
RF/IF hardware design for MKIDs application

Capstone Report
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Abstract:

This report covers work done at Data Processing and Readout System Development Laboratory at Nazarbayev University implementing data processing algorithm for readout electronics. Microwave Kinetic Inductance Detectors (MKIDs) are photon detectors based on superconducting resonators. MKIDs are capable of detecting single photons with very small energy and micro second time resolutions. With proper readout electronic system it is possible to read arrays of thousands MKIDs using single signal line using frequency domain multiplexing (FDM).

This report details the work done developing a laboratory setup for measuring MKIDs and developing code for frequency measurements. All the work was done using readout system based on a Re-configurable Open Architecture Computing Hardware (ROACH) FPGA board and The Collaboration for Astronomy Signal Processing and Electronics Research (CASPER) software.

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Contents

Preface	vi
1 Introduction	1
1.1 Microwave Kinetic Inductance Detectors	2
1.2 ROACH-2 Board	2
1.3 RF/IF Board	3
2 Background	4
2.1 List of abbreviations	4
3 Methodology	5
3.1 Experimental Setup Configuration	5
3.2 Interfacing with ROACH2	5
3.3 Simulation	6
3.4 Attenuation	8
4 Results and Discussions	12
4.1 Results	12
4.2 Discussions	13
5 Conclusion	15
5.1 Future Work	15
Bibliography	16

Preface

First I'd like to thank my supervisor, Prof. Mehdi Shafiee, for giving me the opportunity to work on this exciting project, and for his valuable mentorship and support throughout my capstone project.

For the work in chapter 3.4 I'd like to thank my labmate Bekzat Baigabyl for helping me in working with RF/IF board. We spent a lot of time together trying to combine readout system made by me with updated RF/IF board. His strong understanding of board working principle helped us to get results of our work.

Finally, I'd like to thank my friends and family for their support throughout my studies.

Nazarbayev University, April 26, 2024

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Chapter 1

Introduction

This report presents a comprehensive exploration of the implementation of Microwave Kinetic Inductance Detectors (MKIDs) data processing algorithms in Roachboard2. This data processing algorithm is going to be used for RF/IF board. MKIDs, as a novel technology, offer an unprecedented opportunity to revolutionize the field of astronomical instrumentation with their capability to simultaneously measure energy and arrival time of individual photons with high precision [1] [2] [3]. However, effective data processing for such complex instruments becomes a significant challenge that needs to be addressed. [4][5][6][7][8][9]

The main focus of this study is to develop and implement an efficient data processing algorithm for MKIDs on Roachboard2, a versatile digital signal processing platform [10]. This hardware platform offers numerous advantages including high-speed analog-to-digital and digital-to-analog converters, FPGA for high-speed digital processing, and more. [11][12][13]

Such readout systems were developed by other researchers, using different FPGA boards. Our goal to combine advantages of several readout system algorithms and unite them in one work. [14] [15]

By bridging the gap between cutting-edge MKIDs technology and the powerful processing capabilities of Roachboard2 [16], we aim to enhance the data quality, optimize system performance, and contribute to more accurate and efficient astronomical researches. The report will cover in-depth analysis of the algorithm development process, implementation challenges faced, solutions applied, and the overall performance outcomes observed.

This undertaking is not only important for its scientific implications but also as it opens up new avenues for utilizing modern technologies in astronomical research. The findings of this work are expected to have a significant impact on how future instruments are designed and integrated into astronomy's ever-evolving toolkit.

1.1 Microwave Kinetic Inductance Detectors

Microwave Kinetic Inductance Detectors (MKIDs) are a cryogenically cooled superconducting resonators. They consist of an inductor and capacitor pair. Inductance in the circuit mainly comes from the kinetic energy of the Cooper pairs in the supercurrent. Free electrons known as “quasiparticles” are created from broken Cooper pairs at the moment when a photon is absorbed by the inductor. These “quasiparticles” change the inductance and affects to resonant frequency and quality factor of the circuit. Bigger energy of incident photon affects to number of quasiparticles created. This gives the MKID intrinsic energy resolution. The resonator is operated by a microwave probe signal that is set to its resonant frequency and is watched for changes in its relative phase in order to read out the detector.

Since each pixel’s resonant frequency can be readily adjusted after construction, MKIDs have inherent frequency domain multiplexability, which sets them apart from other superconducting detector technologies. This makes it possible to put many resonators in parallel on a single microwave channel, each tuned to a different frequency. This transfers the complexity to the room temperature readout system and significantly simplifies the cryogenic wiring and electronics. [17] [18] [19] [20]

The intrinsic energy resolution, microsecond-scale time resolution, and single photon sensitivity of MKIDs make them perfect for studying highly time-variable phenomena like compact binaries and pulsars. MKIDs may additionally be utilized as integral field units, or IFUs, for exoplanet direct imaging, which benefits from high temporal resolution and high sensitivity.

