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Low Cost Embedded Passive Bistatic Radar Detection Testbed

by

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Professor Michael Bruenig
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Dear Professor Bruenig,

In accordance with the requirements of the degree of Bachelor of Science (Honours) in the School of Electrical Engineering and Computer Science, I present the following thesis entitled

'Low Cost Passive Bistatic Radar Detection Testbed'

This thesis was performed under the supervision of Professor Bialkowski(EECS). I declare that the work submitted in the thesis is my own, except as acknowledged in the text and footnotes, and that it has not previously been submitted for a degree at the University of Queensland or any other institution.

Yours sincerely,

Flynn Kelly

Acknowledgements

SUPERVISOR, FRIENDS, ETC....

Abstract

> **Abstract: MINIMAL VIABLE PRODUCT OVERVIEW**
> broad need, specific need, response aim, response methods, key outcomes and implications.

ORIGINAL

This thesis presents the background, design and implementation of a low cost testbed for a passive radar based detection system. The relatively recent proliferation and cost reduction of software defined radio technology and the increase in single board computer processing capabilities has enabled passive radar detection systems to be implemented in a low cost, and even embedded manner. This project aims to investigate the feasibility of a low cost, embedded passive radar detection system utilising a digital broadcast signal as the illuminator of opportunity. The project will focus on streamlining the signal sampling and processing process through a singular embedded linux testbed setup, without the need for physical higher cost PC hardware at a given RX location. This will be achieved by using a combination of existing embedded IoT hardware, and through using existing DSP (digital signal processing) and radar filtering algorithms. A central feature of this thesis is its low cost nature, with potential for both scalebility but also cost/quality increases. The project will be evaluated based on the successful detection of aerial vehicles in a controlled environment, the latency of the detection system, and the overall cost of the design. The project will also be compared to existing work in the field of passive radar detection, and the potential for future work and scaleability will be explored.

RECAST

Affordable and effecient passive radar based detection, tracking and situational awareness technology is increasing in demand in a range of sectors and academia. As software-defined radio (SDR) technology becomes more widespread and single-board computers (SBCs) continue to gain processing power, the possibility of deploying passive radar systems in an embedded, cost-effective manner has emerged as a critical area of research and commercial development. The growing need for such systems is particularly evident in scenarios where traditional, expensive PC hardware setups at remote receiver (RX) locations are impractical or cost-prohibitive. This has created a specific need for streamlined, scalable systems that can function independently and effectively in various environments.

In response to these demands, this project aims to design and implement a low-cost, embedded passive radar detection testbed prototype system that leverages a digital broadcast signal as an illuminator of opportunity. The chosen approach involves utilizing existing embedded IoT hardware in combination with established digital signal processing (DSP) techniques and radar filtering algorithms. This integrated solution is intended to form a single embedded Linux testbed capable of handling both signal sampling and processing, along with sampling networking thereby eliminating the reliance on costly and complex physical hardware at each RX location.

Key outcomes of this research include the successful detection of aerial vehicles within

controlled environments, an analysis of the system's latency, and a comprehensive evaluation of the overall cost-effectiveness of the design. The implications of this work include offering valuable insights into the scalability and cost-quality balance that can be achieved in future passive radar system implementations. Moreover, the project aims to deliver a re-usable, scaleable testbed which can be used to further develop and test passive radar based detection and situational awareness systems.

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Chapter 1

Introduction

This section will contain a clear definition of the thesis topic, goals, project scope, and relevance of the project.

1.1 Topic and Relevance

Passive radar detection technology is a class of radar detection whereby the radar system does not emit any radiation. Instead, it uses existing electromagnetic signals in the environment, such as television or radio broadcasts, to detect and track objects. Passive radar can be bistatic, whereby the transmitter and receiver are separate, or multistatic, where there are multiple receivers. The technology has been around since the early 20th century, but has only recently become feasible due to advances in digital signal processing and computing [11]. The technology has a number of advantages over traditional radar systems. It is covert, as it does not emit any radiation, and is therefore difficult to detect and directly jam, leading to a concentrated interest from defence cirlces [14]. It is also relatively cheap, as it does not require a dedicated transmitter and hence has less energy consumption. Conversely, it has a number of disadvantages, such as a lower signal-to-noise ratio, and a requirement for a relatively large amount of computational power to process the received signals [11].

Bistatic passive radar detection has a wide range of applications centered around situational awareness, including air traffic control, border security, and environmental monitoring. Embedding the passive radar technology is a relatively new field buoyed by recent and increasing developments in computational power on Internet of Things (IoT) devices [17]. Key components and processes of a passive radar RX system include the antenna, the receiver hardware (software defined radio), signal sampling hardware and memory, along with the compute to complete the digital signal processing [12]. Advantages of implementing some or even all of these components in a low cost manner include increased scaleability, portability, and lower reliance on external high cost hardware such as a PC.

1.2 Aims and Objectives

To explore the feasibility of a low cost embedded passive bistatic radar detection, and provide a scaleable proof of concept, this thesis aims to provide a user friendly testbed for digital signal based passive radar detection. The work conducted in this thesis and the eventual prototype hopes to decrease the barriers to entry for passive radar detection technology, and provide a platform for further research and development in the field. At a high level, the primary objectives of this thesis project are;

- Develop an understanding and proof of concept of passive radar detection algorithms on low cost single board computers (SBC) connected to software defined radio (SDR) hardware,

- Design and implement a small sized modular passive radar detection system on single board computer hardware with an emphasis on user friendliness and scaleability, and to

- Verify the functionality of the low cost embedded passive radar detection system in a controlled environment against higher power computing results, and investigate the potential for scaling up to a multistatic system through a network.

1.3 Scope

This thesis focuses on the development of a hardware testbed based on software defined radio (SDR) and single board computer (SBC) technology. The scope of this thesis project is limited to the following:

- The development of a passive radar detection system using existing digital broadcast signals as illuminators of opportunity,

- The design of a small scale, modular, low cost system using single board computer hardware, specically with simple user buttons to commence and cease data collection and processing, and

- The verification of the passive radar detection system performance and latency in a controlled environment agains higher cost PC hardware.

- Exploring the potential for scaling up the system to a multistatic, remote RX system through a network.

Given that passive radar based detection is a broad topic with much academic progress and commercial technological development, this thesis will not aim to cover the broad subject area. Consequently, the following topics are out of scope for this project:

- The development of a complete bistatic passive radar detection system optimized for low latency, and object classification,

- The development of a full multistatic passive radar detection system, whereby angle of approach and precise location of a target can be determined, and

- The development of a passive radar detection system using non-digital broadcast signals as illuminators of opportunity.

- The modification and development of digital signal processing / detection algorithms optimized for latency and customised hardware applications.

Chapter 2

Background

Background: this should include all (appropriately cited) information (concepts and prior literature) for a layperson to understand your project/experiment.
- NEED TO RESEARCH AND DISCUSS THE EFFECTS OF NOISE AND TYPICAL ATTNENUATION

This chapter collates the necessary background information for the project, including the fundamentals of passive radar, the use of illuminators of opportunity, range doppler mapping, radio hardware, digital signal processing, IoT architecture, and networking with embedded hardware.

2.1 Passive Radar Fundamentals

The key and unique feature of passive radar is its utilisation of existing illuminators of opportunity, such as television or radio broadcasts, to detect and track objects. The technology has been around since the early 20th century, with modern interest accelerated due to the use of passive radar systems on UHF TV signals and VHF FM radio tranmission systems in the 1980's [12]. Equivalent terms used to describe passive radar include passive coherent location (PCL), and passive covert radar (PCR), parasitic radar, piggyback radar. Specifically, *bistatic* radar refers to the distributed design of the transmitter and receiver, as opposed to classic *monostatic* radar. As reflectd by Figure 2.1 below, the turning parabolic of monostatic radar is able to receive both range and bearing of the signal echo, whereas passive bistatic radar measures time delay of the echos from the target, allowing doppler shift from the relative speed of the target to be measured.

