MELODY: A Platform-agnostic Model for building and evaluating Remote Labs of Software-Defined Radio Technology

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Abstract

MELODY: A Platform-agnostic Model for building and evaluating Remote Labs of Software-Defined Radio Technology

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This dissertation introduces the MELODY model, a comprehensive framework for developing, implementing, and evaluating remote laboratories based on Software Defined Radio (SDR) technology, which is gaining increasing traction in engineering education. MELODY integrates both software and hardware components in a layered approach designed to enhance the functionality and integration across various system elements, focusing on fostering educational accessibility and pedagogical effectiveness.

The dissertation details the architectural structure and technical features of SDR technology as applied in remote laboratory settings, highlighting key aspects such as network types, user requirements, equipment costs, and interoperability. It outlines a classification framework within the MELODY model, aimed at evaluating and improving features such as lab scalability, interoperability, and accessibility. Developed on an open-source and agnostic platform, this framework promotes compatibility across a variety of hardware and software environments, enhancing flexibility for both educators and students. The MELODY model's classification system assesses laboratories using metrics including isolation, characterization, scalability, interoperability, and accessibility, which are all based on engineering standards.

Through three distinct case studies, this research demonstrates the practical application and pedagogical effectiveness of the MELODY model in different educational contexts. The RHL-RELIA lab illustrates the model's implementation in radio communications, providing detailed

insights into its development and the pedagogical evaluations conducted. The RHL-RADAR lab applies the MELODY model to develop a continuous wave radar system, emphasizing the model's adaptability and scalability. Lastly, a study focused on mitigating digital inequalities utilizes surveys and focus groups to integrate user feedback into the model, ensuring equitable access to remote lab resources. These case studies collectively reflect the model's capacity to adapt to diverse educational needs and its significant role in enhancing educational outcomes by addressing both technological and equity challenges.

Looking ahead, this dissertation outlines potential directions for further research and broader application of the MELODY model across various disciplines and regions. The continued development of this model seeks to address the ongoing challenges between technological advancements and educational equity, with the goal of fostering more inclusive and effective learning environments worldwide. Future efforts will build on the groundwork established by this dissertation to enhance and expand the capabilities of remote laboratories. This will ensure that the MELODY model remains a benchmark in the ongoing evolution of educational technologies.

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To my beloved parents,
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Chapter 1

INTRODUCTION

1.1 Models in Engineering

In engineering, models serve as a formal, declarative representation of the requirements specified within a design standard [1]. Models offer a structured framework for conceptualizing, designing, and analyzing complex systems. During the design phase of a engineering project, a model can assist developers in selecting the requirements within the standard that govern the design process, enabling them to focus exclusively on these requirements during design synthesis. Similarly, during the verification process, design standards act as a benchmark for users, ensuring adherence to established standards [2].

A notable example is the Open Systems Interconnection (OSI) model, which aimed to replace all prior computer communications to assist vendors and communications software developers in creating interoperable network systems [3]. Like OSI and other known models, a models is structured in layers. They represent different functionalities or levels of abstraction within the system.

1.2 Software Defined Radio technology (SDR)

SDR technology provides radio system devices with the capability to meet diverse communication needs by enabling their waveform to be modified through software. This flexibility is considered an enabling technology, as it allows devices to adapt to their specific contexts [4].

This technology has bridged the analog-to-digital gap in radio frequency (RF) communications, which were previously solely analog. The first prototypes of SDR, SpeakEASY 1 and SpeakEASY 2, emerged in the 1990s, leveraging Digital Signal Processing (DSP) and FPGA integrated circuit (IC) chip technology. Since then, SDRs have been undertaken by industry, government, and academia to create more versatile, powerful, and functional SDR platforms [5].

The advancements in technology has facilitated the widespread adoption of SDR among communications engineers. This convergence has occurred alongside the increased availability of robust

DSP and communications design software, along with the affordability of devices capable of receiving and digitizing radio-frequency (RF) signals, as observed over the past twenty years [6]. Thanks to its flexibility, SDR has been chosen as the core component for building more complex projects. SDR finds application in a wide range of fields, including radar systems, wireless communication, Radio Frequency Identification (RFID), and cybersecurity [7].

1.3 Educational Remote Laboratories

Throughout this dissertation, the term 'remote laboratories' specifically denotes educational remote laboratories, unless otherwise specified. Remote laboratories have evolved since their inception in the early 1990s [8], garnering continued attention in educational research due to their significant potential [9]. Typically, remote laboratories consist of a configurable equipment or hardware, complemented by additional components such as a server responsible for managing and executing user-requested functions or tasks on the remote hardware, along with a camera for providing visual feedback to users. The interaction of these components is illustrated in Figure 1.1.

