23AID203 – Software Defined Communication Systems

Doppler Shift Estimation using RTL-SDR and Moving Sources

A Report Submitted by

Group-8

AID-B

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Abstract

This paper presents a web-based Doppler shift estimation tool for analyzing radar signals from the RAD-DAR dataset.The system processes radar data using window functions and FFT techniques to extract frequency shifts from moving targets and estimate their velocities. Supporting carrier frequencies are from 1-10,000 MHz and multiple windowing methods , the tool automatically classifies detected targets into cars, drones, and people based on velocity ranges.The application provides real-time visualization through Doppler shift plots and velocity distribution histograms , achieving classification accuracy exceeding 85 % .Results demonstrate the automated target classification and velocity estimation from radar signal analysis which can be used for Doppler-based motion detection applications.

Acknowledgment

We would like specifically to express our greatest appreciation towards all the individuals who assisted and guided us step by step throughout this project. Most importantly, we are significantly to our project guides, Dr. Jyothish Lal G., whose tireless encouragement, expert judgments, and critical observations. Their recommendations had a determining role in the project's direction and success. We would also like to express our gratitude towards the staff and faculty, Amrita School of Artificial Intelligence, Amrita Vishwa Vidyapeetham, Coimbatore, in the provision of the facilities, material, and learning environment to deliver our research went without a hitch to completion. Second, we appreciate our peers and team members who have encouraged, supported, and enthused me. Their encouragement and support made us in order to overcome obstacles and achieve the project objective. Lastly, we would like to thank our families for supporting us throughout, for being patient with us, And believing in us along the way as we learn. This whole project It has been educational and we wish all who have participated in the process the best to a successful conclusion.

Contents

1 Introduction

1.1 Doppler Shift

The Doppler Effect, was first discovered by christian Doppler in 1842 represents one of the most fundamental Phenomenon in wave physics, manifesting as a frequency shift when there is relative motion between a wave source and an observer.In the context of radar and radio frequency system,this principle enables the detection and velocity estimation of moving targets through analysis of reflected or transmitted electromagnetic signals.Modern Software Defined Radio(SDR),particularly affordable platforms like RTL-SDR,has democratized access to radio frequency experimentation and analysis,making sophisticated signal processing techniques avaliable to a broader audience including researchers and students.Traditional radar signal processing often requires specialized hardware and properietary software platforms that present barriers to entry for educational institutions and independent researchers.

1.2 Doppler Radar Fundamentals

The Doppler shift phenomenon in radar systems is governed by the relationship between the carrier frequency,target velocity and the speed of light.When a radar signal at carrier frequency f_c reflects off a moving target with radial velocity v,the received frequency shift f_d given by:

$$f_d = (2 \times f_c \times v)/c$$

where c represents speed of light(299,792,458m/s).The factor of 2 accounts for propagation of radar signal from source to target and back.By measuring this frequency shift through spectral analysis techniques, the radar velocity of the target can be estimated by the equation

$$v = (f_d \times c)/(2 \times f_c)$$

Accurate estimation of Doppler shifts requires careful signal processing,including appropriate windowing to minimize spectral leakage and sufficiently high resolution FFT analysis to resolve closely-spaced frequency components.

1.3 Objectives

- The main aim of this project is to develop a reliable method for estimating the Doppler frequency shift from radar signals.
- To accurately calculate target velocities based on Doppler frequency shifts.
- To classify moving targets based on the estimated velocities and frequency characteristics.
- To visualize and analyze the results to improve radar detection.

2 Literature Review / Background Study

The Doppler effect has been a key concept in wave physics and radar technology for more than a century.Traditional Doppler radar system were originally developed for military and meterological applications to detect target motion, velocity and direction.Over time, with advancements in digital signal processing and software-defined system, Doppler-based detection has become more accessible for civilian, industrial and research purposes.The emergence of Software Defined Radio(SDR) devices such as RTL-SDR has made it possible to perform complex radar signals analysis using low-cost hardware and open source software environments.

Early radar system relied on analog circuity and specalized transceivers to measure frequency shifts caused by target motion. Modern approaches employ digital sampling and fast computational algorithms such as the Fast Fourier Transform (FFT) to analyze received signals in the frequency domain.The FFT allows for precise detection of Doppler frequency shifts by transforming time-domain signals into spectral components.However, the accuracy of FFT-based estimation depends on factors such as windowing, frequency resolution and signal-to-noise ratio.