The geometry of passive bistatic radar can be further explored and equations can be mapped accordingly, with the distance between the transmitter and receiver R being determined by known quantities such as the baseline as reflected below in Figure 2.2.

The bistatic range R_R is given by:

$$R_R = \frac{(R_T + R_R)^2 - L^2}{2(R_T + R_R + L\sin\theta_R)} \tag{2.1}$$

The Doppler shift f_D is given by the rate of change of the bistatic range sum:

$$f_D = \frac{1}{\lambda}\frac{d}{dt}(R_T + R_R) \rightarrow f_D = \frac{2v}{\lambda}\cos\delta\cos(\frac{\beta}{2}) \tag{2.2}$$
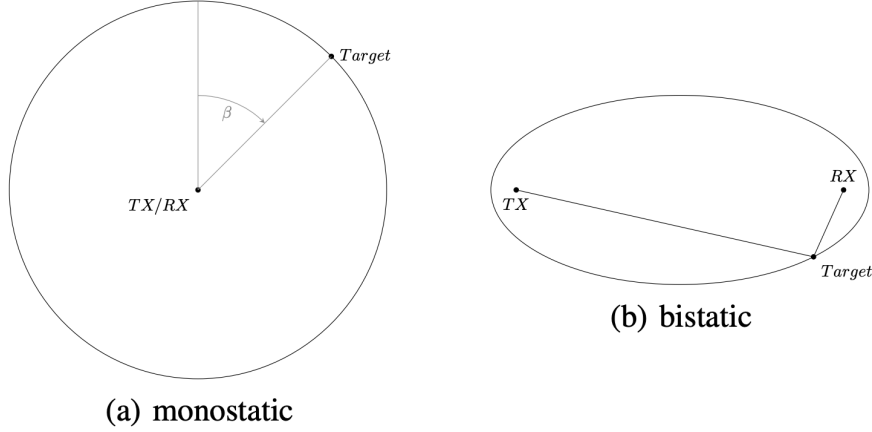
(a) monostatic

(b) bistatic

Figure 2.1: Monostatic (a) and bistatic (b) radar topologies [17]

In the case of this project, both the TX (illuminator of opportunity) and the RX (embedded passive detection system) will be static, and the target will be moving, simplifying the mathematical calculations as much as possible, resulting in the cos version of equation 2 above.

The Doppler shift will be used to determine the speed of the target as well as its relative directional motion, and the range will be used to determine the distance of the target from the receiver. Another important feature of bistatic passive radar systems is its performance which can be equated through the bistatic radar equation, which is equivalently derived as the monostatic radar equation [12].

$$\frac{P_r}{P_n} = \frac{P_t G_t}{4\pi R_T^2} \cdot \sigma_B \cdot \frac{1}{4\pi R_R^2} \cdot \frac{G_r \lambda^2}{4\pi} \cdot \frac{1}{kT_0 BF} \tag{2.3}$$

Where:

- P_r is the received target echo power.

- P_n is the receiver noise power.

- P_t is the transmit power.

- G_t is the transmit antenna gain.

- R_T is the transmitter-to-target range.

- σ_B is the target bistatic radar cross section.

- R_R is the target-to-receiver range.

- G_r is the receive antenna gain.

- λ is the signal wavelength.

- k is Boltzmann's constant (1.38×10^{-23} JK^{-1}).

- T_0 is the noise reference temperature.

- B is the receiver effective bandwidth.

- F is the receiver effective noise figure.

The denominator of the bistatic radar equation includes the term $\frac{1}{R_T^2 R_R^2}$. This term implies that with omnidirectional antenna patterns, the contours of constant signal-to-noise ratio (SNR) are described by the equation $R_T R_R = $ constant, which represents Ovals of Cassini. These ovals represent the locations in a given PBR co-ordinate sytem where the distances from the target to the transmitter and receiver remain the same. In the case of directional antennas,
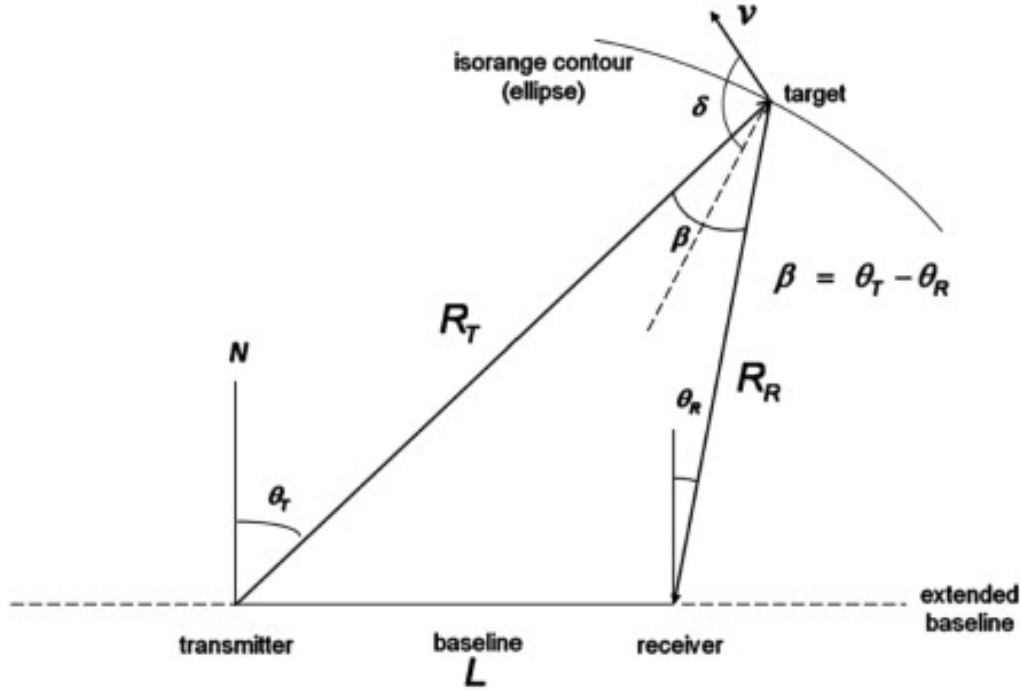
Figure 2.2: Bistatic radar geometry [12]

these contours are altered. Moreover, the signal-to-noise ratio is minimized when the target is equidistant from the transmitter and receiver ($R_T = R_R$), and maximized when the target is closer to either the transmitter or receiver [12].

> NEED TO MENTION / RESEARCH THE EFFECT OF NOISE AND DECIBELS EXPECTED HERE.

2.2 Illuminators of Opportunity

The illuminator of opportunity is the signal that is used to illuminate the target, and is the primary source of the signal that is received by the passive radar system. The illuminator of opportunity can be any signal that is transmitted through the air, such as television or radio broadcasts, and can be tailored to the specific requirements of the passive radar system. Griffiths and Baker outline the three key paramaters when selecting an illuminator [11]:

1. The **Power Density** at the target: It refers to the strength of the signal (in Watts per square meter) that reaches the target area from the illuminator. Higher power density can improve detection performance due to a stronger return signal.

2. The **Nature of the Waveform**: This includes the waveform's properties, such as bandwidth and modulation, which can affect the radar's resolution and ability to distinguish between targets and clutter.

3. The **Coverage**: The spatial area over which the illuminator's signal is spread. Adequate coverage is essential to ensure the target is within the illuminator's effective range.

