High-Resolution Time Delay Estimation for Bistatic OFDM Radar: A Two-Stage Approach with NI PXI Platform

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Abstract

In this paper, we present a two-stage high-resolution time delay estimation method for bistatic orthogonal frequency division multiplexing (OFDM) radar systems using real in-phase and quadrature (IQ) data acquired on a National Instruments-PXI (NI-PXI) platform. The approach leverages a combination of coarse estimation via cross-correlation and fine estimation using the multiple signal classification (MUSIC) algorithm. Experimental validation in an indoor lobby environment demonstrates that the proposed method can achieve nanosecond-level time-of-arrival (ToA) resolution, showing its practical effectiveness in multipath-rich indoor scenarios.

***Index Terms*—Time-of-Arrival, National Instruments, mmWave Transceiver System, OFDM**

I. Introduction

Recent advances in high-speed wireless communication, especially in millimeter-wave (mmWave) systems, have highlighted the importance of precise time-of-arrival (ToA) estimation for both synchronization and high-resolution localization. However, achieving nanosecond-level accuracy remains challenging under multipath and indoor conditions [1]. While discrete Fourier transform (DFT)-based methods are simple, their resolution is limited by sampling constraints, whereas super-resolution techniques like multiple signal classification (MUSIC) offer higher accuracy at greater computational cost [2].

To balance these trade-offs, we propose a two-stage ToA estimation method using orthogonal frequency division multiplexing (OFDM) signals, combining coarse cross-correlation with fine MUSIC-based refinement. Experimental validation using National Instruments' (NI) PXI hardware in an indoor setting confirms the method's effectiveness in bistatic radar and mmWave systems [3].

II. ToA measurement methodology

In this section, we introduce the National Instruments Measurement Test System (NI MTS) for testing. We will explain our methodology for ToA estimation.

A. Hardware and Software Requirements

The experimental environment is shown in Fig. 1. The measurement setup includes two PCI extensions for instrumentation, two antenna modules, two radio frequency up/down converters, two intermediate frequency-local oscillator module, an in-phase/quadrature (I/Q) digitizer, I/Q generator, analog-to-digital converter, and digital to analog converter [4]. NI LabVIEW, TMXLAB Kit, and Python are used for controlling and configuring the entire MTS system. The received I/Q data is logged to technical data management system files. MATLAB is then used to perform cross-correlation analysis between the transmitted OFDM signal and the received data for ToA estimation.

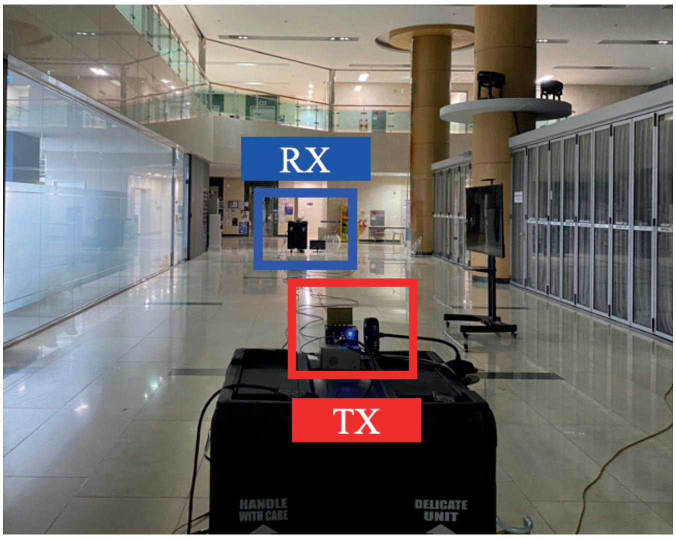

Fig. 1: Experimental setup

To achieve a high degree of precision, a multi-chassis trigger sharing mechanism is used. A 10 MHz synchronization clock driven by an oven controlled crystal oscillator is shared to both the transmitter and receiver chassis using cables of equal length. Likewise, a trigger is sent to both the transmitter and receiver chassis using cables of equal length at a 50 kHz frequency. This trigger is synchronized with the 10 MHz clock and is used to start data transmission and data recording at the transmitter and receiver, respectively.

B. Two-Stage Time-of-Arrival Estimation

To accurately estimate the ToA in a bistatic OFDM radar system, we propose a two-stage method that combines the simplicity of correlation-based coarse estimation with the precision of super-resolution spectral analysis. This approach enables high-accuracy delay estimation while maintaining computational efficiency.