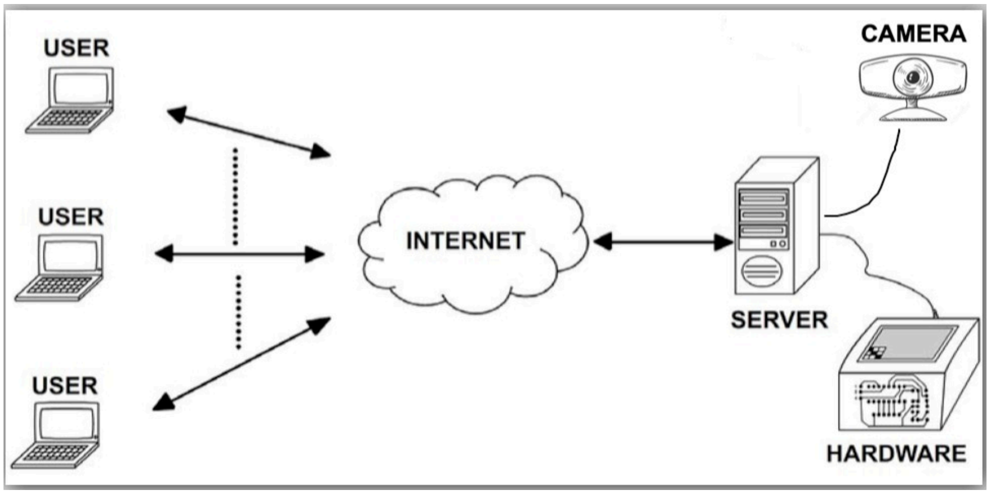

Figure 1.1: General block diagram of a remote laboratory

1.4 Historical Role of Remote Laboratories

Engineering is inherently characterized by hands-on experience and active participation. Even before the establishment of formal engineering institutions, apprenticeship programs served as the primary method of engineering education. In these programs, early engineers learned by designing, analyzing, and constructing their own projects, thus acquiring practical skills through engagement in their field. [10]. The emergence of remote laboratories occurred in the 1980s as a direct consequence of the introduction of computers and distance learning systems over the internet [11]. This technological advancement allowed for the connection of various devices to a dedicated computer, enabling the collection, analysis, and graphical presentation of data for students. It empowered students to analyze more complex systems and delve into them with greater depth [12]. Specifically, LabVIEW, developed by National Instruments, offered a hardware-software solution that enabled remote control, allowing students to operate real instruments from a distance [13].

In Electrical Engineering and related departments courses, a pivotal development was the integration of Field-programmable gate array (FPGA) technology in 1993 [14]. Acting like hardware that can be reconfigured, FPGA technology brought about a significant shift in engineering education, particularly when researchers began combining it with Project-Based Learning approaches [15]. This trend has continued to evolve, with various technologies now providing a wide range of evaluation board options based on microcontrollers, DSPs, embedded systems and more [16]. This technology, coupled with the emergence of internet technology and powerful computing, has complemented the development of building prototypes and integrating them into remote applications for educational purposes [17]. Educational remote laboratories offer advantages in terms of accessibility, flexibility, and cost-effectiveness compared to traditional labs. Table 1.1 provides an overview of their capabilities.

1.5 Digital inequalities in Remote Laboratories

The integration of technological tools in education has revolutionized the dissemination of knowledge among students. However, unequal access to these tools remains a significant concern, prompting numerous studies to investigate the factors contributing to this digital divide. Particularly in engineering education, remote laboratories are gaining prominence, offering students the opportunity

Table 1.1: Overview of Remote Laboratories Effort

Capabilities	**Traditional lab**	**Remote lab**
Accessibility of hardware	Limited to the hardware a student or group of students receive	Unlimited number of modules
Versions of hardware	Only one version	Any version available in the lab network
Interdisciplinary collaboration	Require students' closeness	Requires internet connection
Software requirements	Specialized software	Web browser
Hands On Experience	Requires minimal hands on experience	No hands one experience required
Flexibility	Access on schools hours	Access on anytime
Update of software versions	Yes	No
Laptop/computer requirements	Minimal requirements in Manufacturer website	No minimal requirements

to conduct experiments with specialized equipment remotely via the Internet [18–20]. While these labs enhance learning opportunities, they also have the potential to exacerbate digital inequalities among students, given the advanced hardware and software knowledge required [21].

This thesis explores the impact of digital inequalities on students through surveys and focus groups, aiming to understand the extent of the issue and propose technical solutions within the realm of remote laboratories. Given the social nature of this problem, digital inequalities vary across student populations depending on their social context, nationality, and other factors.

1.6 SDR remote laboratories

In the literature, various educational remote laboratory projects have been developed around one or multiple SDR devices, serving as tools for wireless communication design. Each project provides technological contributions related to hardware accessibility and user interface design, fully exploiting the features of SDR. However, there are some technical aspects that most remote laboratories haven't covered, such as interoperability and isolation. Additionally, there is currently no unified criteria that enables developers and users to compare these projects within a standardized framework based on engineering metrics.

1.7 Research Questions and Original Contributions

In the previous section, SDR within the context of educational remote laboratories and its implications for triggering digital inequalities have been discussed. Consequently, the following research questions arise:

1. *How can a single technology-agnostic application-independent model be employed to define educational remote laboratories for SDR?*
2. *How can this model be optimized to ensure equitable access?*

Developing a model for educational remote laboratories involves more than just researching the current state of the art. While a model is elaborated under technical specifications, they don't necessarily originate solely from technical sources. It's also essential to consider how well the laboratories accommodate and support diverse users and their learning needs.

Moreover, in elaborating a model, it's crucial to understand the reasons for its creation. This facilitates the refinement of both the development process and its practical applications. Case of studies often offer valuable real-world examples of the model's implementation and its influence on educational practices. Figure 1.2 illustrates a systematic approach for the creation of the SDR model proposed on this dissertation.

To address the first question, the Platform-agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology (MELODY) is proposed. This model integrates both hardware and software elements, which can be customized to suit the requirements of SDR technology within a distributed remote laboratory framework. Organized into four layers, MELODY is particularly suitable for communication and radar applications. At its core, the model revolves around two fundamental components: an open-source framework and platform agnosticism.