Illuminator signals are not limited to terrestrial signals, and can also include signals from satellites, and can be tailored to the specific requirements of the passive radar system. The

illuminator of opportunity primarily explored for this project is the DAB+ signal, and the target signal will be aerial vehicles - most likely in the form of civillian passenger jets. The DAB+ signal is a good option due to its high power density, and its relatively high bandwidth, which can be used to improve the radar's resolution and ability to distinguish between targets and clutter. Moreover, the geographical proximity of a DAB+ transmitter at Mt Cootha to the University of Queensland, St Lucia campus, making it a potentially ideal choice for the project. Another prospective digital illuminator signal is DVB-T (digital video broadcast - terrestrial), which is similar in its digital modulation to DAB, but provides increased bandwidth and signal power [8]. Furthemore, as shown by Yin et. al [27], due to the relative complexity of DVB visual signals, more signal processing steps can be required, which could exceed prospective hardware limitations of this project.

A potential problem associated with the use of DAB as an illuminator is direct signal interference (DSI), with the effects being amplified in urban environments. Coleman et. al [6] explain that the sheer signal size of direct illuminator size relative to surveillance signal size results in a high level of DSI. They outline that the cross polarisation of the transmitted DAB signal can be utilised along with illuminator cancellation filtering to attain higher level suppression. The leakage of the illuminator signal into the target signal can be due to a range of factors including buildings, trees and other reflective items as highlighted by Palmer et. al [14].

Typical characteristics of Australian DAB+ signals include frequency of just over 200MHz, bandwidth of approximately 1.5MHz, and a minimal output power of 10kW effective radiated power (ERP), consequently covering a large area [6]. These digital signals employ a modulation scheme called COFDM (coded orthogonal frequency division multiplexing), which is a form of multi-carrier modulation that is robust against multipath interference [11]. COFDM works by dividing the signal into multiple, simultaneous streams which are orthogonal to each other, modulated at a different frequency, maximising robust signal propogation. This is particularly useful in the context of passive radar, as it allows for the target and reference signal to be received by the passive radar system even if it has been reflected off multiple surfaces, such as buildings or trees.

> FM / other signals: why / why not? ALSO TALK ABOUT THE DAB STANDARD SPECIFICALLY

All of the above features result in DAB signals being condusive for ambiguity function performance (analyzed in further detail below). This can mainly be attributed to the relatively wide bandwidth of DAB enabling good resolution, constant DAB envelope stemming from COFDM protocol, and the multipath resistance [13].

2.3   Range Doppler Mapping

Range doppler mapping is a technique used to determine the distance and relative velocity of targets by analyzing the frequency shift (Doppler shift) and time delay of the received signals after they are reflected off the targets. The signal response of a target at a particular range and velocity can be predicted by the ambiguity function seen in equation 2.4 [11].

$$\chi(\tau, f) = \int s_{\text{reference}}(t) s_{\text{received}}^*(t - \tau) e^{j2\pi ft} \, dt \qquad (2.4)$$

Where:

- $\chi(\tau, f)$ is the ambiguity function.

- τ is the time delay.

- f is the Doppler frequency.

- $s_1(t)$ is the transmitted signal.

- $s_2(t)$ is the received signal.

- $s_2^*(t - \tau)$ is the complex conjugate of the received signal, time-shifted by τ.

- $e^{j2\pi ft}$ is the complex exponential representing the Doppler shift.

- The integral is taken over all time t.

The ambiguity function can be plotted, thereby visualising resolution, sidelobe patterns and any discrepancies in range and doppler. This is especially important for passive bistatic radar, whereby waveforms are not explicitly designed for radar and the geometry also has an impact [12]. Hughes visualises the geometry considerations and potential flaws of generic passive bistatic configuration below in Figure 2.3.
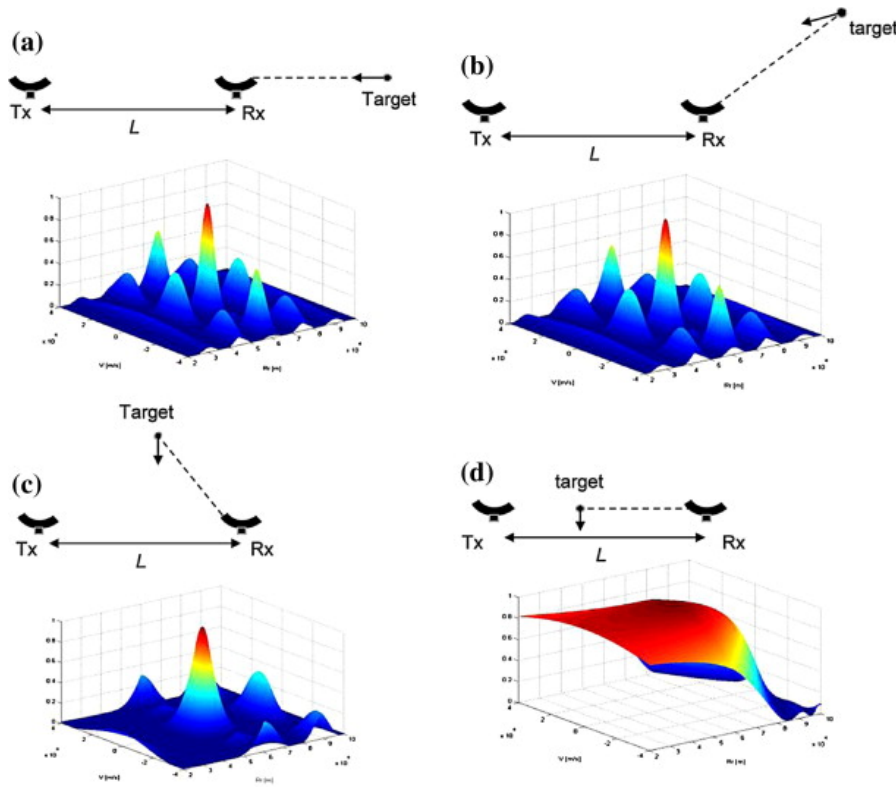
Figure 2.3: Geometry and ambiguity function [12]

Understanding the link between geometric configuration and theoretical signal properties, the practical manifestation of the ambiguity function is range doppler mapping. As shown in Figure 2.4, the map is a heat map and is derived with filters for noise minimsation, allowing for the visualisation of the target signal with minimal clutter.

Should i use a better RDM??

In the case of this project, the time delay will be utilised to calculate the bistatic range (x axis) and the Doppler shift will be used to calculate the relative velocity of the target (y axis). In summary, ambiguity function and subsequent range doppler mapping will be vital for mapping the DAB+ signal characteristics for given geometry and motion of the surveilled target.

MORE DETAIL
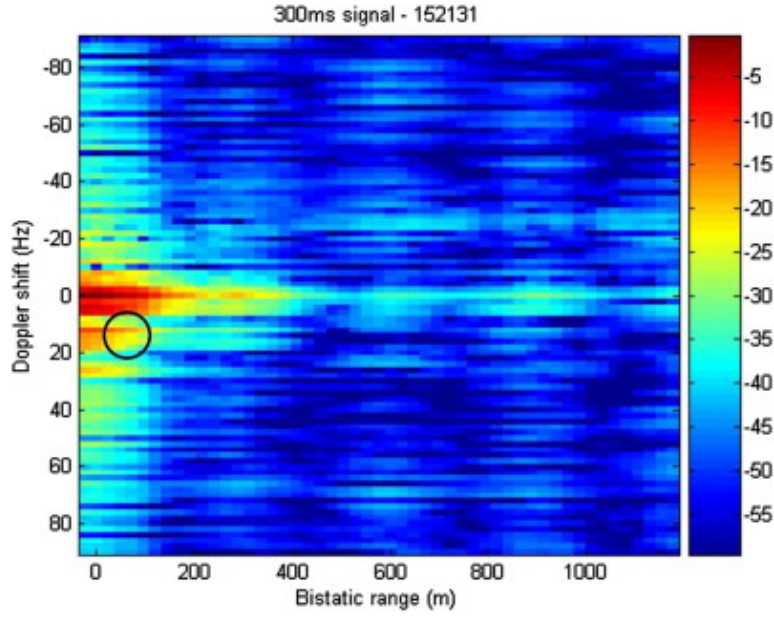
Figure 2.4: Example of range doppler map for WiFi PBR [12]

2.4 Radio Hardware

Fundamentally, the relevant radio hardware for a passive radar project can be broken into the antenna and the SDR module. Given the low cost aims of this testbed, hardware cost and performance is a major consideration.