1.2 ROACH-2 Board

The UC Berkeley CASPER cooperation developed the ROACH-2 [21] [22]. The Xilinx Virtex-6 FPGA (XC6VSX475T-1FFG1759C) served as the focal point of its design. It features an Ethernet connection interface, DDR3 and QDR memory modules, and a PowerPC CPU. The Virtex-6 FPGA is used to handle channelization, filtering, and pulse detection—the three main digital signal processing functions for the readout system. Because CASPER offers a comprehensive set of tools and an FPGA programming interface, we decided to employ the ROACH-2 platform. The polyphase filter bank and other complicated signal processing blocks, along with connections to a large portion of the ROACH-2 hardware, are all part of the CASPER toolflow. Additionally, CASPER has made available a number of Python libraries for ethernet programming and communication with the FPGA.

1.3 RF/IF Board

For analog up/down conversion between the IF band ($-1 - 1$ GHz) and the RF band ($4 - 6$ GHz or $6 - 8$ GHz), the RF/IF board uses IQ modulation. In the process of upconversion, a local oscillator (LO) tone at the center of the RF band (for example, a 5 GHz LO would be used for a 4–6 GHz resonator band) is mixed with the complex IF band frequency comb. This creates a real-valued output that is shifted into the resonator frequency band. The opposite operation is called downconversion, in which the cryostat's real-valued RF output is combined with the same LO to produce an IF band signal with complex values that the ADCs can digitize.

On the PCB Figure 1.1, a programmable phase locked loop (PLL) integrated circuit generates the LO. The ADC/DAC board provides an external 10 MHz signal that the PLL is referenced to. The frequency range is shifted into the resonator band (600 MHz – 9.6 GHz) by a frequency doubler applied to the output. MMIQ6789 I/Q mixers are analog devices that are utilized for both down- and up-conversion.

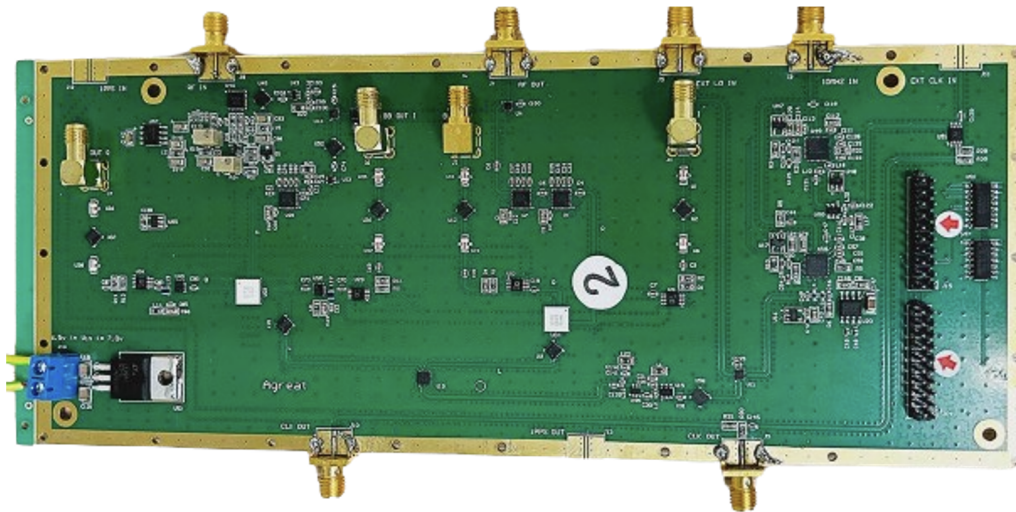


Figure 1.1: RF/IF board

Chapter 2

Background

2.1 List of abbreviations

ADC	Analogue to Digital converter
CASPER	Collaboration for Astronomy and Signal Processing and Electronics Research [10]
DAC	Digital to Analogue Converter
DSP	Digital Signal Processing
FDM	Frequency Domain Multiplexing
FPGA	Field Programmable Gate Array
MKID	Microwave Kinetic Inductance Detector
ROACH	Reconfigurable Open Access Computer Hardware

Chapter 3

Methodology

3.1 Experimental Setup Configuration

To start working with the ROACH2 we need a proper laboratory setup. According to the CASPER Toolflow [23] documentation for ROACH2 the following software and libraries are needed:

Hardware	Operating System	MATLAB Version	Xilinx Version	Python Version
Roach 2	Ubuntu 14.04	2013b	ISE 14.7	Python 2.7

All needed software and libraries were installed on the PC with Ubuntu 14.04 Figure 3.1. For MATLAB installation, given instructions were followed which allows to use ISE Xilinx programming blocks inside MATLAB Simulink.

