THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

School of Electrical Engineering and Computer Science

PROJECT PROPOSAL

Low Cost Embedded Passive Radar Detection

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Mode of study: Full-time - Internal
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Contents

1 Introduction

This proposal introduces the theory, motivations and planned process for the creation of a low cost embedded bistatic passive radar detection system utilising DAB+ as the illuminator of opportunity.

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 [5].

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 [8]. 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 [5].

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 [12]. This project aims to reinforce and build on existing technology by creating a low-cost, modular, small-scale embedded passive radar detection system. Moreover, this project will also explore the possibility of scaling up this bistatic setup to a multistatic system, and the potential advantages and disadvantages of such.

More specifically, the project will focus on streamlining the signal processing and computational requirements of both the line of sight signal and the reflected target signal onto a singular embedded setup, without PC hardware. 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. Initially, the illuminator of opportunity selected is the DAB+ (digital audio broadcasting) signal, and the target signal will be aerial vehicles - most likely in the form of civillian passenger jets. Noting that a range of other terrestrial illuminator signals can be utilised, often depending on the required use case, such as the tracking target and environment [4].

1.2 Goals

The primary goals of the project include the following, provided in order of logical progression;

- Implement and investigate passive radar detection algorithms on high end computer architecture (PC) connected to SDR hardware and antenna for line of sight and target signal processing.
- Scaling down the passive radar detection system and associated algorithms to run on embedded IoT hardware, and investigate the computational and signal processing requirements, including the possible design of custom hardware such as peripheral functionality

and printed circuit boards. A central feature of this specific goal is its ideally low cost nature.

- Verify functionality of 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.
- Design and develop suitable housing for embdedded project implementation with ideal features such as modularity, portability and potential scaleability.

2 Background and Literature Review

2.1 Literature Review

The below subsections reflect the neccessary research considerations for the project, and will be used to inform the project plan and optimize the implementation.

2.1.1 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 passive radar systems on UHF TV signals and VHF FM radio tranmission systems in the 1980's [6]. 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 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.

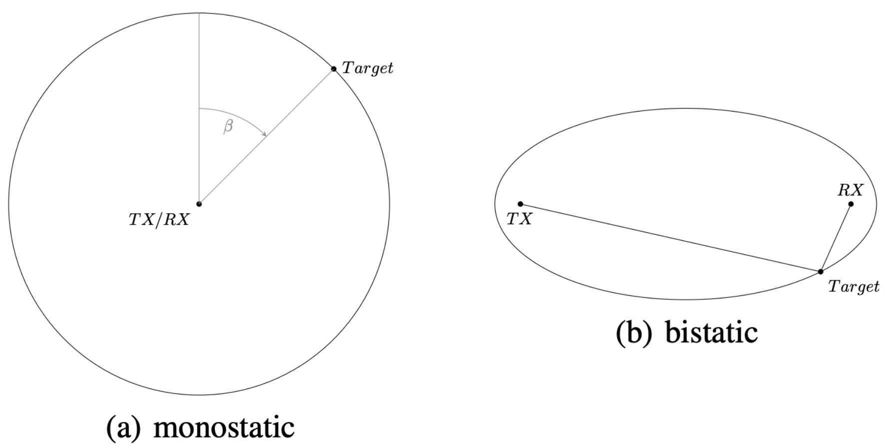

Figure 1: Monostatic (a) and bistatic (b) radar topologies [12]

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.