2.4.1 Software Defined Radio

Luckily, the proliferation of general purpose SDR hardware modules has enabled easy access to radio frequency (RF) signals [22]. In general, a SDR system can exist purely as a receiver (lower cost modules) or as a transceiver, whereby connected software (e.g. PC) are utilised for the modulation and demodulation of signals [10]. The SDR system can be used to sample the RF signal, and then process it digitally, enabling the use of a wide range of software tools for further signal processing. Typically, as seen in the block diagram below in figure 2.5, SDR's comprise of an analogue front end, an analogue to digital converter (ADC) / digital to analagoue convertor (DAC), and some sort of band processing [10].
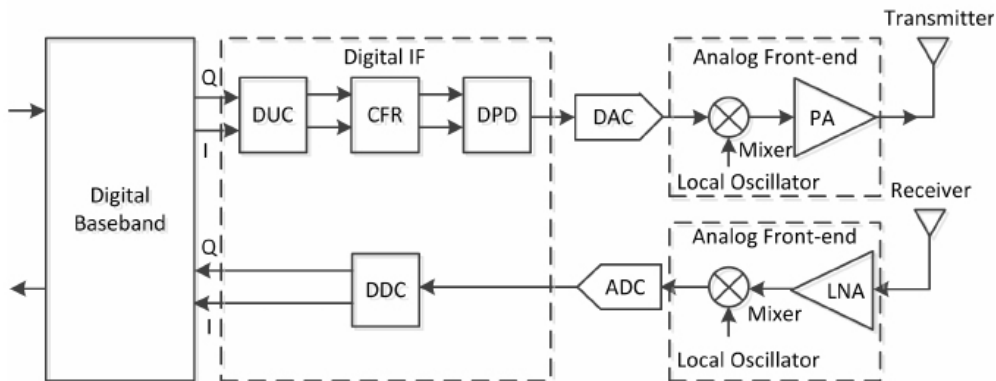
Figure 2.5: Block diagram of SDR transceiver [10]

The most popular and lowest cost SDR module is the RTL-SDR, which is a USB dongle that can be used to receive (note the RTL-SDR is RX only) and decode a wide range of RF signal bands. This includes FM radio, DAB, and DVB-T signals, which are all potential illuminators of opportunity for passive radar systems. Typical bandwidth of the RTL-SDR is 2.4MHz, and the frequency range is 24MHz to 1.7GHz [21].

A plethora of other SDR modules exist, with varying costs and capabilities. A range of common SDR modules are listed in the table below 2.1, along with their key specifications.

Table 2.1: Comparison of SDR's [23]

SDR	Frequency Range	Bandwidth	RX ADC	Sampling Rate
USRP	0-6 GHz	Up to 160 MHz	12-14 bits	Up to 200 MS/s
RTL-SDR	24 MHz - 1.75 GHz	Up to 2.4 MHz	8 bits	Up to 3.2 MS/s
bladeRF	47 MHz - 6 GHz	Up to 56 MHz	12 bits	Up to 61.44 MS/s
HackRF	1 MHz - 6 GHz	20 MHz	8 bits	Up to 20 MS/s
LimeSDR	0.1 MHz - 3.8 GHz	61.44 MHz	12 bits	Up to 61.44 MS/s
SDRplay	1 kHz - 2 GHz	Up to 10 MHz	12 bits	Up to 10.66 MS/s
KrakenSDR	24 MHz - 1.76 GHz	Up to 2.5 MHz	8 bits	Up to 2.56 MS/s

As performance increases for the SDR's above so does the unit cost, which is an important consideration for the testbed design explored in scection 4.1. As seen in table 2.1, other than the RTL-SDR all of the SDR's have a large bandwidth making them suitable for digital illuminators, furthemore, the ADC sampling bits are often larger, resulting in more more accurate signals. However, the increased resolution of an ADC also results in larger storage requirements and potentially bottlenecks in the processing chain [23]. Another interesting specification to note which is not seen on 2.1 is the the number of RX channels. The RTL-SDR has one RX channel, whereas the USRP has two RX channels, which can be used to receive two signals simultaneously. This could be useful for the testbed, as it would allow for the simultaneous reception of the illuminator signal and the target signal, which could be used to improve the accuracy of the passive radar system. Specifically, the KrakenSDR features up to five channels, based on clustered RTL R820T2 tuners along with hardware to ensure the synchronisation of the channels [5]. A key advantage of the KrakenSDR in passive radar receiver systems is their ability to achieve angle of direction measurements, which can be used to determine the location of the target as shown by Cass [5].

2.4.2   Antenna

Quite simply defined by the IEEE as *That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves* [1], an antenna is crucial for any radio system, and in the case of passive bistatic radar, receiving all relevant signals. This section will provide a brief background of the key concepts and types of antennas relevant to passive bistatic radar. The ITEE standard definition of terms for antennas [1] also succinctly defines the following terms which are relevant;

1. **Radiation Pattern**: This describes the angular variation in radiation at constant distances from the antenna. The radiation pattern depends on the signal strength and is categorized into three main types: Isotropic, Directional, and Omnidirectional.

2. **Directivity**: Defined as the ratio of the power density in the direction of the pattern's maximum to the average power density at the same distance from the antenna.

3. **Gain**: Closely related to directivity but includes losses. Gain is defined as the directivity minus any losses experienced by the antenna.

4. **Polarisation**: This refers to the nature of the electric field radiated by the antenna. If the polarisation direction is not specified, it is assumed to be in the direction of maximum gain.

5. **Bandwidth**: The range of frequencies over which the antenna operates effectively.

6. **Beamwidth**: The angle between two points on the radiation pattern where the power is at its maximum. The two main types of beamwidth are Half Power Beamwidth (HPBW) and First Null Beamwidth (FNBW).

7. **Impedance**: The ratio of voltage to current at the antenna terminals.

As with considering the SDR module, the cost versus performance trade-off is also a key factor when selecting an antenna. The most common types of antennas used in passive radar systems are the dipole antenna and the Yagi-Uda antenna. The dipole antenna is a simple, low-cost antenna that is easy to construct and has a wide bandwidth. The Yagi-Uda antenna is a more complex, directional antenna that has a higher gain and a narrower bandwidth. Given the utilisation of digital broadcast signals with relatively high power, a simple dipole antenna may be sufficient for the testbed, however, the Yagi-Uda antenna may be required for more complex applications. High gain directional antennas can be chained together to receive signals from all directions, and in a passive radar context, determine the direction of the target [5].

2.5   Digital Signal Processing

Broadly, the goal of the signal processing for general passive bistatic radar is to extract a range doppler map from a received signal. Obtaining a range doppler map involves a few steps, with specifics depending on the IOO chosen along with number of sampling channels. Furthermore, there is the option of autocorrelating these signals via correlation integrals which is the most time and compute intense, or through Batches algorithm in the frequency domain . Prior [batches citation needed] to the advent of of digital broadcasts, analague broadcast processing involved comprehensive filtering and synchronisation of at least two input channels[16]. However, more recently, given the nature of DAB / DVB-T and its COFDM modulation, filtering and synchronisation can be replaced with reconstruction of the surveillance signal [3], replacing the need for dual channel configuration.