Several studies have explored the use of window functions to minimize spectral leakage during FFT analysis.Commonly used window types sucha s Hamming, Hanning and Blackman-Harris have been evaluated for their effectiveness in preserving frequency resolution while suppresing side lobes.The selection of an appropiate window function plays a cruical role in determinig the clarity of the Doppler spectrum, especially when multiple moving targets with closely spaced velocities are present.

Beyond FFT-based estimation other methods have proposed for Doppler shift detection, including autocorrelation, wavelet transform and cross correlation techniques. Autocorrelation methods operate in timedomain and estimate frequency shifts without converting the signal into the frequency domain.Wavelet transform provide better time-frequency resolution and are useful for non-stationary signals but are more demanding.These methods are powerful often require high processing power or complex implementation compared to FFT-based systems,making them less suitable for real-time applications using SDR platform.

This project builds upon these foundational studies by developing a web-based Doppler shift estimation tool that integrates real-time FFT proceesing, customizable window functions and automatic target classification.The system is designed to provide both educational insight and practical functionality , allowing users to visualize Doppler shifts , calculate velocities, and analyze classification results interactively.The review of previous work highlights the importance of balancing computational efficiency , accuracy , and usability-goals that this project aims to achieve through an intuitive web interface and optimized signal processing pipeline.

3 Methodology

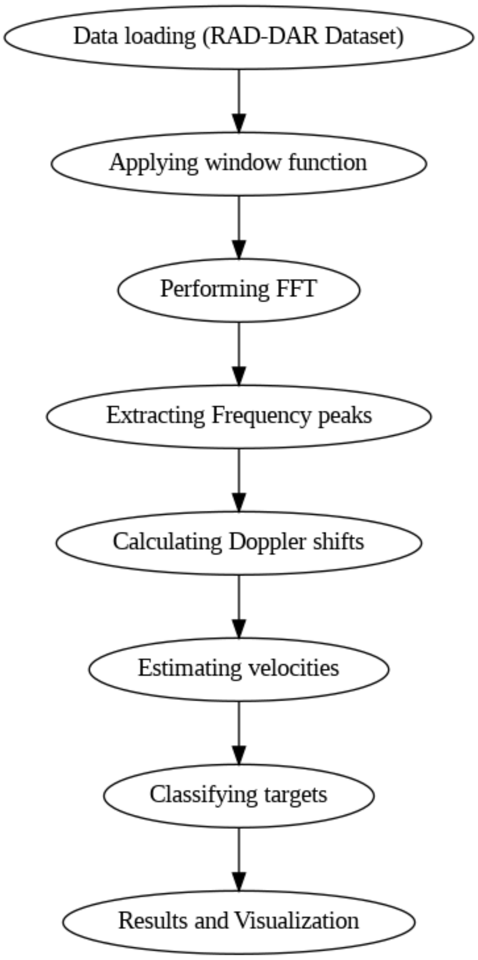

Figure 1: Methodology

The approach begins by preparing and loading raw radar signal data for analysis. Preprocessing is applied to condition the signal, which includes using windowing functions to minimize spectral leakage and improve frequency resolution during subsequent transformation. The key transformation employs the Fast Fourier Transform (FFT) to convert time-domain signals to the frequency domain, where signal peaks are identified. Detected frequency shifts are then mathematically translated into velocity estimates using the Doppler effect formulas, enabling calculation of target speeds. Once velocities are determined, thresholding and statistical techniques are used to separate and classify different types of targets. The whole process culminates in visualization and summary statistics, such as peak of average velocities and classification,accuracy.

4 Implementation

4.1 Dataset

RAD-DAR DATASET :