Additionally, the model includes a classification framework that facilitates the application of a rubric across various categories, incorporating engineering standards and addressing technical

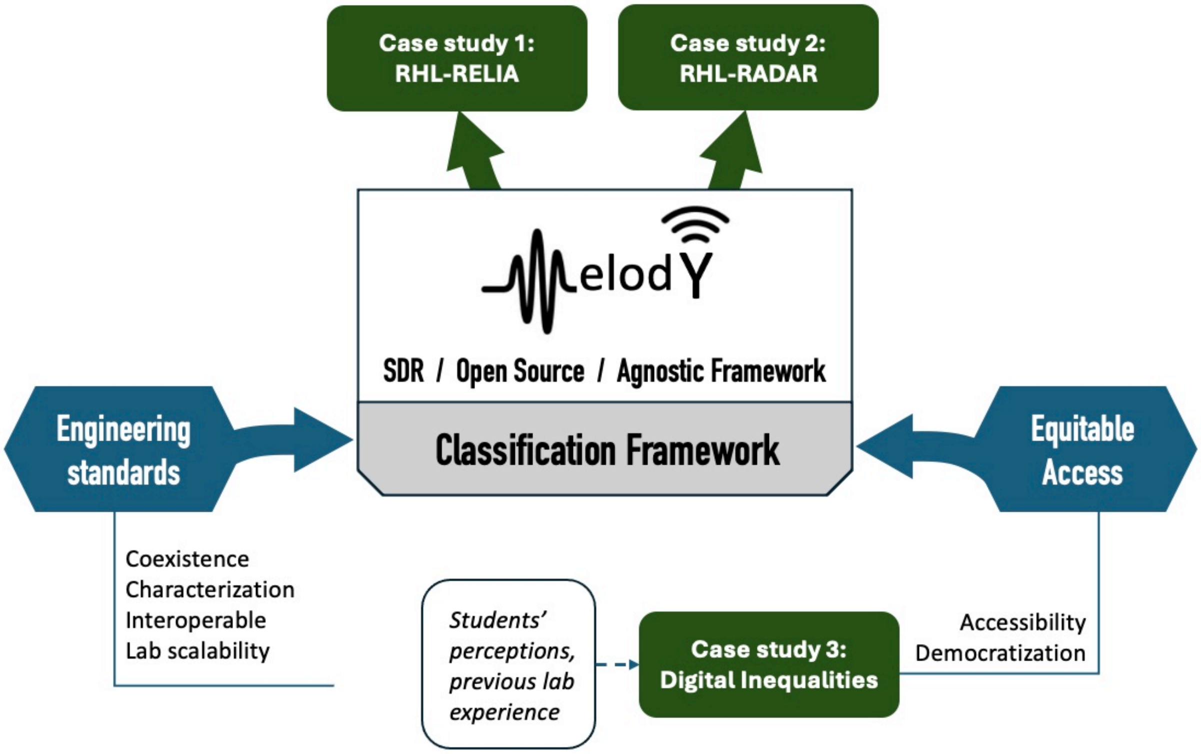

Figure 1.2: Components that form MELODY model

challenges specific to distributed SDR remote laboratories. These categories include coexistence, characterization, interoperability, and lab scalability. To showcase the model's effectiveness in real-world remote laboratories, RHL-RELIA (case study 1) and RHL-RADAR (case study 2) are presented. These implementations are developed based on the MELODY model and evaluated using MELODY's classification framework.

To address the second question, technical features from an equitable access perspective are explored to be included in MELODY's classification framework. This exploration is informed by a study of the impact of digital inequalities in remote labs (case study 3). Through an examination of existing literature, as well as surveys and focus groups conducted with students who have experience with previous remote laboratory setups, insights into accessibility and the promotion of democratization are obtained.

1.8 Thesis Organization

Chapter 1 introduces key concepts that will be developed in this thesis. It explains the significance of models in engineering, the impact of SDR on industry and academia, defines remote laboratories and their impact on education, and motivates the study of digital inequalities within the context of remote laboratories. These discussions underscore the impetus behind developing a comprehensive model that encompasses the technical requisites and evaluation metrics for SDR remote laboratories.

Chapter 2 delves into the most relevant technical details of SDR remote laboratories while providing an overview of the current state-of-the-art in this domain. It scrutinizes five previous projects, emphasizing their principal contributions while also identifying areas that require further exploration and coverage.

Chapter 3 provides a detailed exposition of the MELODY model, starting with an examination of the essential technical attributes that constitute the core components of an efficient SDR remote laboratory. Subsequently, the chapter proceeds to dissect the model's structure into four fundamental elements: Architecture and shared terminology, Creation guidelines, Datasets for standardized testing, and Classification Framework.

Chapter 4 focuses on the development of rubrics for the classification framework, which comprises six categories: isolation, characterization, scalability, availability, usability, and interoperability. The chapter elaborates on the specific engineering standards utilized within each category to assess and rate the effectiveness of the SDR remote laboratory model. Ratings range from 1 to 5 stars, providing a comprehensive evaluation of each aspect based on established criteria.

Chapter 5 focuses on the MELODY case study #1: RHL-RELIA. It explores the deployment of this remote lab and the development of its web user interface, which replaces the traditional QT interface commonly used in standard SDR Graphic User Interfaces (GUIs). Additionally, the chapter evaluates the RHL-RELIA implementation based on MELODY's rubric. Finally, it presents the findings of an independent evaluation report.

Chapter 6 delves into the case study #2, which explores the implementation of MELODY with RHL-RADAR, specifically emphasizing its utilization in Continuous Wave radar experiments. The chapter outlines the results obtained from these experiments and evaluates the RHL-RADAR implementation based on MELODY's rubric.

Chapter 7 explores Case Study #3 of MELODY, examination of Digital Inequalities within remote laboratories. Initially, the chapter investigates how the three levels of digital inequalities manifest in remote labs, focusing on contexts within the United States and Latin America. Subsequently, inputs are gathered from users who have utilized other remote laboratories, employing an equitable access approach. The conclusions drawn from these studies will inform the integration of technological features into MELODY, with the aim of developing remote labs with equitable access as a core component.

Chapter 8 presents the research conclusions and provides a discussion of future work.

1.9 Publications

All publications to date are listed below:

1. **Inonan**, M. & Hussein, R. Focus Group Insights into Digital Inequalities and Equitable Access in Remote Laboratories. Paper accepted for presentation at the American Society for Engineering Education (ASEE). Annual Conference and Exposition, Portland, 2024.

2. **Inonan**, M., Zhang, Z., Orduna, P., Hussein, R. & Arabshahi, P. (2024, March 6-8). RHLab Interoperable Software-Defined Radio (SDR) Remote Laboratory. 21st International Conference on Smart Technologies & Education (STE), Helsinki, Finland.