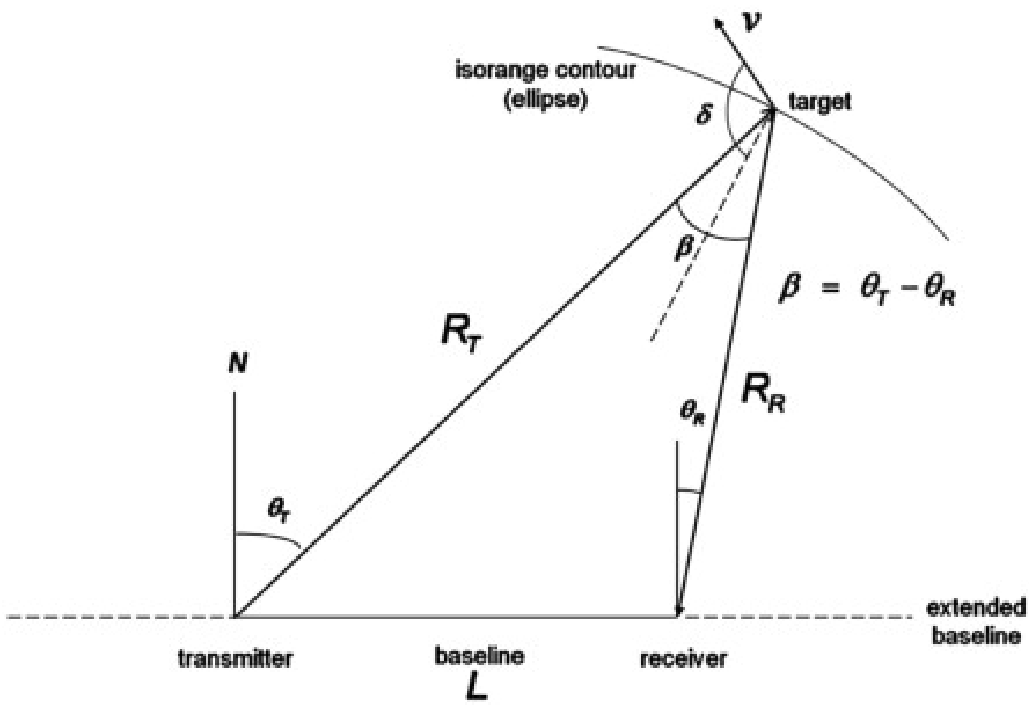

Figure 2: Bistatic radar geometry [6]

The bistatic range R_R is given by:

$$R_R = \frac{(R_T + R_R)^2 - L^2}{2(R_T + R_R + L\sin\theta_R)} \tag{1}$$

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

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

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 [6].

$$\frac{P_r}{P_n} = \frac{P_t G_t}{4\pi R_T^2} \cdot \sigma_B \cdot \frac{1}{4\pi R_R^2} \cdot \frac{G_r \lambda^2}{4\pi} \cdot \frac{1}{kT_0 BF} \tag{3}$$

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. In the case of directional antennas, 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 [6].

Ideally this project would process just the target signal, however, that is an unrealistic expectation due to the presence of clutter. Clutter refers to unwanted signal that eminates from objects in the natural environment such as buildings, trees and ground [18]. This process of target signal clutter suppression and its impact on range doppler mapping will be discussed later in the literature review.

2.1.2 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 [5]:

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 selected 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 was selected 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, makes it an ideal choice for the project.

****** DIRECT SIGNAL INTERFERENCE??? *******

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 [3]. 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 [5]. 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.

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 [7].

2.1.3 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 bounce 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 4 [5].

$$\chi(\tau, f) = \int s_1(t) s_2^*(t-\tau) e^{j2\pi f t} \, dt \tag{4}$$

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.
- $e^{j2\pi f t}$ 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 [6]. Hughes visualises the geometry considerations and potential flaws of passive bistatic below in Figure 3.

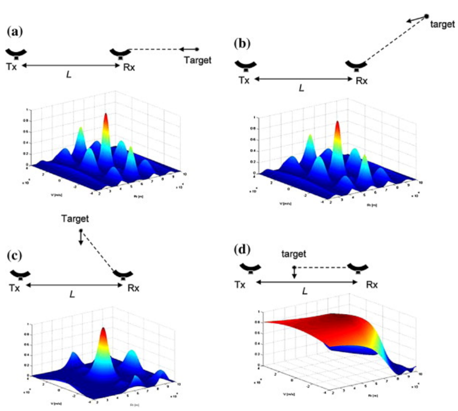

Figure 3: Geometry and ambiguity function [6]

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 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.

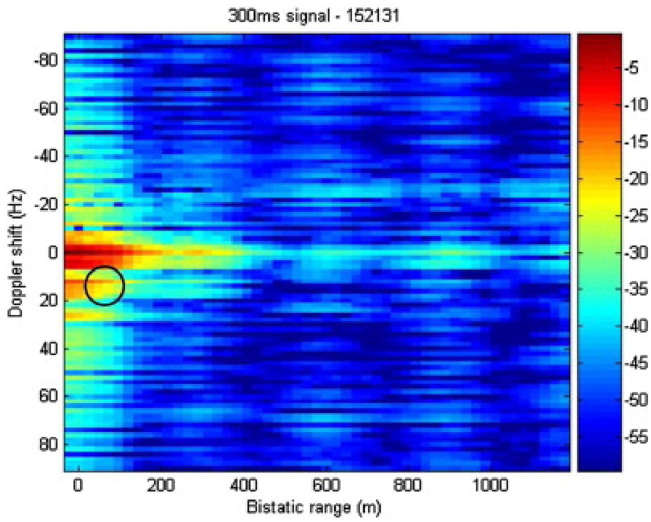

Figure 4: Example of range doppler map for WiFi PBR [6]

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 subequent range doppler mapping will be vital for mapping the DAB+ signal characteristics for given geometry and motion of the surveilled target.