For CasperFpga and Casper Toolflow separate virtual environments were created and required libraries were installed. Figure 3.2 shows their existence.

3.2 Interfacing with ROACH2

ROACH2 supports two types of connection. First is a USB Serial connection and second it through the network. In order to connect through the network, IP address or hostname of the board should be known, also both PC and Roach2 should be on a same network. In order to get the MAC-address of the board, PC and Roach2 were connected to the router in the laboratory. By using router's admin panel, MAC address of the Roach2 was known. MAC-address was used



Figure 3.1: PC laboratory setup

to get the IP-address of the board on the local network, by using arc-scan library. Figure 3.3 illustrates the process.

IP-address is required to create communication. Casperfpga python library by CASPER was used to test the connection between PC and the Roach2.

3.3 Simulation

Following CASPER Toolflow tutorials the Simulink test was made. This test helps to get familiar with Matlab and Simulink environment. For creating a program for FPGA we need to use Xilinx programming blocks. This tutorial ensures that everything is imported correctly and all libraries I installed before works as it should.

In this tutorial, I created a simple Simulink design using both standard Xilinx system generator blockset, as well as library blocks specific to CASPER boards. At the end of this tutorial, I learned how to generate an fpg file, program it to a CASPER FPGA board, and interact with my running hardware design using casperfpga via a Python Interface. Figure 3.5 shows simulink interface and suc-