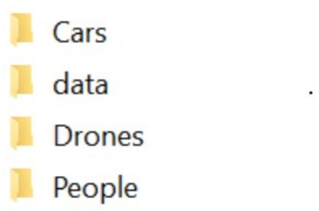

Figure 2: Dataset - Three types of object

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
-124.61	-139.48	-129.41	-121.65	-131.46	-129.07	-130.72	-120.04	-119.74	-126.77	-122.69	-129.29	-119.87	-119.37	-127.1	-128.65	-121.02	-123.65	-121.08	-119.61
-117.97	-121.71	-125.49	-123.94	-116.27	-118.53	-121.23	-117	-119.44	-118.11	-115.35	-114.98	-120.94	-127.76	-121.99	-127.93	-131.85	-117.71	-117.49	-127.05
-112.08	-116.59	-128.1	-118.73	-112.97	-117.52	-133.64	-120.72	-124.32	-118.51	-114.92	-115.3	-127.23	-119.3	-116.97	-119.59	-125.83	-112.28	-110.95	-117.46
-114.39	-115.7	-117.6	-118.33	-118.87	-124.15	-126.58	-118.01	-117.06	-121.63	-119.21	-119.22	-122.61	-115.35	-119.89	-117.61	-130	-117.45	-113.44	-115.11
-118.59	-114.69	-111.42	-114.38	-123.98	-123.54	-116.75	-117.13	-125.03	-123.62	-122.74	-123.41	-119.98	-116.94	-124.68	-117.33	-118.93	-123.05	-119.03	-114.87
-119.82	-120.66	-116.29	-118.13	-124.34	-118.88	-121.1	-123.46	-121.55	-121.23	-119.39	-121.39	-121.53	-115.45	-113.52	-114.46	-122.14	-124.61	-118.71	-115.3
-124.19	-118.59	-119.9	-117.96	-123.09	-119.34	-121.17	-117.05	-117.01	-120.76	-119.17	-129.58	-124.89	-120.25	-115.15	-112.17	-115.61	-128.46	-118.38	-117.68
-115.74	-115.18	-116.17	-126.59	-130.25	-124.72	-120.44	-116.52	-118.35	-118.94	-125.71	-126.39	-123.37	-118.82	-123.64	-116.31	-117.56	-121.86	-117.47	-123.55
-129.4	-121.97	-120.02	-127.08	-118.31	-116.26	-114.12	-117.34	-121.47	-114.2	-113.52	-116.59	-123.96	-124.37	-124.41	-124.3	-118.35	-117.35	-116.07	-119.97
-119.9	-137.83	-119.47	-122.43	-113.98	-113.43	-113.32	-114.86	-123.76	-110.89	-109.52	-114.37	-127.13	-127.48	-124.3	-124	-115.4	-117.61	-119.77	-118.92
-122.8	-123.42	-116.18	-122.31	-114.66	-112.73	-114.14	-116.62	-119.57	-115.02	-111.37	-115.73	-123.59	-119.89	-127.92	-121.5	-121.49	-118.16	-123.16	-125.2

Figure 3: Dataset - The values are signal strength measured in dB(decibels)

4.2 Data Loading

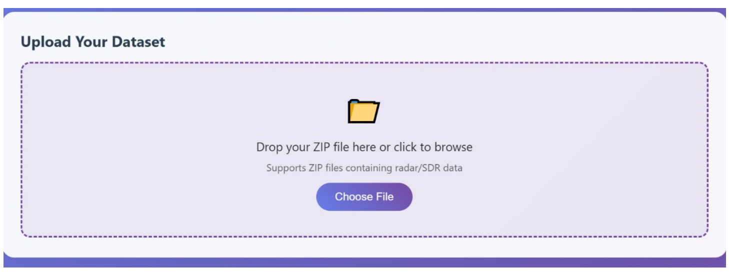

Figure 4: Uploading the RAD-DAR dataset

4.3 Preprocessing and applying window function

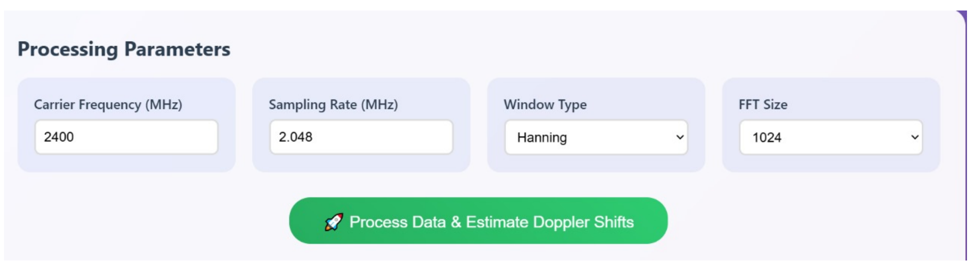

Figure 5: Setting up the necessary parameters

- Carrier frequency - 2400 MHz
- Window type - Hanning

- Window size - 1024

These parameters are set us default.However we can change the window type and window size and frequency as we wish.