Figure 2.6 from Poullin [20] shows the main steps of the required signal processing, which includes signal acquisition, reconstruction, and correlation.

Once signal has been demodulated, according to Moser et. al, a FFT the size of 2048 for the range domain and 512 for the doppler domain can be computed [17], see Figure 2.7. This can be combined with a decluttering chain, which can implement something along the lines of a weiner filter, or a matched filter, to remove unwanted signals from the range doppler map [12]. Logically, the step above relfects the most computationally intensive process of the project ... hence, considerations with regard to signal processing algorithms will need to be taken in order to keep the overall detection system low cost.

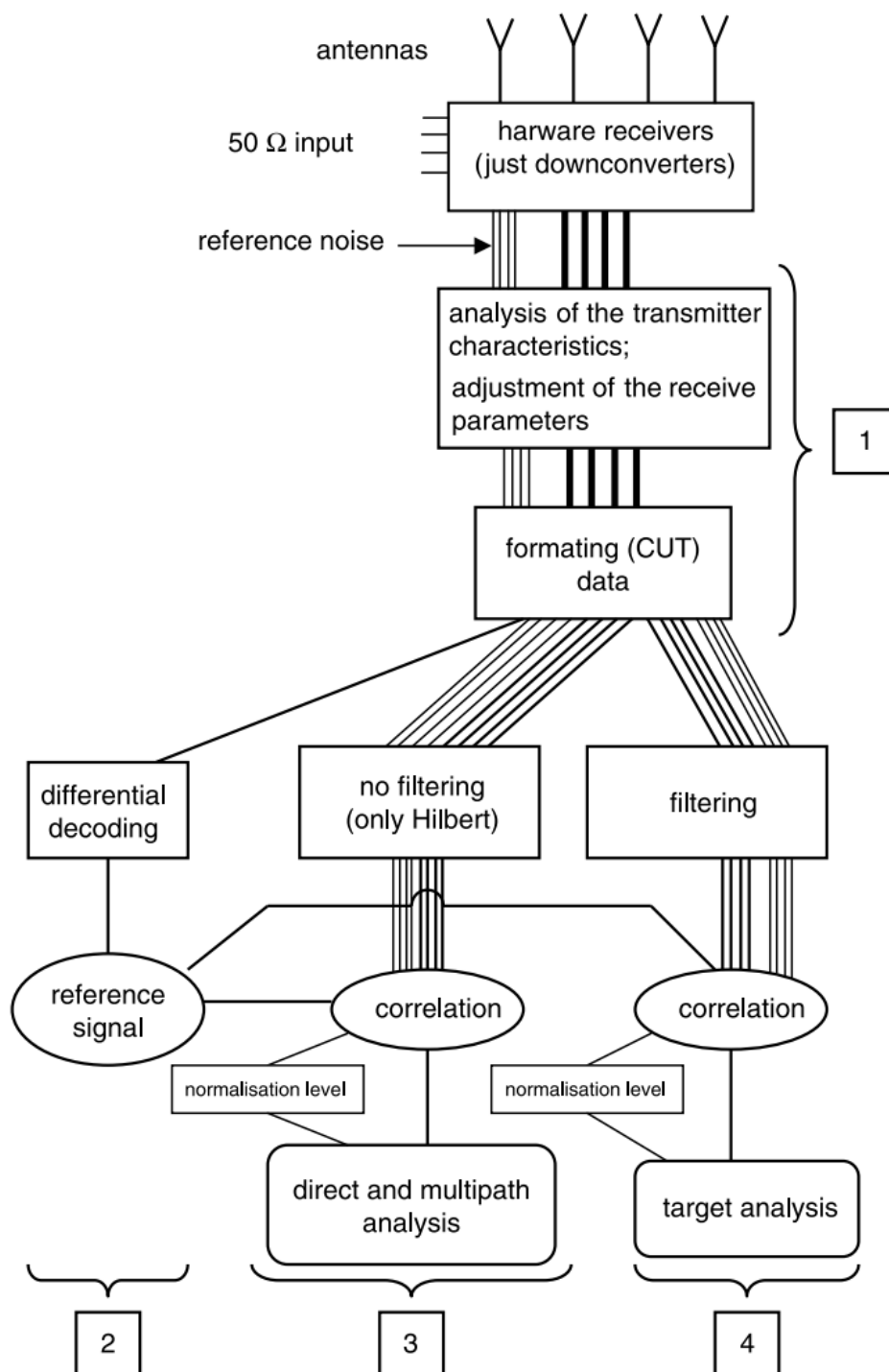more general detail about the processing chain?

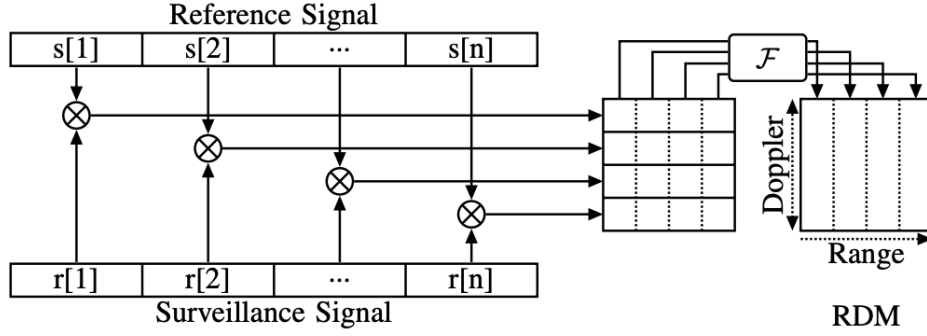Figure 2.6: Main steps of signal processing [20]

Figure 2.7: Correlation and FFT for Range Doppler Mapping [17]

2.6   IoT Architecture

The IoT architecture in the scope of this project refers to the computational platforms utilised to undertake the digital signal processing which then maps to tracking and detection of the target. At a high level, ITEE defines the Internet of Things (IoT) as *"as a world of interconnected things that are capable of sensing, actuating, and communicating among themselves and with the environment ... provides the ability to share information and autonomously respond to real/physical world events by triggering processes and creating services with or without direct human intervention"* [2]. In terms of PBR, existing studies have demonstrated the ability of off the shelf laptops [25], and there is a few studies that use IoT platforms for FM signal processing [17]. The vital consideration when exploring hardware are the DSP and sampling requirements for a given illuminator signal and antenna configuration. More broadly, IoT hardware has been used in a range of general tracking and detection applications. A prime example of this is the Flightradar24 service which utilises a network of ADS-B receivers to track aircraft in real time, where they provide a hardware kit of a Raspberry Pi and a DVB-T dongle (RTL-SDR) [9], channelling the data to a central server for processing and mapping.

According to Schupbach et. al [24], the broad scope capability requirements of the computational platform and associated processing can be grouped into signal acquisition, signal reconstruction and then the correlation function calculation. With a single board computer, this can be largely achieved through a combination of software libraries along with python script, however the hardware facilitating this processing is a key consideration. Largely, the IoT hardware is limited to single board computers, as microcontroller units (MCU) are not capable of the sampling and detection processing requirements, along with the fact that the project requires a full operating system for relevant SDR libraries. Exploring other potential architecture such as FPGA's, again are not as well suited, given their high cost and complexity, although their is precedent for the signal processing and recording [15]. A range of single board computers are available, and can be compared primarily based on their processing power, memory / memory access, and cost [26], as viewed in the table below.

