explore multi-target scenarios, adaptive clutter modeling and further enhancements to estimation accuracy.

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