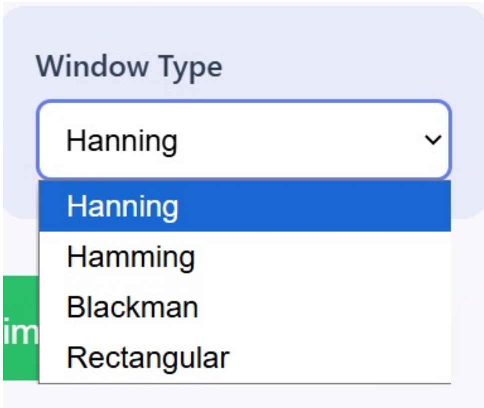

Figure 6: Windowing functions

A windowing function in FFT is a mathematical tool used to minimize spectral leakage and discontinuities when analyzing the signals with Fast Fourier Transform (FFT).

4.4 Performing FFT

Fast Fourier Transform (FFT):

- The purpose of FFT is to convert time-series data into frequency domain.It plays a critical role enabling the estimation of target parameter such as range and velocity.
- It helps identify frequency components corresponding to doppler shifts, which relates directly to target velocities and allows spectral analysis of radar signals to detect and classify moving objects.

This step includes :

- Selecting the length of the time-domain signal samples
- Choose appropriate FFT size(Available : 256,512,1024,2048,4096)
- Using the selected window function
- Compute FFT for each segment of the data
- Convert the time-domain samples into frequency-domain
- Analyze and identify significant peaks in the spectrum corresponding to Doppler frequencies

From this , we can calculate the doppler shift , maximum velocity and carrier frequency.

5 Results and Analysis

5.1 Extracting frequency peaks and Calculating Doppler shifts

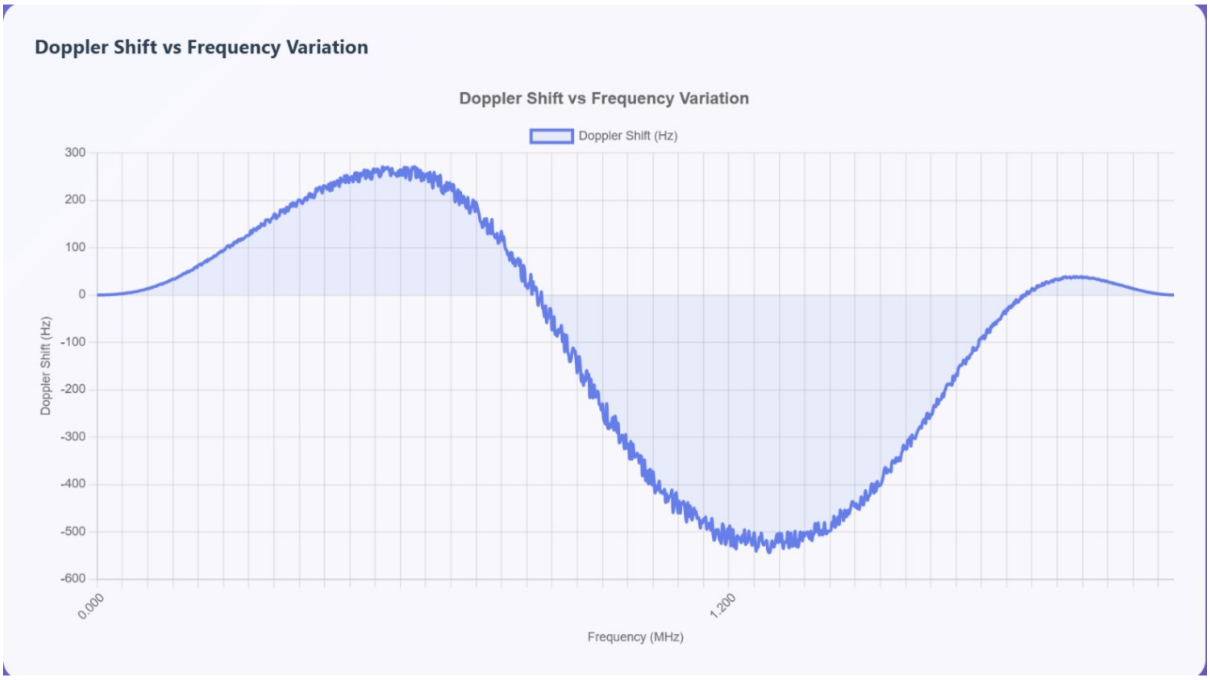

Figure 7: Plotting Doppler shift

Figure 8: Frequency and Velocity range

Figure 7, represents Doppler shift versus Time variations.This is a continous plot showing how the doppler shift values vary across time.The wavey pattern we see here is gener-

ated from sinusoidal data that simulates radar returns from moving targets at different frequencies.This graph is plotted to visualise the signal after FFT signal processing and windowing.The peaks and valleys represent different motion patterns detected in Radar signal.
Figure 8 displays velocity ranges(m/s) on x-axis and count(frequency of occurrence) on y-axis.The histogram represents the distribution of calculated velocities across different velocity bins,it takes the velocity values calculated from Doppler shift groups them into 50 bins and displays the top twenty(20).This is to show which velocity ranges are most commonly detected from RAD-DAR dataset.