There is precedent of previous use for the Raspberry Pi platform as demonstrated by Moser et. al [17] An alternate, higher powered choice in which Sednall demonstrated is the higher powered Nvidia Jetson, which includes faster processing times due to its quad core architecture [25]. The price for these options is $60 compared to $250 respectively. Ultimately, the choice of embedded IoT hardware for the project can be reduced to the trade off between low cost

SBC	CPU	RAM	Storage Access	OS Support	Size (mm)	Price (USD)
Raspberry Pi Zero 2 W	Quad-core Cortex-A53, 1 GHz	1GB	microSD	Raspberry Pi OS, Linux	65 x 30	15
Raspberry Pi 4	Quad-core Cortex-A72, 1.5 GHz	2/4/8GB	microSD, USB	Raspberry Pi OS, Linux	85.6 x 56.5	35-75
Raspberry Pi 5	Quad-core Cortex-A76, 2.4 GHz	8GB	microSD, PCIe (through HAT), USB	Raspberry Pi OS, Linux	85.6 x 56.5	from 60
Nvidia Jetson Nano	Quad-core Cortex-A57, 1.43 GHz	4GB	microSD, PCIe (through adapter)	Ubuntu, JetPack	100 x 80	100
Orange Pi 5	Octa-core Cortex-A76/A55, 2.0 GHz	8GB	eMMC, microSD, PCIe	Android, Linux	90 x 60	80

Table 2.2: Comparison of Single Board Computers [26]

and processing power, and will be a key consideration in the project plan. Furthermore, there is possibility to design custom hardware or utilise the GPIO functionality of the single board computer, as reflected by the high level definition of IoT architecture by ITEE [2].

2.7   Networking with Embedded Hardware

Given that the overall goal of this thesis project is to create a low cost, embedded passive radar detection system, valuable to consider how this would be visualised, be it wired via ethernet / UART to PC or wireless protocol.

add more about the theory of TCP/IP and networking over uq cloud, etc.

Chapter 3

Literature Review

This chapter will explore and summarise previous work on the topic of passive bistatic radar detection and associated hardware, ranging from academic literature to currently available commercial technology. The literature review will be divided into the following sections: low cost IoT hardware receiver, digital signal based illuminator of opportunity and existing commercial technology.

3.1   Low Cost IoT Hardware PBR Reciver Design

The Swiss army have conducnted a very informative pilot study utilising both FM radio and DAB+ signals as illuminators of opportunity for an IoT based receiver design. Moser et. al explore the performance of a Raspberry PI 3 GPU and CPU against a quad-core intel i7 equipped PC [17] . This paper also provided a good starting point for information regarding the difference in signal processing between digital (DAB+) and analogue (FM) illuminators of opportunity, including key characteristics as seen in Figure 3.1 .

Include their results too

	FM	DAB
Frequency	88 - 108 MHz	174 - 230 MHz
Modulation	analogue (FM)	digital (OFDM/DQPSK)
Bandwidth	0.05 MHz	1.536 MHz
Availability	Global	Local
Network	multi-frequency	single-frequency
Content dependency	yes	no

Figure 3.1: Comparison Table - Analog vs Digital Signals [17]

Moser et. al also provide a summary of the range doppler map generation process which itself is derived from Batches algorithm [16], including valuable performance measurements which indicate the efficacy of GPU processing over CPU processing. The specific hardware utilised in Moser's paper was a Raspberry Pi v3; 1.2GHz Cortex A53 CPU along with a 400MHz VideoCore IV GPU. As of writing, the estimated cost to recreate this exact hardware (including SDR-RTL hardware) would be approximately $100 AUD, representing a very low cost setup. Noting that hardware has also made significant advancements since the time of the paper (2019), with the Raspberry Pi v5 now available. The paper provides good hardware reference values for real-time processing limits of DAB frame computations, a key consideration area when optimizing for low cost hardware. Overall, this conference paper provides a good starting point for understanding the hardware requirements and limitations of a low cost IoT based passive bistatic radar receiver. Overall, this conference paper proides a valuable

benchmark and proof of concept for the capabilities of low cost IoT hardware (circa 2019) in PBR applications, highlighting that the Raspberry Pi 3 is capable of real-time processing of DAB+ signals. Notably this paper is difference from the thesis proposed given that it focuses on implementing real time processing and optimisation of detection DSP algorithms on low cost hardware, rather than the design and construction of a user friendly, scaleable testbed.

3.2   Illuminators of Opportunity

Throughout the literature review, a range of papers exploring illuminator signals were explored, the DTSO report Written by Palmer, Palumbo, Van Cao, and Howard provides a good theoretical basis. Whilst the scope of this proposal is confined to terrestrial illuminators (specifically digital audio), Palmer et. al highlight the wide range of use cases made available by other illuminators, including satellite signals and mobile phone signals. The report also provides a good overview of range doppler mapping, and target classification properties (despite the scope of this proposal not including target classification).
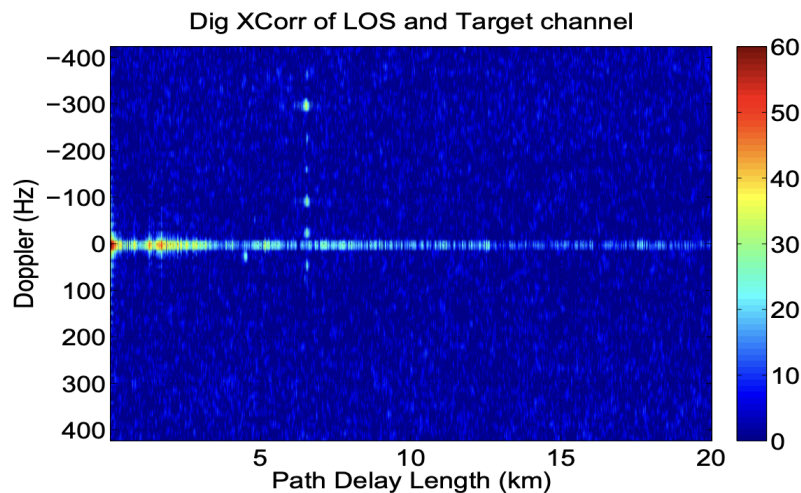
> more comprehensive overview

Figure 3.2: RDM of target moving away from receiver [14]

As seen above in Figure 3.2, in the .gif version of the image, the dot can be seen moving upwards (indicating motion away). This example also reflects effective de-cluttering of the RDM, a key step in passive tracking. An important consideration raised in this report is the edge case whereby the target moves along the bistatic ellipse as viewable in Figure 2.1, resulting in the doppler shift to be minimal and making tracking difficult.

3.3   Existing Commercial Technology

Commercial industry has been developing passive radar for a number of years now, with the majority of such development occuring in the military space. Specifically,these innovations are in the realm of air sureveillance and can be either ground based or air based [12]. Structurally, passive radar provides numerous advantages for defence applications including covert tracking due to the lack of a transmitter.

Lockheed Martin - SilentSentry: One of the earliest commercial products utilising passive radar, the SilentSentry utilises analog illuminator signals with a dual horizontal linear phased array antenna to passively detect and track airborne targets [14]. It claims a detection range of up to 200km with an azimuth coverage of 60-360 degrees. Given the analog nature of the signals (FM and other terrestrial signals), it has a receiver for the direct line of sight signal and the echoed target signal before applying a signal processing algorithm.

Chapter 4

Methodology and Design

Implementation: how was your experiment/project accomplished? Include enough details of your method and tooling that someone can easily replicate your results.

This chapter contains the design decision and steps taken to complete the testbed creation and testing. The project can broken into the three main areas of hardware, software and digital signal processing.

4.1 Hardware

4.1.1 Software Defined Radio

The fundamental hardware aspect for this project is the Software Defined Radio (SDR), specifically, the SDR receiver module. As mentioned in section 2,4, software defined radio technology has been recently experienced decreasing costs and proliferation (CITE!!!). Broadly, the testbed was designed to accomodate a potential range of USB-A capable SDR modules, with the capability initially tested on a low cost RTL-SDR, before progressing to later prototyping on higher end MODEL X.