3. Zhang, Z., **Inonan**, M., Orduna, P., & Hussein, R. (2024, March 6-8). Towards the Implementation of a SDR Remote Lab with Partial Reconfiguration application. 21st International Conference on Smart Technologies & Education (STE), Helsinki, Finland.

4. **Inonan**, M., Reynolds, M., & Hussein, R. (2024, March 6-8). RHL RADAR Remote Laboratory. 21st International Conference on Smart Technologies & Education (STE), Helsinki, Finland.

5. **Inonan**, M., Diaz, B., Oonlamom, N., Peterson, K., Orduña, P., Aramburu, C., & Hussein, R. (2024, March 6-8). Evaluation of RELIA Remote Laboratory: First results. 21st International Conference on Smart Technologies & Education (STE), Helsinki, Finland.

6. **Inoñan**, M. J., Orduña Fernandez, P., and Hussein, R. (2023). Adaptación de un laboratorio remoto de SDR para analizar desigualdades digitales en educación de comunicaciones inalámbricas en Latinoamérica. Innovaciones Educativas, 25(Especial), 32–43. https://doi.org/10.22458/ie.v25iEspecial.4920

7. **Inonan**, M., and Hussein, R., "MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology," in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399.

8. **Inonan**, M., Paul, A., May, D. & Hussein, R. RHLab: Digital Inequalities and Equitable Access in Remote Laboratories. American Society for Engineering Education Annual Conference and Exposition, Baltimore Convention Center, MD, June 25 - 28, 2023

9. Paul, A., **Inonan**, M., Hussein, R. & May., D. Exploring diversity, equity, and inclusion in remote laboratories. American Society for Engineering Education Annual Conference and Exposition, Baltimore Convention Center, MD, June 25 - 28, 2023. **Best Paper Award**

10. Chap, B., **Inonan**, M., Zhang, Z., Orduna, P., & Hussein, R. RHLab RELIA: An Integrated Remote Environment for Embedded Computing and RF Communication Systems. American Society for Engineering Education Annual Conference and Exposition, Baltimore Convention Center, MD, June 25 - 28, 2023

11. **Inonan** M., Chap B., Orduña P., Hussein R., and Arabshahi P. Rhlab scalable software defined radio (sdr) remote laboratory. 20th annual International conference on Remote Engineering and Virtual Instrumentation REV 2023, 2023.

12. Hussein, R., Chap, B., **Inonan**, M., Guo, M., Monroy, F., Maloney, R., Alves, S. and Kalisi, S. Remote hub lab – rhl: Brodly accessible technologies for education and telehealth. 20th annual International conference on Remote Engineering and Virtual Instrumentation REV 2023, 2023

Chapter 2

LITERATURE REVIEW

This chapter is a modified version of Section II in [22]:

- **Inonan**, M., and Hussein, R., ”MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology,” in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399.

2.1 Overview

This chapter analyzes previous and ongoing projects related to educational labs for wireless communication based on SDR technology, aiming to provide students with a practical, hands-on learning experience.

2.2 Features of SDR educational laboratories

In the context of educational labs, SDR technology provides a range of hardware options, each with distinct specifications, capabilities, and price points. Selections are often made based on the experiments and educational objectives they aim to fulfill, with some projects even opting to develop custom hardware tailored to their specific needs. Six key features are typically evaluated when considering SDR technology for educational labs:

- **User requirements:** This feature denotes the platform required for users to access the lab. Various user interfaces are available, including generic SDR software tools such as GNU Radio Companion (GRC), LabVIEW, or web-based interfaces.

- **Type of network:** This characteristic describes the system network that facilitates secure interaction among registered users in a class. The most commonly utilized network type is the Virtual Private Network (VPN).

- **Access to computer:** This characteristic delineates how users access and control the equipment. They may either directly control the equipment from their own computer or access a dedicated computer that controls the SDR hardware.

- **SDR equipment & computer cost:** This feature encompasses the overall cost of all equipment required for the remote lab setup, including SDR hardware, the computer or embedded system that controls it, and additional instrumentation.

- **Isolation:** This characteristic explains the mechanism used to isolate signals from other units when designing a distributed remote lab setup. Isolation techniques may include physical isolation mechanisms, such as shielding or spatial separation, as well as considerations for coexistence to ensure efficient operation in shared environments.

- **Interoperability:** This property describes the lab's capability to support the operation of several types of SDR devices. Interoperability allows for flexibility and compatibility with different SDR hardware options.

2.3 Previous initiatives

This study encompasses both remote and non-remote SDR lab setups, acknowledging the novelty of SDR technology. The following projects are described, highlighting their most significant contributions:

2.3.1 EMONA TIMS

The Australian company Emona Instruments Pty Ltd provides a comprehensive array of hardware and software solutions under the name Emona TIMS (Telecommunications Instructional Modeling System) [23]. This system, comprising modular experiments, is tailored for both analog and digital communication systems curricula and has gained popularity in communication systems laboratories across various universities. Further insights into its educational utility can be found in [24–26].

The hardware consists on a base platform named the TIMS-301C, which allow other hardware to connect like the TIMS-451 SDR that is a plug-in peripheral that contains SDR modules to complete experiments. Most relevant features are the Dual I and Q basedband analog inputs and outputs.

This design permit to develop a SDR transmitter and receiver implementations [27]. Enhancing the student experience, the system integrates a built-in virtual instrument that interfaces with PCs, offering oscilloscope functionalities and spectrum analysis using Fast Fourier Transform (FFT). Its user-friendly design incorporates color-coded inputs and outputs for easy identification [28]. Under EMONA SDR, users can develop their own experiments without the need for cumbersome file downloads, Linux installation, or code compilation. The TIMS-SDR Kit is designed as a zero-install, plug-and-play solution, featuring a complete Linux system and the latest version of GNU Radio on a USB stick. This approach maximizes the accessibility and user-friendliness of GNU Radio for students.