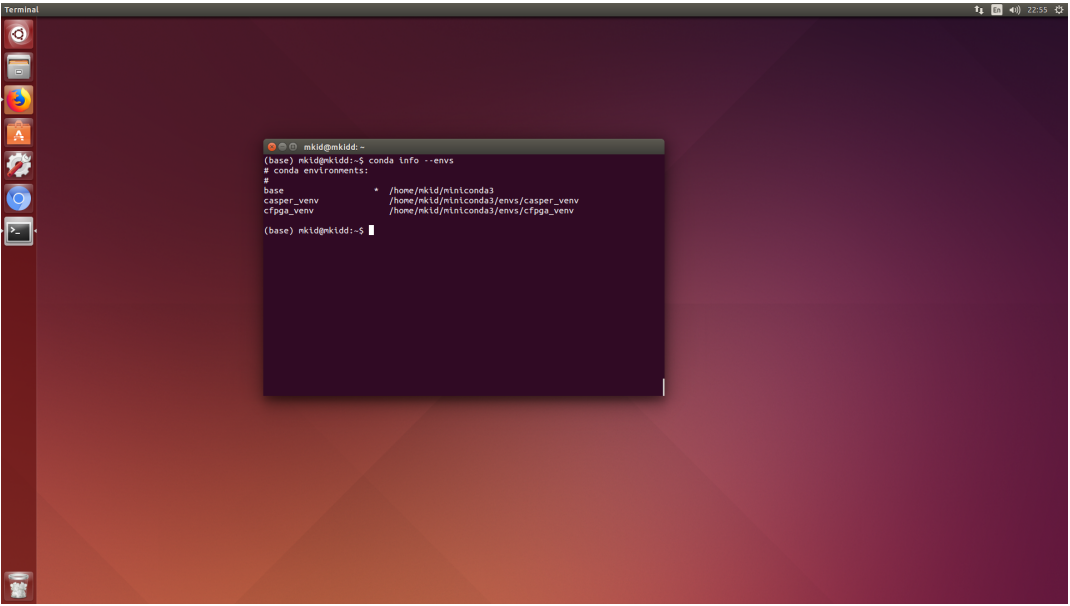


Figure 3.2: Conda virtual environments

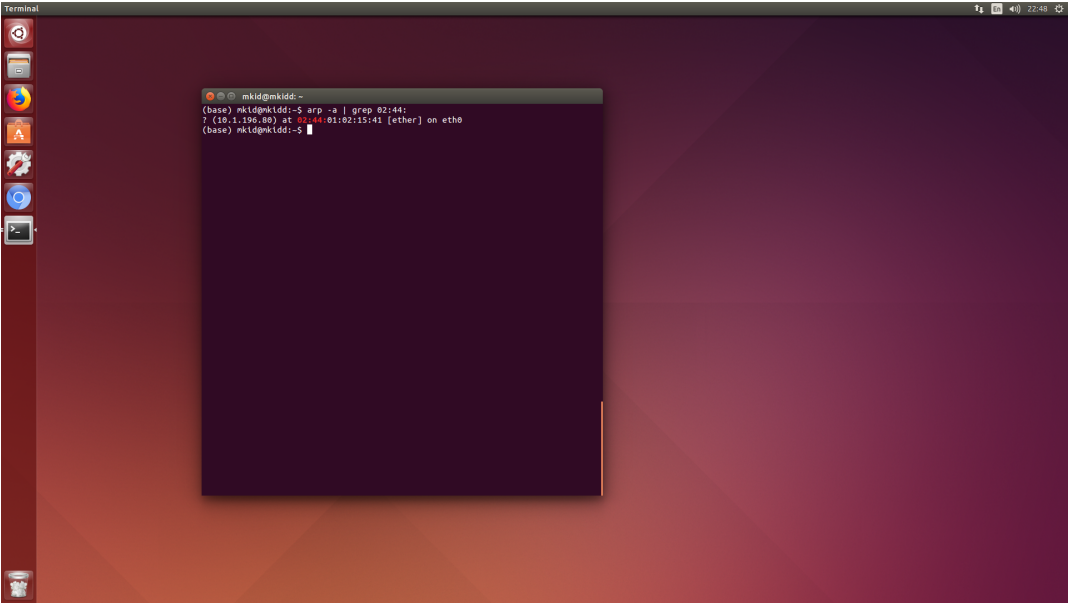


Figure 3.3: ROACH2 IP-address in the local network

cessfully running simulation.