2.1.4 Radio Hardware

Given the low cost aims of this project, hardware cost will majorly impact the overall cost. Luckily, the proliferation of Software Defined Radio (SDR) has enabled low cost hardware modules enabling easy access to radio frequency (RF) signals [15]. The most popular SDR module is the RTL-SDR, which is a USB dongle that can be used to receive and decode a wide range of RF signals. 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. The RTL-SDR is also compatible with a wide range of software, including MATLAB, and GNU radio [14]. Given the digital nature of the DAB+ signal, the direct reference signal and the target surveillance signal can in theory be sampled by a singular RTL2832U module as shown by Barrot et.al [1]. Given the wide bandwidth of DAB signals, it is optimal to connect the RTL module to a LPDA antenna [10], which at the low end retail for around $50 AUD. Regardless of sampling hardware architecture, based on previous studies and the nature of the DAB+ signal and modulation framework, a sampling rate of 2.048 MS/s is prudent [12]. (CLARIFY ANTENNA CONFIG)

2.1.5 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. Existing studies have demonstrated the ability of off the shelf laptops [17], and there is a few studies that use IoT platforms for FM signal processing [12]. The vital consideration when exploring hardware is the DSP requirements of the bistatic passive detection process (explored further in the next section).

The broad scope capability requirements of the computational platform is identified below in Figure 5, which also highlights the division of responsibility between system hardware (IoT computer and SDR hardware).

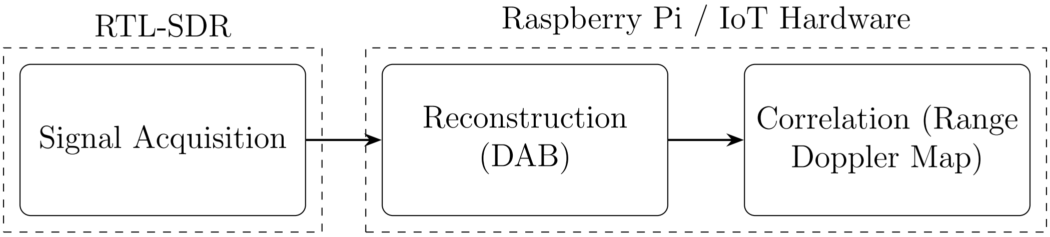

Figure 5: Block diagram showing the high level hardware process

A possible IoT device that could be used, and has evidence of previous use as demonstrated by Moser et. al [12] is the Raspberry Pi platform, which despite having increased processing times, demonstrated its functionality. 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 [17]. 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 and processing power, and will be a key consideration in the project plan. Furthermore, there is possibility to design custom hardware to optimise for processing speeds and project cost, for example, a PCB extension utilising a Raspberry Pi with DSP IC chips and/or custom user buttons.

2.1.6 Signal Processing and Algorithms

Broadly, the goal of the signal processing for this project is to extract a range doppler map from the received reference and surveillance signals. In order to achieve this, a range of steps are required to be undertaken. A range of literature exists for the signal processing of FM illuminator of opportunity signals, including Batches algorithm [11]. However, given the nature of DAB and its COFDM modulation (explored above), filtering and synchronisation can be replaced with reconstruction of the surveillance signal [2]. The use of a singular antenna is affirmed by Schupbach et. al [16] who utilised DAB passive radar to track micro-UAVs.

Figure 6 from Poullin [13] shows the main steps of the required signal processing, which includes signal acquisition, reconstruction, and correlation.

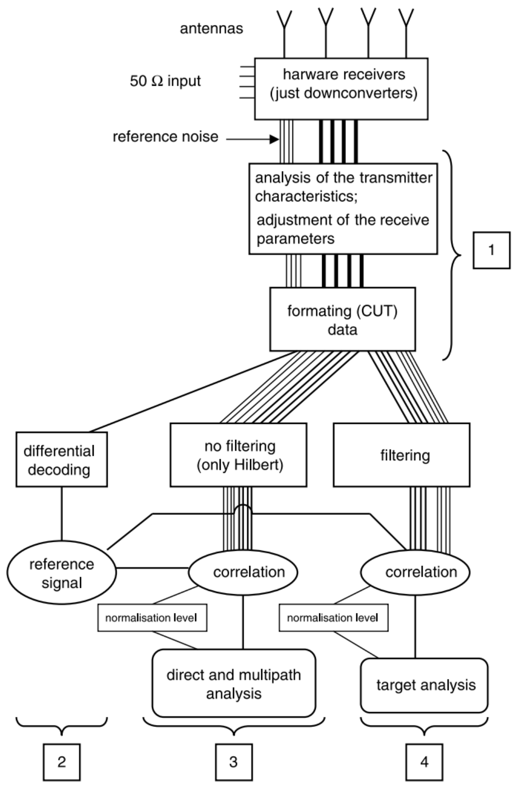

Figure 6: Main steps of signal processing [13]