ADD SECTION LABELS

(i) RTL-SDR Prototyping The low cost RTL-SDR was chosen as the initial SDR module for testbed prototyping due to its low cost and wide availability. The specifics of the RTL-SDR are stated in section 2.4 , it was connected to the RPi5 and higher level M1 Mac along with a simple SMI antenna as seen in the figure below 4.1.

REF

Figure 4.1: RTL-SDR with Simple SMA Antenna

The RTL-SDR is based on the Realtek RTL2832U chipset, and has a frequency range of 24MHz to 1.7GHz, and a bandwidth of 3.2MHz. The RTL-SDR is also relatively cheap, with a price of around $40 AUD, coming with compatibility to a wide range of software, including MATLAB, and GNU radio [21]. More specifically, the RTL-SDR was originally designed as a DVB-T receiver for digital TV, but due to its versatility, it has been repurposed by the hobbyist community for a wide range of RF signal reception applications. Fundamentally, the RTL-SDR is compised of two IC chips as seen in the block diagram figure below 4.2; the RTL2832U, which is the digital TV demodulator, and the R820T, which is the tuner. The R820T is the chip that allows the RTL-SDR to tune to a wide range of frequencies, converting those signal frequencies to an intermediate baseband frequency which is processed by the RTL2832U. Inside the RTL2832U, the signal is then digitized and demodulated and sent to the host computer via USB.
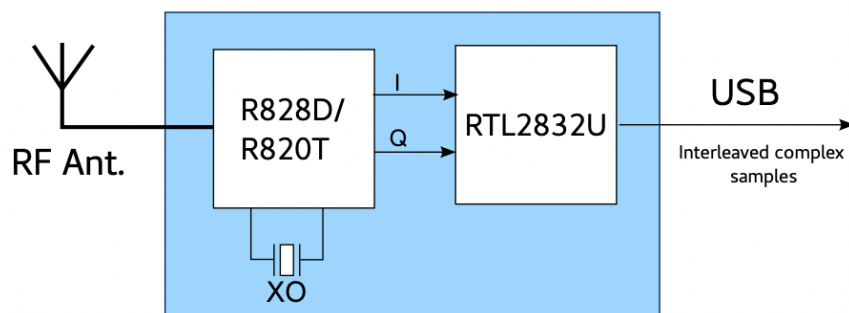
Figure 4.2: RTL-SDR Block Diagram [4]

The RTL-SDR was tested with a range of software as mentioned in 4.2.1 to ensure hardware was correctly functioning and to gain familiarity with the process. Specifically, given the nature of the digital signals utilised in this project, it was tested at the appropriate frequency range (approx 200Mhz). Furthemore, this was valuable to obtain ball park noise floor measurements, which eventuated to around -80dB when using the basic antenna.

(ii) MODEL X Implementation

WHAT ARE THE SPECS OF SDR X

4.1.2 Embedded Computing Platform

The embedded computing platform chosen for the testbed was the Raspberry Pi 5 (RPi5), specifically the version with 8GB of RAM [7].

Figure 4.3: Raspberry Pi 5 with NVME SSD [19]

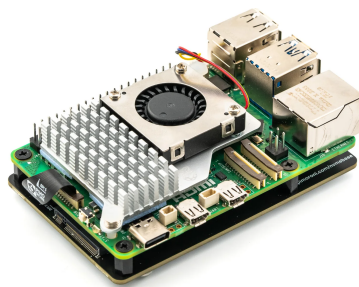As seen in Table 2.2, the RPi5 has a quad-core ARM Cortex-A72 CPU, 8GB of LPDDR4-3200 SDRAM, and a 1Gbit Ethernet port. The RPi5 was chosen for its relatively low cost, small form factor, and wide range of software support. Other SBC's from Table 2.2 were considered, but the Rpi5 represented the best balance of performance and cost for the project, for example, the higher cost of the Nvidia Jetson was not justified for the project requirements. The viability of the Raspberry Pi5 in the context of testbed design and functionality was analysed based on the following points:

Advantages

- **Storage:** The RPi5 supports external storage options via microSD, along with configurable HATs (hardware attached on top) for NVME SSDs, see section 4.1.3 [19].

- **Size:** Its small form factor (85.6 x 56.5 mm) - roughly the size of a credit card, makes it easy to integrate into a testbed setup. Easily obtainable cooling fan.

- **GPIO:** 40 Pin GPIO header, can be used for interfacing with a prospective testbed user. Driven by the RP1 (custom I/O controller chip) [7], the I/O is programmable with python.

- **Networking Capability:** Includes a 1Gbit Ethernet port and Wi-Fi 802.11ac, facilitating high-speed data transfer and network communication. Capable of 217.6 MB/s over Wi-Fi [18].

- **Processing Capability:** Equipped with a quad-core ARM Cortex-A72 CPU and 8GB of LPDDR4-3200 RAM, enabling 2.4 GHz clock [7].

- **Cost-Effectiveness:** Price of $150 AUD, making it an affordable option for the project, approximately 1.5 the cost of the RPi4 (however almost double the performance) [7]

- **Software Support:** Extensive community support and availability of a wide range of software tools and libraries, especially for Linux-based systems, e.g. RTL-SDR, GNU Radio, etc. see section 4.2.1.

Disadvantages

Add to this as project pre-ogresses

- **Limited Built-In Storage:** The built-in storage is minimal, so additional external storage is necessary for handling large volumes of data.

- **Performance Constraints:** While powerful, it may not handle very high-frequency or complex radar signal processing as efficiently as more specialized or high-performance computing platforms, custom algorithms potentially required [17].

- **Heat Management:** Under continuous heavy load, the RPi5 may require additional cooling solutions to prevent overheating.

- **Limited I/O Bandwidth:** The available I/O bandwidth might be a bottleneck for applications requiring very high-speed data acquisition and processing.

- **Power Supply:** Requires a stable power supply of 5.1V / 15W; not ideal for potentially portable or battery-powered applications [18].

4.1.3 NVME Based Storage

Following on from the selection and testing of the Raspberry Pi 5 as the testbed computing platform, it became evident that the default 32GB microSD card used to boot and run the operating system was insufficient for the storage requirements of the project. The chosen solution for the bottleneck was to utilise a NVME SSD drive, connected via PCIe to the Raspberry Pi 5, specifically the Pimoroni Base [19].

In order to compare and quantify the differences in the storage performance between the microSD card and the NVME SSD, a series of tests were conducted, utilising the following linux commands via the terminal of the RPi5.

```
lsblk
sudo hdparm -t --direct /dev/nvme0n1
sudo hdparm -t --direct /dev/mmcblk0
```

Resulting in the following output seen below in Table 4.1.

Table 4.1: Disk Read Performance: NVMe vs MicroSD Card

Device	Read Performance
NVMe SSD (/dev/nvme0n1)	751.22 MB/sec
MicroSD Card (/dev/mmcblk0)	84.83 MB/sec

The results in Table 4.1 clearly show the obtained significant performance increase when using the NVME SSD compared to the microSD card. Given the large amount of data that generated and processed during the SDR sampling. Further NVME SSD configuration details include:

- **File System:** The NVME SSD was formatted with the ext4 file system, which is the default file system for most Linux distributions.

- **Mounting:** The NVME SSD was mounted to the RPi5 at the following location: /mnt/nvme0n1

- **Connector**: PCIe x4 interface Gen 2.0, which is a high-speed interface standard that is commonly used for connecting storage devices to a computer.

- **Supported NVMe Drives**: Supports M.2 NVMe drives (2280 size)

- **SSD Model:** Patriot P300 NVMe M.2 SSD, 128GB capacity, used for both storage and booting the RPi5.