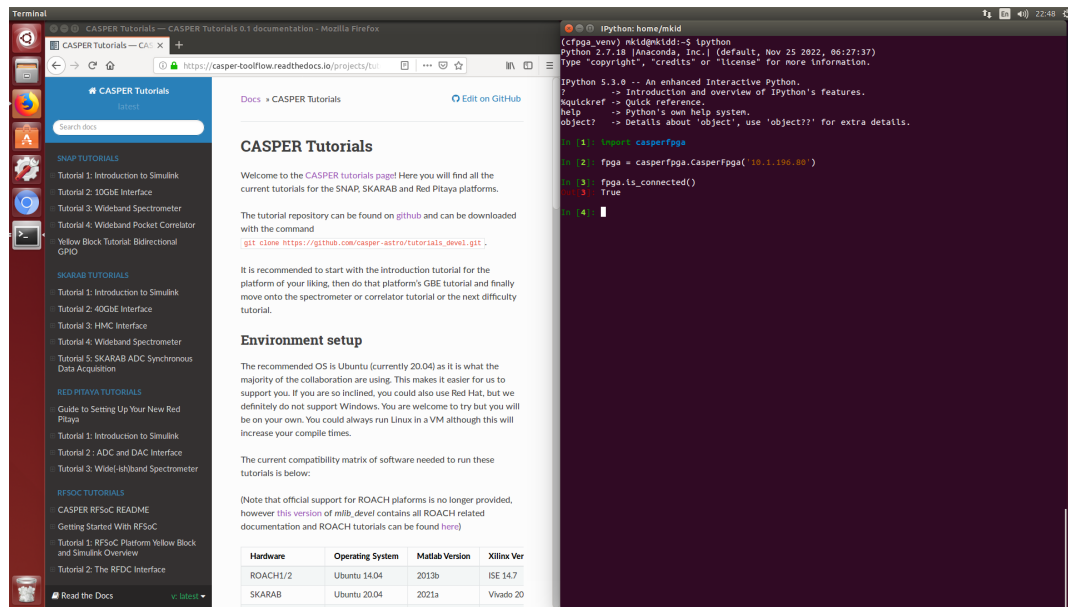


Figure 3.4: ROACH2 successful connection through local network

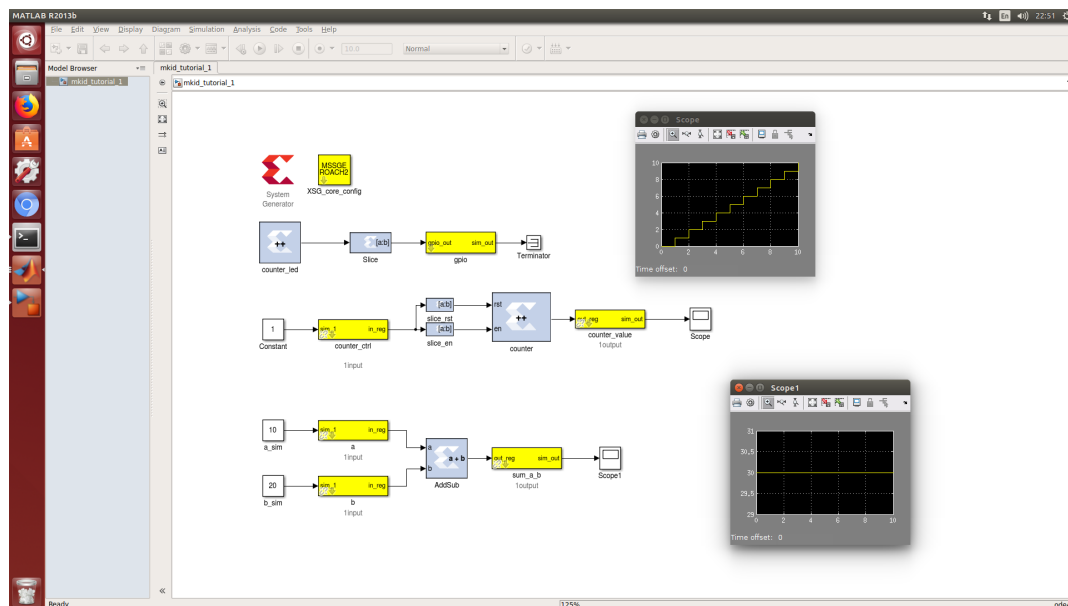


Figure 3.5: CASPER Simulink tutorial

3.4 Attenuation

In order to maximize the signal-to-noise ratio (SNR), match the impedance between the microwave source and detector, avoid saturation, maintain temperature

stability in cryogenic environments, control the system's dynamic range for various observations, and make calibration processes easier, attenuation control is essential in Microwave Kinetic Inductance Detector (MKID) circuits. MKID circuits can effectively handle microwave signals by varying the attenuation levels, guaranteeing optimal sensitivity, stability, and precision in a range of scientific applications, including quantum computing and astronomy.

Our RF/IF board has several Analog Devices HMC624A programmable attenuators providing a total of 31.5 dB attenuation control range in 0.5 dB steps.

To control the attenuation of RF/IF board its schematic was deeply studied. Figure 3.6 shows connections of one ADF4355 attenuator.

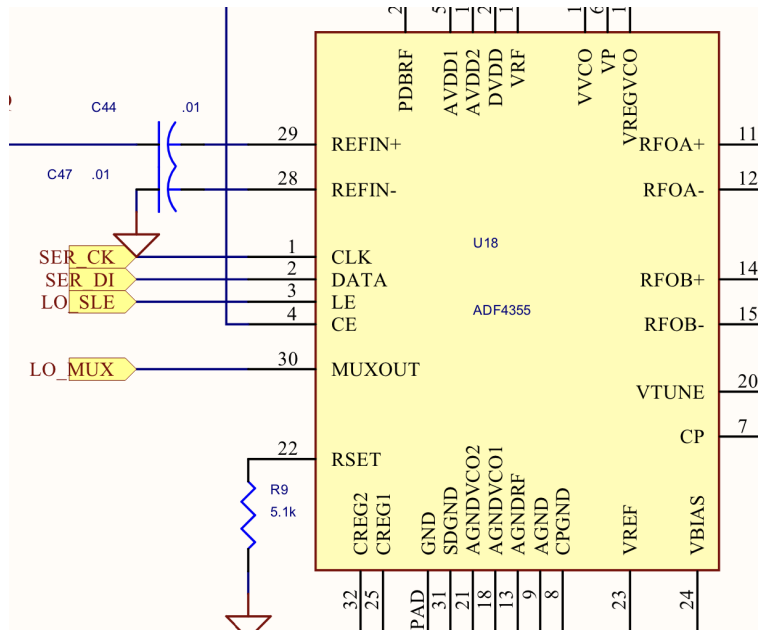


Figure 3.6: ADF4355 attenuator

From the schematic we see that to control the attenuator we need only 3 serial connections. They could be easily controlled via SPI bus.

For quick attenuation control we used Arduino Uno and I wrote code for that. This code Figure 3.7 sets up a SPI interface to control an adjustable attenuation system with an encoder and a button. It includes necessary libraries like SPI, Encoder, Wire, and LiquidCrystal i2c. Constants are defined for pins and parameters. Global variables track states and values. In the setup() function, it initializes components and prints the initial attenuation value on the LCD. printAttenuation() function displays the current value on the LCD. In loop() function, it reads encoder input, adjusts attenuation, toggles adjustment capability with the button, and updates the LCD display accordingly. Additionally, it sends attenuation values over SPI if

adjustment is locked. This code enables us to adjust attenuation, toggle adjustment capability, and view values on the LCD.

```
long encNewPos = enc.read();
if (encNewPos != encLastPos) {
    if (canAdjust) {
        if (encNewPos > encLastPos) { if (adjVal > 0) adjVal--; }
        else { if (adjVal < 63) adjVal++; }
    }
    encLastPos = encNewPos;
    attenuation = (float) adjVal / 2.0;
    printAttenuation(attenuation);
}
int r = digitalRead(BTN_PIN);
if (r != lastButtonState) lastDebounceTime = millis();
if ((millis() - lastDebounceTime > 25) && (r != buttonState)) {
    buttonState = r;
    if (buttonState == 0) canAdjust = !canAdjust;
    if (!canAdjust) {
        digitalWrite(CS_PIN, LOW);
        SPI.transfer(adjVal);
        digitalWrite(CS_PIN, HIGH);
    }
    Serial.println(attenuation);
    printAttenuation(attenuation);
}
lastButtonState = r;
```