The scope of this project involves
branches 1 through 3, with target analysis representing a logical extension for a more complicated version of the project.

****** NEED MORE RESEARCH AND UNDERSTANDING OF DECODING AND DEMODULATION OF DAB → CORRELATE / INTEGRATE FOR RDM ?*****

Once signal has been demodulated, according to Moser et. al, FFT the size of 2048 for the range domain and 512 for the doppler domain can be computed [12], see Figure 7. NEED MORE UNDERSTANDING HERE!!!

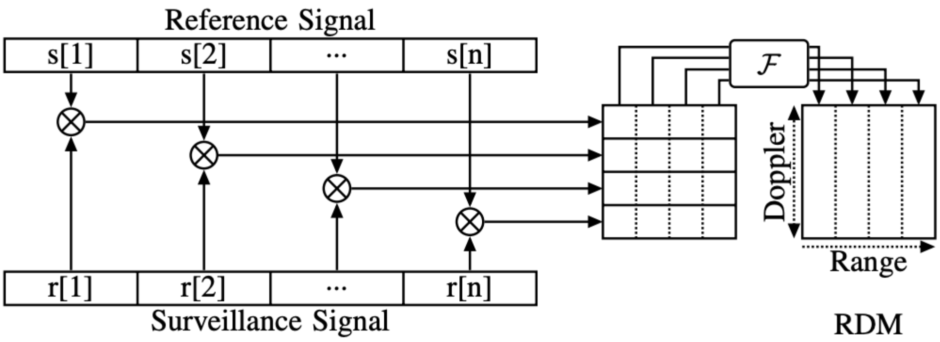

Figure 7: Correlation and FFT for Range Doppler Mapping [12]

Logically, the step above relfects the most computationally intensive process of the project .... EXPLAIN hardware considerations!!!

2.2 Pilot Studies & Existing PBR Technology

As briefly alluded to in the above literature review, there is a plethora of existing research and pilot projects which utilise a range of hardware and illuminator of opportunity signals, including existing commercial products.

2.2.1 Low-Cost Passive Radar Receiver Based on IoT Hardware - Swiss Army

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 GPU and CPU against a quad-core intel i7 equipped PC [12]. 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 8 .

	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 8: Comparison Table - Analog vs Digital Signals [12]

Moser also provides a summary of the range doppler map generation process which itself is derived from Batches algorithm [11], 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.

2.2.2 DTSO Illuminator of Opportunity Research Project

Written by Palmer, Palumbo, Van Cao, and Howard on behalf of Australia's Defence Science and Technology Organisation (DTSO), this report provided a good theoretical starting point for literature review, with specific focus on illuminator of opportunity properties [8]. 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).

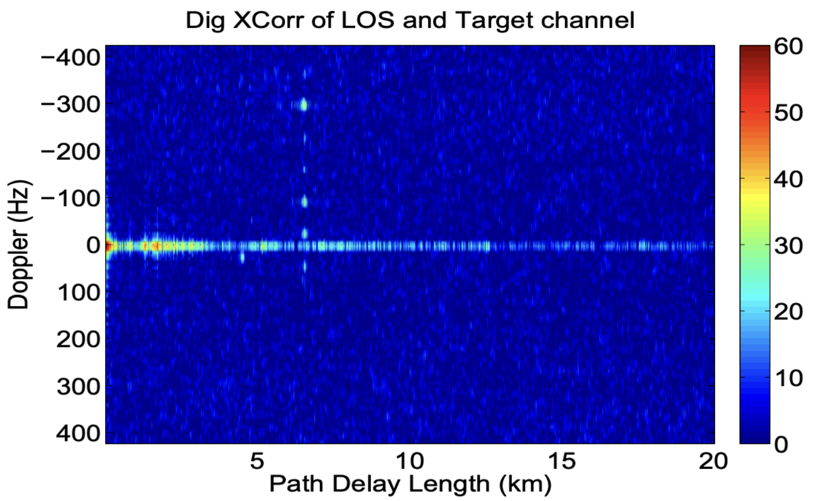

Figure 9: RDM of target moving away from receiver [8]

As seen above in Figure 9, 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 1, resulting in the doppler shift to be minimal and making tracking difficult.