4.1.4 Antenna Configuration

Intially, a simple SMA whip antenna was used for the RTL-SDR, as seen in Figure 4.1. These low cost antennas are typically used for general purpose reception, and are not optimised for any specific frequency range. The whip antenna was used for initial testing and prototyping, and was capable of receiving a range of broadcast signals with a NOISE FLOOR X. Eventually a more specialised antenna was used, the Yagi-Uda antenna, which is a directional antenna that is commonly used for point-to-point communication. The Yagi-Uda antenna was used for the final testing and validation of the testbed. The Yagi-Uda was utilised with a CLF200 50 Ohm coaxial cable, which was connected to the RTL-SDR.

The physical setup of these antennas for testing comprised of an "Over the Shoulder" geometry whereby the antenna was placed behind a building in the line of sight of the TX signal (in this case Mt Cootha). For a single channel / antenna PBR setup, this geometry works to attenuate the direct path signal, and allow for the reflection to be better received by the antenna.

> diagram of geometry of map / antenna

Antenna Signal Strength Testing

Before calculations or detection was performed, the signal strength of the received signal was measured. This was done by first using the RTL-SDR and the monopole SMA antenna and compared to the Yagi-Uda antenna. The received signal strength, representing the illuminator DAB signal, was measured approximately 6km away from the transmitter tower. The results of the signal strength measurements are shown in Table 4.2.

> image of maps reference

Table 4.2: Noise Floor and SNR Comparison with -14.2 dB Gain (RTL-SDR)

Antenna Type	Noise Floor (dB)	Signal Strength (dB)	SNR (dB)
SMA Monopole	-60	-40.9	19.1
Yagi-Uda	-60	-17	43

The above table reflects the high gain of the Yagi-Uda antenna, which is a directional antenna, compared to the monopole SMA antenna. Overall, this testing was valuable to benchmark a noise floor and appreciate the neccessity for a high gain antenna, especially in the context of the low power target signal.

4.1.5 Testbed Design

4.2 Software

4.2.1 SDR Software

4.2.2 Networking Requirements

4.3 Digital Signal Processing Testing & Simulation

Chapter 5

Results and Discussion

Results: latency comparison, design cost, sucessful detection

5.1   Detection Performance

5.2   Latency Comparison

5.3   Overall Design Cost

5.4   Comparison to Existing Work

Chapter 6

Conclusion

Conclusion: what conclusions can be drawn from the results of your research?

6.1 Summary & Conclusions

6.2 Limitations

6.3 Possible Future Work

Chapter 7

Bibliography

[1] Ieee standard definitions of terms for antennas. *IEEE Std 145-1993*, pages 1–32, 1993.

[2] *Introduction to the Internet of Things*, pages 1–50. 2018.

[3] Christian R. Berger, Bruno Demissie, JÖrg Heckenbach, Peter Willett, and Shengli Zhou. Signal processing for passive radar using ofdm waveforms. *IEEE Journal of Selected Topics in Signal Processing*, 4(1):226–238, 2010.

[4] Konstanty Bialkowksi. Coms4105 prac 1. University of Queensland, 2024. Image retrieved from the assignment sheet.

[5] Stephen Cass. Passive radar with the krakensdr > spot stuff with tv antennas and a software-defined radio. *IEEE Spectrum*, 59(11):16–18, 2022.

[6] C.J. Coleman, R.A. Watson, and H. Yardley. A practical bistatic passive radar system for use with dab and drm illuminators. In *2008 IEEE Radar Conference*, pages 1–6, 2008.

[7] Core Electronics. Raspberry pi 5 model b (8gb), 2024. Accessed: 2024-09-01.

[8] Michael Edrich, Alexander Schroeder, and Fabienne Meyer. Design and performance evaluation of a mature fm/dab/dvb-t multi-illuminator passive radar system. *IET Radar, Sonar & Navigation*, 8(2):114–122, 2014.

[9] Flightradar24. Build your own ads-b ground station. `https://www.flightradar24.com/build-your-own`, 2024. Accessed: 2024-09-01.

[10] Vijay K. Garg. Software-defined radio. In *Wireless Communications & Networking*. Elsevier, 2007. Accessed: 2024-08-20.

[11] H. Griffiths, Christopher J. Baker, and Ieee Xplore. *An introduction to passive radar*. Artech House radar series. Artech House IEEE Xplore, Boston Piscataqay, New Jersey, first edition edition, 2017.

[12] Hugh Griffiths. Chapter 16 - passive bistatic radar. In Nicholas D. Sidiropoulos, Fulvio Gini, Rama Chellappa, and Sergios Theodoridis, editors, *Academic Press Library in Signal Processing: Volume 2*, volume 2 of *Academic Press Library in Signal Processing*, pages 813–855. Elsevier, 2014.

[13] Abdulkadir Guner. Ambiguity function analysis and direct-path signal filtering of the digital audio broadcast (dab) waveform for passive coherent location (pcl). 2002.

[14] Tri-Tan Van Cao James Palmer, Simon Palumbo, , and Stephen Howard. A new illuminator of opportunity bistatic radar research project at dsto. Report, Defence Science and Technology Organisation, May 2009 2009.

[15] Filip Michalak, Wojciech Zabołotny, Łukasz Podkalicki, Mateusz Malanowski, Marcin Piasecki, and Krzysztof Kulpa. Universal rfsoc-based signal recorder for radar applications. In *2022 23rd International Radar Symposium (IRS)*, pages 136–140, 2022.

[16] C. Moscardini, D. Petri, A. Capria, M. Conti, M. Martorella, and F. Berizzi. Batches algorithm for passive radar: a theoretical analysis. *IEEE Transactions on Aerospace and Electronic Systems*, 51(2):1475–1487, 2015.

[17] Daniel Moser, Giorgio Tresoldi, Christof Schüpbach, and Vincent Lenders. Design and evaluation of a low-cost passive radar receiver based on iot hardware. In *2019 IEEE Radar Conference (RadarConf)*, pages 1–6, April 2019.

[18] Avram Piltch. Raspberry pi 5's wi-fi gets faster. 2024. Accessed: 2024-09-01.

[19] Pimoroni. Nvme base, 2024. Accessed: 2024-08-20.

[20] D. Poullin. Passive detection using digital broadcasters (dab, dvb) with cofdm modulation. *Radar, Sonar and Navigation, IEE Proceedings -*, 152:143 – 152, 07 2005.

[21] RTL-SDR.com. Buy rtl-sdr dongles (rtl2832u). `https://www.rtl-sdr.com/buy-rtl-sdr-dvb-t-dongles/`, 2024. Accessed: 2024-03-11.

[22] Mathew NO Sadiku and Cajetan M Akujuobi. Software-defined radio: a brief overview. *Ieee Potentials*, 23(4):14–15, 2004.

[23] Dilusha Samarasekara. Popular sdrs, 2023. Accessed: 2024-08-20.

[24] Christof Schüpbach and Samuel Welschen. Direct signal interference mitigation by slow-time frequency correction for ofdm-based passive radar. In *2018 19th International Radar Symposium (IRS)*, pages 1–10, 2018.

[25] Joshua Leigh Sendall. Implementation of a low-cost bistatic radar. Master's thesis, 2016.

[26] XDA Developers. Best single board computers, 2024. Accessed: 2024-09-01.

[27] Ying Yin, Shunsheng Zhang, Fuxia Wu, Zhulin Zong, and Wei Zhang. Passive radar detection with dvb-t signals. In *2016 CIE International Conference on Radar (RADAR)*, pages 1–5, 2016.

Appendices

Appendix A

Example Appendix Item

> Appendix: Appendices are useful for supplying necessary details or explanations which do not seem to fit into the main text, perhaps because they are too long and would distract the reader from the central argument. Appendices are also used for program listings.

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