Figure 3.7: Arduino code that controls the attenuation

Final setup can be seen on the Figure 3.8

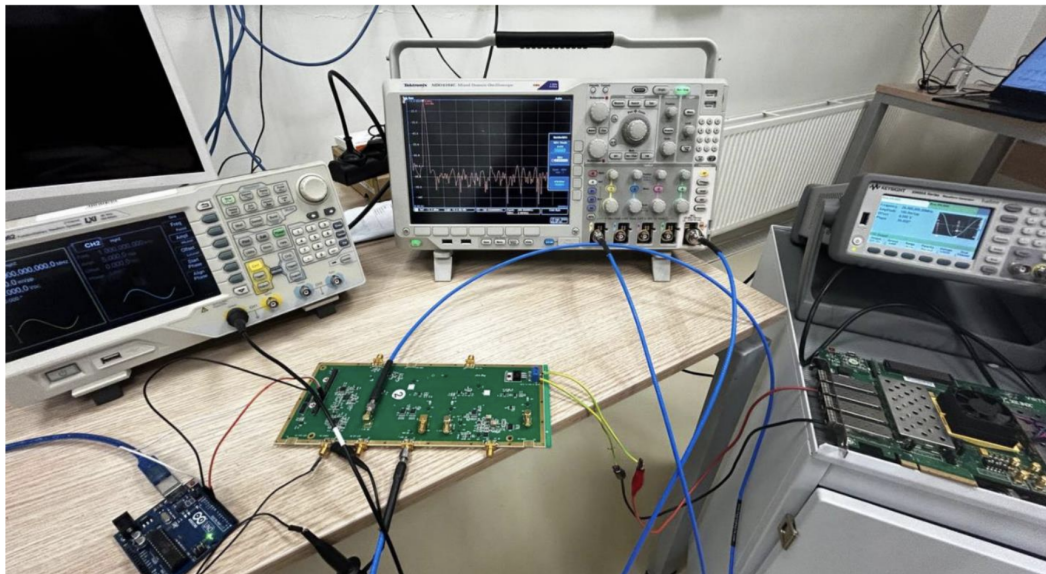


Figure 3.8: RF/IF PCB testing setup

Chapter 4

Results and Discussions

4.1 Results

- Laboratory Setup:
 - A complete laboratory setup was achieved to work with the ROACH2 platform.
 - All necessary software and libraries as per the CASPER Toolflow documentation were successfully installed on a PC running Ubuntu 14.04, including MATLAB 2013b, Xilinx ISE 14.7, and Python version 2.7.
 - MATLAB was set up to use ISE Xilinx programming blocks within MATLAB Simulink by following the provided instructions.
 - Separate conda virtual environments were created for CasperFpga and Casper Toolflow, ensuring that required libraries were present, as shown in Figure 3.2.
- ROACH2 Connection:
 - Both USB Serial connection and network connections are supported for ROACH2.
 - The MAC-address of the ROACH2 was obtained through the router's admin panel after connecting both the PC and ROACH2 to the same network.
 - The MAC-address was used to determine the IP address of ROACH2 on the local network via the arp-scan library, as illustrated in Figure 3.3.
 - A successful network connection between the PC and ROACH2 was established using the casperfpga python library, as confirmed by Figure 3.4.

- Simulation:
 - A Simulink test was performed using CASPER Toolflow tutorials to ensure familiarity with Matlab and Simulink as well as proper functioning of installed libraries.
 - A simple Simulink design was created combining standard Xilinx system generator blockset with CASPER-specific library blocks.
 - The tutorial provided experience in generating an .fpg file, programming a CASPER FPGA board, and interacting with hardware using casperfpga through a Python interface.
 - The functioning Simulink interface and simulation process are shown in Figure 3.5.
- Attenuation:
 - FR/IF board schematics particularly ADF4355 attenuation IC datasheet was studied.
 - Arduino code was written to control the attenuation using encoder and displaying its value to the LCD display.
 - Arduino Uno microcontroller was connected to RF/IF board and attenuation control was tested. Figure 3.8.