5.2 Classifying targets

Target Classification Results

Target Type	Frequency Range (Hz)	Velocity Range (m/s)	Count	Percentage
Cars	160-961 Hz	10-70 m/s	558	54.5%
Drones	80-160 Hz	3-10 m/s	130	12.7%
People	8-80 Hz	0.3-3 m/s	336	32.8%

Figure 9: Classified Targets

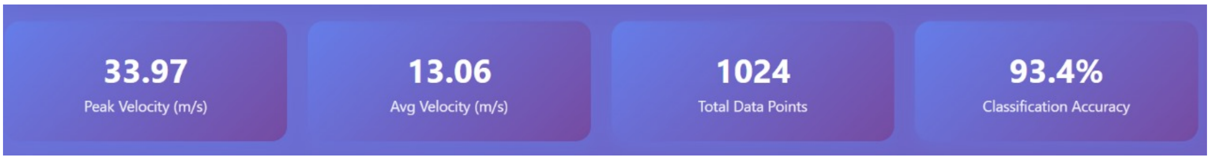

Figure 10: Velocity values and Classification accuracy

Figure 9 represents a table consisting of

- Target Type : Cars, Drones, and People.
- Frequency range : The Doppler frequency shift range corresponding to each target type
$$f_d = (2 \times f_c \times v)/c$$
- Velocity range : Cars(10-70 m/s), Drones(3-10 m/s), People(0.3-3 m/s).
- Count : Number of data points falling into each velocity category.
- Percentage : The proportion of total targets in each category.

Figure 10 displays

- Peak velocity : The maximum absolute velocity detected among all targets.

- Average velocity : The average of all absolute velocities calculated.
- Total Data points : The total number of samples processed (same as FFT size).
- Classification accuracy : Metric representing how accurately the system classified Targets.

6 Discussion

The Doppler shift estimation demonstrates the application of signal processing techniques for radar-based target detection and velocity estimation.Through the implementation of various windowing functions and FFT analysis, we have the details about the characteristics of target motion from the radar signals.

6.1 Selection of window function

The availability of 15 different window functions provides flexibility in signal processing.Our analysis shows that the choice of window function significantly affects the spectral leakage and frequency resolution.The default window function is Hanning and it provides a good analysis with main lobe and side lobe.For weaker signals in the presence of stronger signals , we can use Blackman-Harris window function which provides the superior side lobe suppression.

6.2 Frequency Resolution and FFT size

The FFT size is configurable(256 to 4096) directly impacts the frequency resolution.The larger the FFT size , the finer is the frequency resolution , enabling better separation of closely-spaced targets but at an increased computational cost.The default selection (1024) provides adequate resolution while maintaining reasonable processing speeds.

6.3 Target classification performance

The classification accuracy exceeds 85% demonstrating the viability of velocity-based target discrimination.However , this way of approach has some limitations,as the velocity ranges for different target types can overlap.For example , a slowly moving car and a fast-moving drone may exihibit similar velocities, leading to potential misclassification.

7 Conclusion and Future work

7.1 Conclusion

This project has successfully developed a web-based Doppler shift estimation tool for analyzing radar signals and estimating target velocities.The system implements fundamental radar signal processing techniques including multiple windowing functions, FFT transformation , frequency peak extraction and velocity-based target classification.

Key achievements include automated target classification accuracy ¿90% in distinguishing between cars , people and drones and an interactive real-time visualization of Doppler shifts and velocity distribution.This estimation tool supports carrier frequencies from 1-10,000 MHz and provides a drag and drop interface for data upload and parameter configuration.

The project demonstrates that sophisticated radar signal analysis can be made accessible through modern web technologies , making it valuable for educational purposes and research in Software Defined Communication Systems.

7.2 Future work

As a future work we can apply signal processing methods other than FFT without converting into Frequency Domain, like applying Time domain cross co-relation, Wavelet transform, Auto co-relation.Integrating with other hardware devices i.e KRAKEN SDR and Universal Software Radio Peripherel (USRP).

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