While the EMONA TIMS-SDR Kit offers numerous advantages, such as ease of use and simplified setup, its reliance on specific EMONA hardware may pose limitations on scalability for providing flexible laboratory access to a large number of students. Table 2.1 summarizes the most important features.

Table 2.1: EMONA TIMS - Highlights

User requirements	GNU Radio (open source) Specific Hardware Computer or Laptop in Lab
Type of network	Not applicable
Access to computer?	Yes in person
SDR equipment & Computer cost	TIMS-301C: $13K TIMS-451: $525 Computer: $800
Isolation	Not specified
Interoperability	Not applicable

Table 2.3: Huazhong University - Highlights

User requirements	Web browser (open source) with M file input
Type of network	Not applicable
Access to computer?	NO
SDR equipment & Computer cost	2 XDRP SDR devices - Not available 2 computers (2 x $800) 2 oscilloscopes (2 x $4800)
Isolation	Not specified
Interoperability	Not applicable

2.3.2 Huazhong University

This project offers an online experiment platform for principles of communication. In addition to software and hardware development, this initiative offers features such as experiment scheduling, upload capabilities, and runtime recording [29].

Utilizing the Browser/Server (B/S) architecture, this web-based system establishes connections among teacher servers, student clients, hardware devices, and other functional elements over the network. This framework enables students to access all resources remotely without the need for physical presence in the laboratory [30]. The experimental setup includes a software radio platform and an online test instrument, tailored to specific requirements. The client interface displays experiment results, measurement data, and instrument images [31]. For instance, two oscilloscopes are employed to measure the modulated signal of the transmission section and the demodulated signal of the reception section. The obtained results and measurements can be visualized on the client interface. Additionally, students can observe real-time experimental images captured by a camera [32]. Further details on the features of this project are provided in Table 2.3.

2.3.3 Technical University of Cluj Napoca

The Technical University of Cluj-Napoca in Romania is actively involved in a project for a Software-Defined Radio (SDR) remote laboratory. Users can access this laboratory via a Virtual Private Network (VPN) and interact with it through virtual machines [33]. The setup consists of two ADALM-PLUTO SDRs and one computer per unit. User requirements include the use of GRC, an open-source software [34, 35].

Once the VPN connection is established, the computer and ADALM-Pluto SDR operate as if they are on the same local network. This remote control setup enables students to access SDR resources [36]. This approach enhances user convenience, particularly given the typically limited availability of platforms confined to laboratory premises, enabling uninterrupted work. However, it should be noted that the level of SDR isolation is not specified in the available information (Table 2.5).

Table 2.5: Cluj-Napoca Highlights

User requirements	GNU Radio (open source)
Type of network	VPN
Access to computer?	Yes, through virtual machine
SDR equipment & Computer cost	2 ADALM-Pluto (2 x \$200) 2 computers (2 x \$1000)
Isolation	Not specified
Interoperability	NO

2.3.4 Hyderabad University

The FM transmitter project located in Hyderabad, India, utilizes the GNU Radio software and incorporates one USRP device for FM transmission reception [37].

The design of this FM transmitter achieves a high-quality sound signal transmission. This tool is to educate students on fundamental digital signal processing tools and RF concepts, encompassing filtering, sampling rate conversion, and demonstrating the utilization of SDR for real-time application design. Leveraging the SDR package greatly simplifies the utilization of the FM framework. Using LabVIEW as a software tool to program USRP enables the creation of communication system prototypes, enabling real-time performance verification. Substantial research is underway to explore SDR applications in diverse fields, aiming to make it viable for commercial deployment [38]. Further insights on the FM transmitter project are presented in Table 2.7.

Table 2.7: Hyderabad Highlights

User requirements	LabVIEW
Type of network	Not applicable
Access to computer?	NO
SDR equipment & Computer cost	1 USRP N210 ($3000)
Isolation	Not specified
Interoperability	NO

2.3.5 FORGE

The FORGE (Forging Online Education through FIRE) initiative provides educators and higher education students with access to the remarkable FIRE testbed infrastructure [39]. Among its various project domains, wireless communication holds a significant position. In this particular

Table 2.9: FORGE

User requirements	GNU Radio (open source)
Type of network	Unknown
Access to computer?	NO
SDR equipment & Computer cost	IRIS (Implementing Radio In Software) testbed composed by USRP N210 (16 x $3000)
Isolation	Not specified
Interoperability	NO

context, the FORGE initiative utilizes a testbed called IRIS, which comprises 16 USRP (Universal Software Radio Peripheral) software-defined radios [40].

Each individual USRP unit is connected to a virtual machine, operating either on the IRIS software or GRC. Resource allocation is automated through the gateway server, which also facilitates the initiation of experimentation services, such as data collection from measurement points.

In this laboratory environment, students explore the fundamental principles of Orthogonal Frequency-Division Multiplexing (OFDM) for wireless signals. This lab not only grants students access to cutting-edge research hardware but also provides them with the opportunity to delve deeply into the intricate workings of the digital multi-carrier modulation technique in the context of wireless communications [41]. Over the past year, this course has been delivered nine times across Brazil, Mexico, and Ireland, engaging a total of 148 students and enabling them to conduct at least 1,400 experiments [40]. Key features of the FORGE project are summarized in Table 2.9.

2.4 New technology for SDR remote laboratories

From the SDR laboratories reviewed, it is evident that there's potential to integrate new technological advancements observed in remote labs from diverse courses. These approaches are oriented towards enhancing security, reducing costs, and fostering collaboration among institutions.

2.4.1 Ultra-concurrent remote laboratories

An ultra-concurrent laboratory is a form of remote laboratory that allows students to engage with real data, although all data and multimedia have been pre-recorded. This type of remote lab is advantageous when infrastructure challenges exist, and setting up a remote laboratory station for each student is impractical [42]. The benefits of ultra-concurrent laboratories include their lack of time constraints, unlike real-time remote laboratories [43].