These results indicate that all initial setup requirements for working with ROACH2 were met, including successful installation of software and libraries, establishing communication with the board, and performing a simulation that interacted with hardware through a Python interface. Additionally attenuation control for RF/IF board was made.

4.2 Discussions

The establishment of a laboratory setup for working with the ROACH2 platform marks a significant milestone in the project. Configuration adheres strictly to the CASPER Toolflow documentation, ensuring that all software and library dependencies are correctly addressed. The ability to use ISE Xilinx programming blocks within MATLAB Simulink has streamlined the development process and underscores the importance of following detailed installation instructions. Furthermore, the creation of separate conda virtual environments for CasperFpga and Casper Toolflow not only avoids potential conflicts between library versions but also represents a best practice in managing Python-based projects.

The simulated environment, as evidenced by Figure 3.5, has proven to be an invaluable step in validating not just the correct setup, but also in fostering a deeper

understanding of both hardware-software integration and FPGA programming. Completing the CASPER Toolflow tutorial has not only ensured that all necessary components interact harmoniously but also equipped us with practical knowledge for creating programmable logic designs and interfacing them with high-level languages like Python.

Overall, these initial steps have provided a solid foundation from which to develop more advanced applications. The immediate goal is to leverage this laboratory setup to create a data processing algorithm for Microwave Kinetic Inductance Detectors (MKIDs). Developing an effective algorithm for MKIDs will require a deep understanding of both the hardware capabilities of ROACH2 and the software intricacies that have been explored through the CASPER Toolflow and simulations. The groundwork laid during the setup phase will be instrumental in facilitating the design, simulation, and testing of this specialized algorithm, ultimately contributing to advancements in astrophysical research and instrumentation.

Chapter 5

Conclusion

The research and experimentation conducted for working with the Reconfigurable Open Architecture Computing Hardware version 2 (ROACH2) and RF/IF board have culminated in a comprehensive understanding and successful execution of the necessary laboratory setup, connection protocols, and simulation procedures. This conclusion reflects on the future work based on the findings presented in the Results and Discussions chapters.

5.1 Future Work

As we look ahead, with working attenuation control, the next step is to establish PLL. After that we can involve leveraging this established setup to tackle challenges specific to MKIDs data processing. There is tremendous potential in optimizing signal processing techniques and in exploring new methods for data interpretation that could significantly enhance the performance of MKIDs. Continued innovation in this area may lead to breakthroughs in astrophysics research, revealing new insights into our universe.

In conclusion, this project has not only reached its objective by establishing a robust platform for FPGA-based development but also set the stage for future explorations into high-precision instrumentation. The diligent research and preparation carried out provide confidence that subsequent developments will be built on a strong foundation, facilitating progress in both educational settings and cutting-edge astrophysical research.

Bibliography

- [1] Paul Szypryt. “Development of Microwave Kinetic Inductance Detectors for Applications in Optical to Near-IR Astronomy”. In: (2017), pp. 5–9.
- [2] Bruno Serfass Seth Meeker Kieran O’Brien Ran Duan Rick Raffanti Dan Werthimer Sean McHugh Benjamin A. Mazin. “A readout for large arrays of Microwave Kinetic Inductance Detectors”. In: (2012), pp. 7–9. DOI: <https://doi.org/10.1063/1.3700812>.
- [3] B. A. Mazin. “Microwave Kinetic Inductance Detectors”. In: (2004), pp. 51–53. DOI: [10.7907/GZ72-V784](https://doi.org/10.7907/GZ72-V784).
- [4] LeDuc H. Mazin B. et al. Day P. “A broadband superconducting detector suitable for use in large arrays.” In: *Nature* 425.1 (2003), 817–821. DOI: [10.1038/nature02037](https://doi.org/10.1038/nature02037).
- [5] Benjamin A. Mazin et al. “A superconducting focal plane array for ultra-violet, optical, and near-infrared astrophysics”. In: *Opt. Express* 20.2 (2012), pp. 1503–1511. DOI: [10.1364/OE.20.001503](https://doi.org/10.1364/OE.20.001503).
- [6] Benjamin A. Mazin et al. “Position sensitive x-ray spectrophotometer using microwave kinetic inductance detectors”. In: *Applied Physics Letters* 89.22 (2006), p. 222507. DOI: [10.1063/1.2390664](https://doi.org/10.1063/1.2390664).
- [7] Jiansong Gao et al. “Experimental evidence for a surface distribution of two-level systems in superconducting lithographed microwave resonators”. In: *Applied Physics Letters* 92.15 (2008), p. 152505. DOI: [10.1063/1.2906373](https://doi.org/10.1063/1.2906373).
- [8] Sean McHugh et al. “A readout for large arrays of microwave kinetic inductance detectors”. In: *Review of Scientific Instruments* 83.4 (2012), p. 044702. DOI: [10.1063/1.3700812](https://doi.org/10.1063/1.3700812).
- [9] Jonas Zmuidzinas. “Superconducting Microresonators: Physics and Applications”. In: *Annual Review of Condensed Matter Physics* 3.1 (2012), pp. 169–214. DOI: [10.1146/annurev-conmatphys-020911-125022](https://doi.org/10.1146/annurev-conmatphys-020911-125022).
- [10] Collaboration for Astronomy Signal Processing and Electronics Research. *Reconfigurable open architecture computing hardware*. <https://casper.ssl.berkeley.edu/wiki/ROACH>. 20.11.2023. 2013.