TABLE I: OFDM waveform specification

Parameters	Value
Carrier Frequency	28 GHz
Bandwidth	768 MHz
Sampling Rate	3.072 GHz
Modulation	QPSK
Symbol Duration	2.5 μs
Cyclic Prefix	0.417 μs
Symbols per Pulse	10 symbols

In the first stage, cross-correlation is performed between the known transmitted OFDM signal $x[n]$ and the received IQ data $y[n]$ to obtain a coarse delay estimate. The sample delay corresponding to the peak of the cross-correlation function is selected as:

$$\hat{\tau}_{\text{coarse}} = \arg\max_{\tau} |r_{xy}[\tau]|, \quad r_{xy}[\tau] = \sum_{n} x[n]y^*[n-\tau]. \quad (1)$$

Here, $x[n]$ and $y[n]$ represent the transmitted and received baseband signals, respectively.

In the second stage, a high-resolution delay estimate is obtained using the MUSIC algorithm. A covariance matrix is constructed from a short window of the received signal centered around the coarse estimate. The MUSIC pseudo-spectrum is then computed by projecting delay-dependent steering vectors onto the estimated noise subspace:

$$P_{\text{MUSIC}}(\tau) = \frac{1}{\mathbf{a}^H(\tau)\mathbf{E}_n\mathbf{E}_n^H\mathbf{a}(\tau)}, \quad (2)$$

where $\mathbf{a}(\tau)$ is the steering vector corresponding to delay τ, and $\mathbf{E}_n$ contains the noise eigenvectors derived from the eigen-decomposition of the sample covariance matrix.

III. Analysis on Estimation Results

Figure 2 illustrates the first stages of the proposed two-stage time delay estimation process. The top and middle subplots show the transmitted and received IQ data, respectively. Despite strong noise and multipath effects in the received signal, the cross-correlation result (bottom subplot) clearly reveals periodic peaks corresponding to repeated OFDM bursts. The most prominent peak indicates the initial coarse estimate of the ToA.

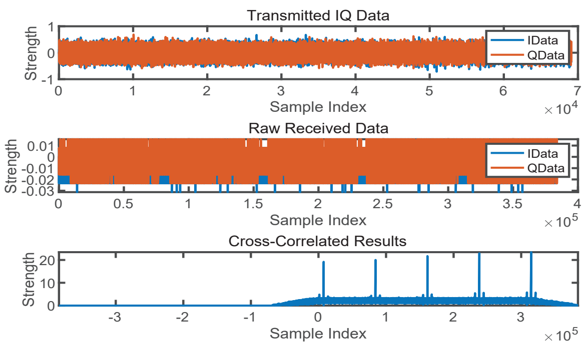

Fig. 2: IQ waveform and coarse time delay estimation

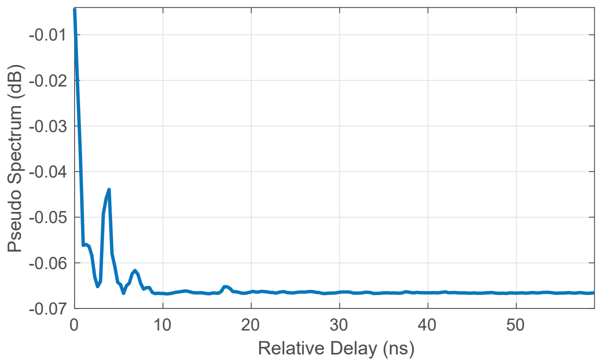

Fig. 3: Experimental results

To analyze the fine structure of the first received OFDM symbol, a high-resolution MUSIC algorithm is applied using the frequency-domain response derived from a full 7680-sample window, starting at a predefined coarse peak location. As shown in Figure 3, the resulting spectrum reveals the internal delay structure within the first detected symbol. Just for reference, if one were to scan the full range of possible delays across all 6400 subcarriers at a sampling rate of 3.072 GHz, the total delay span would be approximately 0 to 2.08 microseconds. The results confirm the effectiveness of the proposed approach in capturing high-resolution spectral information at the symbol level, without requiring antenna array beamforming or absolute propagation delay estimation.

IV. Conclusion

In this paper, we investigated the internal time-delay structure of the first received OFDM symbol using real measurement data from the NI MTS platform. Instead of estimating absolute propagation delay, we assumed a predefined arrival point and focused on extracting high-resolution delay features within a single OFDM symbol. A MUSIC-based spectral estimation method was applied over the frequency-domain channel response, enabling nanosecond-level resolution without relying on antenna arrays. Future work may explore extending this approach to continuous symbol tracking and multi-symbol joint delay estimation in dynamic indoor scenarios.

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