The ultra-concurrent lab approach provides an experience closely resembling both traditional hands-on labs and real-time remote labs [44–46]. Notably, ultra-concurrent labs surpass mere videos by offering interactivity, allowing students to actively engage and make choices. This interactivity is facilitated by a dataset containing numerous experimental combinations. Unlike simulations, these labs rely on authentic data collected from real equipment, eliminating dependency on simulation engines.

This innovative solution empowers users to interact with authentic results while accommodating numerous concurrent users without the need for real-time manipulation of physical equipment. Instead, requests are routed to a database containing the pre-recorded lab dataset. These labs offer the advantage of simultaneous access by multiple students, eliminating the need for duplicate physical equipment. Moreover, their maintenance primarily involves software updates, making them more cost-effective. However, these labs are more suitable for experiments with limited variable control. In the context of SDR remote labs, this feature is beneficial as it reduces equipment costs to a single unit and mitigates potential interference from other RF units during simultaneous transmission.

2.4.2 Federated remote laboratories

By default, SDR remote labs are designed to operate independently, isolated from external networks. Universities typically provide VPN access to students enrolled in specific lab courses to minimize the risk of network attacks by tracking and identifying users through their university credentials. However, the concept of Federated remote labs allows students to access any remote lab, regardless of its location at their university. This approach enhances the student experience and further reduces the cost of lab access, promoting a collaborative approach to resource sharing across multiple institutions or organizations while maintaining the security provided by isolated remote labs through VPN access. This ensures that students can only use the equipment for educational purposes, preventing any potential network attacks [47, 48].

2.5 Conclusions of the Chapter

From the array of reviewed projects, a wide spectrum of contemporary examples in SDR remote labs emerges, showcasing their varied applications and advancements. Projects like EMONA TIMS, Huazhong University's web-based system, Cluj-Napoca University's VPN-based setup, FORGE, and Hyderabad University's FM transmitter project all offer unique approaches to SDR labs.

Table 2.11 offers a summary into the primary features of SDR educational labs, showcasing variances in their attributes despite shared elements. Particularly noteworthy is the observation that certain projects opt for an intermediary computer in the "Access to computer" category, instead of direct access to the device. This choice could result in lengthy queues and vulnerability to external attacks. Additionally, the absence of labs incorporating features related to "Computer cost," "Isolation," and "Interoperability" underscores potential areas for enhancement and standardization within SDR educational lab setups.

Furthermore, there is a lack of uniformity in their evaluation methods from an engineering perspective. The absence of a standardized, technology-agnostic framework model impedes the efficient development of both basic and advanced SDR remote laboratories. Hence, it is crucial to establish a comprehensive model that addresses these limitations, facilitating the enhanced development and evaluation of SDR remote laboratories.

Table 2.11: Summary of features of Remote Laboratories Efforts

	Cluj-Napoca	**Huazhong**	FORGE	Hyderabad
User requirements	GNU Radio (open source) + Remote Desktop client	External solution	GNU Radio (open source) + Remote Desktop client	LabVIEW Remote Panel
VPN required	Yes	No	No	Unknown
Access to computer?	Yes	No	Yes	No
SDR equipment cost	\$2400	\$11200 + 2 XSDR	\$48000	\$3000
SDR Isolation	Only one setup	Only one setup	Unknown	Only one setup
Interoperatibility	No	No	No	No

🟦 No problematic 🟨 Medium 🟪 Problematic

New technologies such as federated remote labs and ultra-concurrent laboratories can seamlessly integrate into SDR remote laboratories, offering advantages in cost reduction and scalability. Federated remote labs facilitate cost reduction and promote collaboration between institutions while maintaining user security, which is particularly crucial for expensive equipment. On the other hand, ultra-concurrent laboratories provide a solution where multiple students can interact with pre-recorded real data, offering an authentic experience without the need for real-time handling of physical equipment. While these labs excel in scenarios where the radio transmitter's power is high or they occupy large areas, they are limited in control flexibility as the parameters available for modification are predetermined by the developer during the data recording setup.

Chapter 3

MODEL FOR SOFTWARE DEFINED RADIO REMOTE LABORATORIES (MELODY)

This chapter is a modified version of [22]:

- **Inonan**, M., and Hussein, R., "MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology," in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399.

3.1 Overview

The MELODY model stands as a specialized framework crafted to systematize the development, execution, and evaluation of SDR remote laboratories within the realm of radio-frequency (RF) communication. This chapter delves into an exploration of MELODY, elucidating its conceptual origins and structural framework. Through this analysis, the underlying principles guiding MELODY's design and its organizational structure are unveiled, providing invaluable insights into its application within the field of RF communication.

3.2 Fundamental of the creation of MELODY

The development of the MELODY model stems from several critical factors necessitating a standardized framework for SDR remote laboratories:

- Standardization: The model sets forth a benchmark standard that outlines the technical challenges to be anticipated in advance. This standardization ensures a uniform and systematic method for evaluating SDR projects, thereby enhancing their quality and reliability.

- Layered Approach: The model facilitates the structuring of the communication process into discrete layers, defining the interactions between software and hardware components. This structured approach brings clarity and organization, facilitating the efficient development and assessment of SDR systems.

- Interoperability: The model underscores the significance of promoting interoperability among various SDR capabilities. By establishing common protocols and interfaces, it enables seamless communication and compatibility across a range of SDR devices and platforms.

- Modularity and Flexibility: Recognizing the distinctive attributes and scalability of SDR devices is vital. The model advocates for modularity and flexibility in system design, enabling adaptability and growth as SDR technology continues to advance.

3.3 MELODY model

The MELODY model integrates diverse SDR device platforms into a unified or distributed network, streamlining the configuration of remote SDR operations across a multitude of applications. This architecture caters to educational endeavors in RF SDR communication, radar systems, and various other RF-related tasks, offering a comprehensive solution for educators and researchers alike.