- [11] Louis Woods and Gustavo Alonso. “Fast data analytics with FPGAs”. In: (2011), pp. 296–299. DOI: [10.1109/ICDEW.2011.5767669](https://doi.org/10.1109/ICDEW.2011.5767669).
- [12] Ramprasad Raghavan and Darshika G. Perera. “A fast and scalable FPGA-based parallel processing architecture for K-means clustering for big data analysis”. In: (2017), pp. 1–8. DOI: [10.1109/PACRIM.2017.8121905](https://doi.org/10.1109/PACRIM.2017.8121905).
- [13] Louis Woods and Gustavo Alonso. “Fast data analytics with FPGAs”. In: (2011), pp. 296–299. DOI: [10.1109/ICDEW.2011.5767669](https://doi.org/10.1109/ICDEW.2011.5767669).
- [14] K. J. Ramos, L. H. Arnaldi, and L. Tosi. “Towards a Low-Cost Readout System for Arrays of Cryogenic Detectors”. In: *2023 Argentine Conference on Electronics (CAE)*. 2023, pp. 19–23. DOI: [10.1109/CAE56623.2023.10086976](https://doi.org/10.1109/CAE56623.2023.10086976).
- [15] Joris van Rantwijk et al. “Multiplexed Readout for 1000-Pixel Arrays of Microwave Kinetic Inductance Detectors”. In: *IEEE Transactions on Microwave Theory and Techniques* 64.6 (2016), pp. 1876–1883. DOI: [10.1109/TMTT.2016.2544303](https://doi.org/10.1109/TMTT.2016.2544303).
- [16] Eoin Baldwin. “Developing a Next Generation Readout System for Microwave Kinetic Inductance Detectors”. In: (2022), pp. 128–140.
- [17] B. A. Mazin et al. “ARCONS: A 2024 Pixel Optical through Near-IR Cryogenic Imaging Spectrophotometer”. In: *Publications of the Astronomical Society of the Pacific* 125.933 (Nov. 2013), 1348–1361. ISSN: 1538-3873. DOI: [10.1086/674013](https://doi.org/10.1086/674013). URL: <http://dx.doi.org/10.1086/674013>.
- [18] Seth R. Meeker et al. “DARKNESS: A Microwave Kinetic Inductance Detector Integral Field Spectrograph for High-contrast Astronomy”. In: *Publications of the Astronomical Society of the Pacific* 130.988 (Apr. 2018), p. 065001. ISSN: 1538-3873. DOI: [10.1088/1538-3873/aab5e7](https://doi.org/10.1088/1538-3873/aab5e7). URL: <http://dx.doi.org/10.1088/1538-3873/aab5e7>.
- [19] Alexander B. Walter et al. “The MKID Exoplanet Camera for Subaru SCExAO”. In: *Publications of the Astronomical Society of the Pacific* 132.1018 (Nov. 2020), p. 125005. ISSN: 1538-3873. DOI: [10.1088/1538-3873/abc60f](https://doi.org/10.1088/1538-3873/abc60f). URL: <http://dx.doi.org/10.1088/1538-3873/abc60f>.
- [20] Jonas Zmuidzinas et al. “Multiplexable Kinetic Inductance Detectors”. In: (June 2002).
- [21] Jack Hickish et al. *A Decade of Developing Radio-Astronomy Instrumentation using CASPER Open-Source Technology*. 2016. arXiv: [1611.01826](https://arxiv.org/abs/1611.01826) [astro-ph.IM].
- [22] Dan Werthimer. “The CASPER collaboration for high-performance open source digital radio astronomy instrumentation”. In: *2011 30th URSI General Assembly and Scientific Symposium, URSIGASS 2011* (Aug. 2011). DOI: [10.1109/URSIGASS.2011.6051282](https://doi.org/10.1109/URSIGASS.2011.6051282).

- [23] Collaboration for Astronomy Signal Processing and Electronics Research. *CASPER Toolflow*. <https://casper-toolflow.readthedocs.io/en/latest/>. 20.11.2023. 2018.