2.2.3 FM Based Low Cost Passive Bistatic Radar Masters Thesis

A masters thesis by Sendall, was a very useful reference and pilot given its very similar scope, looking to optimise for cost without sacrificing too much computational performance [17]. A valuable takeway from this thesis was the intialisation and definition of project constraints, given the broadness of passive radar use cases and its optimisation areas it will be important to refine the scope scope and constraints.

Sendall provides a hardware overview with valuable comparisons of the processor family, including performance/cost considerations of using DSP or FPGA architecture. Most valuably, he provides comprehensive detail about the signal processing chain, despite its analogue nature, it still provides a good starting point for shared obstacles such as de-cluttering and range doppler mapping.

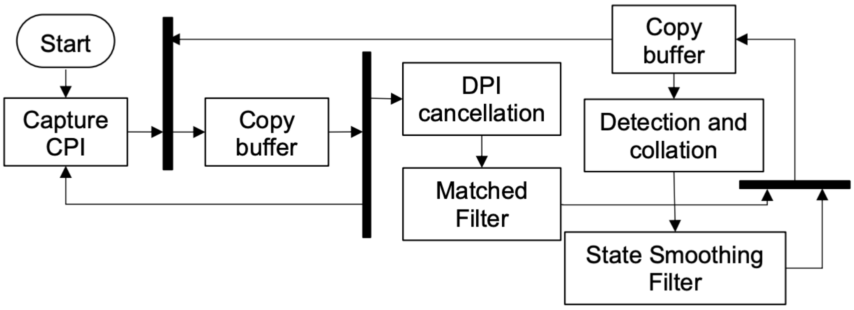

Figure 10: FM PBR Processing Chain [17]

Sendall's processing chain is based on his own literature review, and includes a comparison of different clutter minimisation filters, including adaptive filters, Wiener-Hoph filters and FDC filters. Valuably, Sendall outlines a range of evaluation metrics for the filter and hardware configuration including time complexity, floating point operations, maximum throughput, and power consumption (correlated to GPU occupancy).

2.2.4 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 [6]. 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 [8]. 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.

Silentium Defence - Maverick-M: Silentium is an Adelaide based company which produces man-portable low power, claiming to track small objects such as UAVs and drones. The Maverick-M utilises a bistatic configuration with a single receiver, and is able to track targets up to 100km away. The Maverick-M is also able to track multiple targets simultaneously, and is able to be used in a range of environments, including urban and mountainous areas [9]. It utilises a range of ambient waves in the UHF and FM spectrums allowing maximul detection ability.

2.3 Critique, Use and Evolution of Pilot Studies

Given the nature of an undergraduate thesis project, it is unreasonable to assume revolutionary progress will be made. However, it is possible to utilise the cumulative knowledge and progress from existing technology and pilot projects to optimise a certain subject area. In the case of this embedded low-cost passive radar detection project, a lot of the same processes and technology will be utilised. This project will utilise the GPU process explored in section 2.2.1 whereby processing times are drastically faster than CPU processing. The project will also utilise the RTL-SDR hardware, and the DAB+ signal as the illuminator of opportunity. Furtermore, the FFT correlation calculations can be mimicked within the DSP. Importantly, the cost of hardware has decreased whilst computational power has simultaneously increased, hopefully allowing for a more efficient and cost effective iteration of Moser et. al implementation. Section 2.2.3 provided valuable performance metrics enabling a tested quantification method for this project, allowing comparison of hardware cost, configuration and performance.

3 Project Plan

Intially, this this project can be broken into manageable milestones throughout both semesters allowing a progressively phased and consistent workload. In order to achieve completion by the end of the year, consistent communication with supervisor and adherence to self imposed deadlines will be vital. The project plan will be broken into the following sections:

3.1 Milestone 1 - Implementation of Signal Reception and Processing Algorithms on PC Hardware

3.2 Milestone 2 - Selection/Design of Embedded Hardware Optimised for Cost

USER FUNCTIONALITY? ON OFF BUTTON?

3.3 Milestone 3 - Application of Signal Processing Algorithms and Tracking on Embedded Hardware

VISUALISATION GUI??

3.4 Milestone 4 - Modular Housing and Design for Final Product

Scaleable???

4 Risk Assessment

5 Ethics Assessment

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