At its core MELODY model is composed by 4 elements: Architecture and shared terminology, Creation guidelines, Datasets for standardized testing, Classification Framework. The initial two elements constitute the model's design, while the latter two are essential for evaluating its effectiveness. A visual representation of these key components is presented in Figure 3.1 through a block diagram.

3.4 Architecture and shared terminology

The architecture and shared terminology aspect pertains to establishing a comprehensive structure, components, and interactions within the system among various elements through a layered design. When considering an RF remote laboratory built upon SDR technology, the hardware, firmware, and software components are interconnected in a modular manner. This design approach ensures that the hardware and firmware elements are treated as software entities, resulting in independent layers. This configuration facilitates a streamlined redesign process and offers flexibility to accommodate emerging hardware and software technologies.

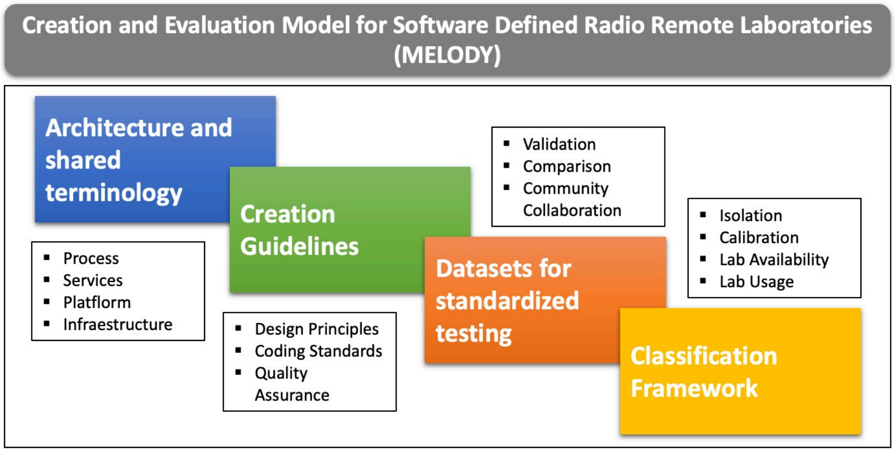

Figure 3.1: Block diagram MELODY model and implementations

Within MELODY, this particular element comprises of four distinct components: Process, Services, Platform, and Infrastructure. Each of these components fulfills a specific role within the system. A block diagram with all components are illustrated in Figure 3.2.

3.4.1 Process

Within this element, the focus lies on the precise actions undertaken by users within the system. This layer encompasses two distinct user categories: students and instructors. Notably, instructors possess enhanced privileges, enabling access to private files and the ability to monitor the activities of registered students in a laboratory setting. Moreover, this layer is responsible for validating user credentials and managing ongoing user sessions.

3.4.2 Services

This software component incorporates modules that furnish essential functions facilitating interaction between the Process layer and the Platform layer. MELODY integrates 12 high-level software blocks, each characterized by distinct functionalities, as detailed below:

- `access()`: This block verifies the availability of lab resources for a designated user.

- `interactLab()`: Enabling dynamic access, this module allows users to engage with the lab in real time.
- `loadFile()`: This functionality permits the inclusion of scripts within the design, such as sequences for modulation or coefficients for specific filters.
- `saveFile()`: Of particular significance for RF applications, this block enables the preservation of received data, whether real or simulated, in either the time or real domain.
- `dataExchanger()`: This module enables the visualization of received data within a web browser, enhancing user interaction.
- authentication(): This module verifies user permissions and privileges, assigning the appropriate resources as required.
- `scheduledLab()`: Responsible for time allocation and queue management, this module coordinates student access to specific lab modules.
- `accessLab()`: Enabling lab entry, this component facilitates the allocation of a designated SDR module.
- `checkAvailability()`: This module ensures the availability and access of both Transmitter and Receiver modules.
- `getResults()`: Acknowledging correct outcomes and data transfers from the Platform layer, this component confirms successful operations.
- `getStudentInfo()`: Recognizing and retrieving user information, this module retrieves pertinent user data.
- `setStudentInfo()`: This block associates user data with a specific name, allowing students to access and retain their files for future sessions, enhancing usability and continuity.

3.4.3 Platform

Within the Platform component, essential system resources are encompassed, potentially subject to alterations during runtime. Operations within this layer constitute a combination of software and firmware interactions, engaging with the computer or embedded system responsible for managing SDR hardware. This layer comprises 14 distinct blocks.

- `updateVariables()`: This block receives user inputs to modify SDR parameters or view parameters, facilitating updates to acquisition or display settings.

- `preProcessing()`: Responsible for applying preliminary processing before data streaming is displayed, this block often involves domain transformation, such as time or frequency domain integration, to effectively mitigate noise.

- `queueWaiting()`: Utilizing computer resources, this block buffers data streaming to prevent potential data loss and maintain smooth data flow.

- `accessAssignment()`: Enabling data transfer within an assignment rather than a test scenario, this block ensures proper data display or storage.

- `dataTransfer()`: Charged with the complete and uninterrupted transfer of data, this block safeguards against glitches or losses by transmitting a sequence of zeros in such cases.

- `melodyEngine()`: A dynamic component housing signal processing blocks applicable to transmission and reception stages. Tailored to each experiment and application, this block showcases distinct configurations.

- `melodyGRCLibraries()`: Housing the Gnu Radio Companion Libraries, this block establishes standardization for operations.

- `melodyReset()`: Offering the ability to reset acquisitions, this block is triggered when an experiment starts or when data loss or corruption is detected.

- `setStudentInfo()`: Similar to the description in the Services layer, this block shares user information.
- `getStudentInfo()`: As in the Services layer, this block retrieves user information.
- `addWidget()`: Incorporating widgets to visualize varying data or the same data in different domains (Time, I/Q, Frequency, etc.), this block enhances visualization flexibility.
- `dataUploader()`: Collecting data from the Platform layer and facilitating its transfer to the Services layer, this block supports efficient data movement.
- `setTimeOfUse()`: This resource sustains SDR component functionality during user-authorized periods.
- `reserveLab()`: Ensuring exclusive SDR component access for specific users, this resource maintains operational integrity.

3.4.4 Infrastructure

This component refers to the physical elements that support the system's operation. It includes SDR devices, antennas, and mechanisms for isolation. The selection of SDR hardware is made within the SDR Lab Station, allowing developers to choose the appropriate SDR hardware for their needs. This layer is composed by four integral elements.

- Isolation: This component pertains to the implementation of isolation mechanisms when scaling up the remote lab. RF transmissions can generate interference that affects other modules and compromises data quality due to elevated noise or spurious signals. Mechanisms for isolation can be achieved through both hardware and software means.
- SDR Lab Station: This element corresponds to the hardware aspect. SDR technology encompasses a diverse array of hardware options, each possessing unique features such as ADC bit count, transfer rate, channel count, noise figure, dynamic range, etc. Selecting an appropriate SDR hardware hinges on the specific RF application's requirements. The MELODY

model offers versatility by allowing integration of any SDR hardware within its framework, thus enabling users to operate seamlessly through various web interfaces. This component consists of four constituent parts, which are visually depicted in Figure 3.3 and elaborated upon subsequently.

  - Controller: Functioning within an embedded system like a Raspberry Pi, this firmware component commands the SDR Unit, issuing instructions for initiating or terminating transmissions. Its structure encompasses a runner and specialized GRC libraries.
  - SDR Unit: This entity encompasses hardware drawn from the SDR spectrum, varying from simple RTL devices to more intricate USRP units.
  - Transducer: This pertains to the antenna designated for transmission and reception functions. The selection of a suitable transducer hinges on the application's needs, ranging from straightforward antennas for wireless communication to larger ones essential for radar applications, which require focused beams and signal dispersion.
  - Non-cooperating Unit: This constituent is discretionary. In scenarios involving wireless communication, it typically holds less relevance, as both transmitter and receiver units cooperate in the communication process. Nonetheless, in use cases like radar systems, the target subject to analysis remains autonomous from the system and is consequently categorized as a non-cooperating unit.

- Ultra-Concurrent SDR Lab Station: This element comes into play when the remote lab is intended to operate in an ultra-concurrent manner. This configuration is typically chosen in SDR applications where resource consolidation is paramount, physical space is constrained, or when the components themselves are too large to be feasibly scaled. This scenario often arises in applications such as radar systems.

It's worth noting that initially, MELODY does not incorporate a camera web in the Infrastructure layer. This omission is rooted in the understanding that RF signals cannot be visually perceived by the human eye. Moreover, among the SDR remote projects analyzed in Section II, three of them do not utilize a camera. Similarly, the VISIR remote lab, renowned as the most popular remote laboratory for basic analog electronics, also operates without a camera for its functionality [49]. However, it's essential to highlight that a camera can be optionally added if a developer deems it advantageous for their specific application.

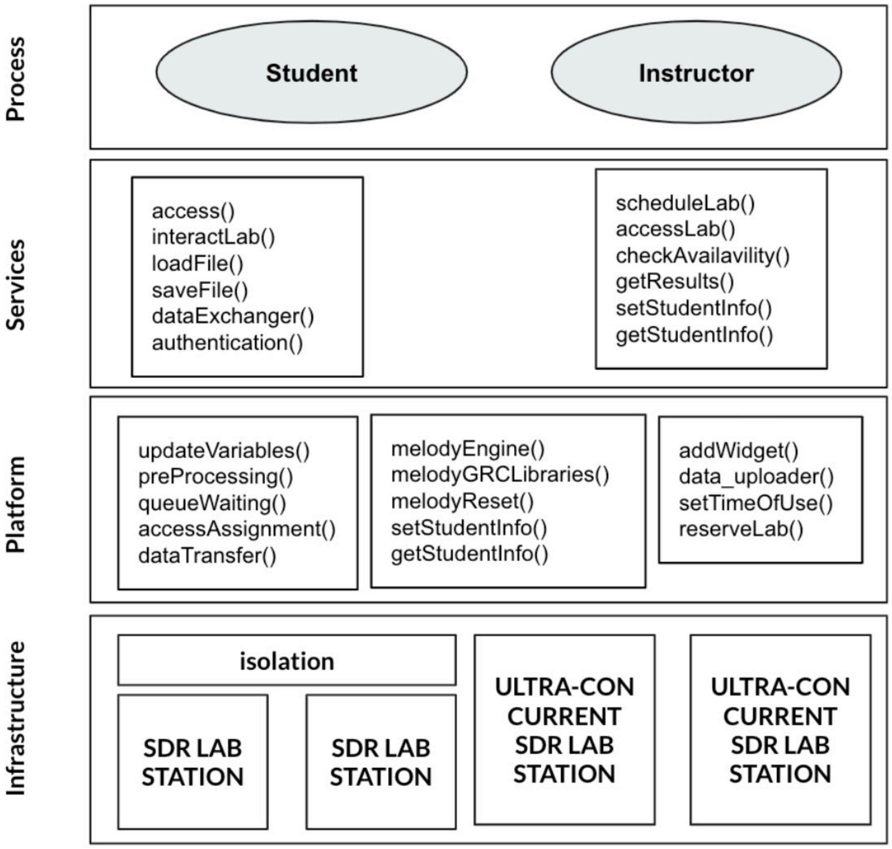

Figure 3.2: MELODY architecture and its components

3.5 Creation guidelines

In essence, the Creation guidelines serve as a comprehensive set of rules and recommendations for developing successful SDR lab projects. These guidelines encompass various aspects, including design principles, coding standards, best practices, and quality assurance procedures. These principles guide developers in creating SDR designs that meet the necessary timing requirements for an effective real-time SDR lab.

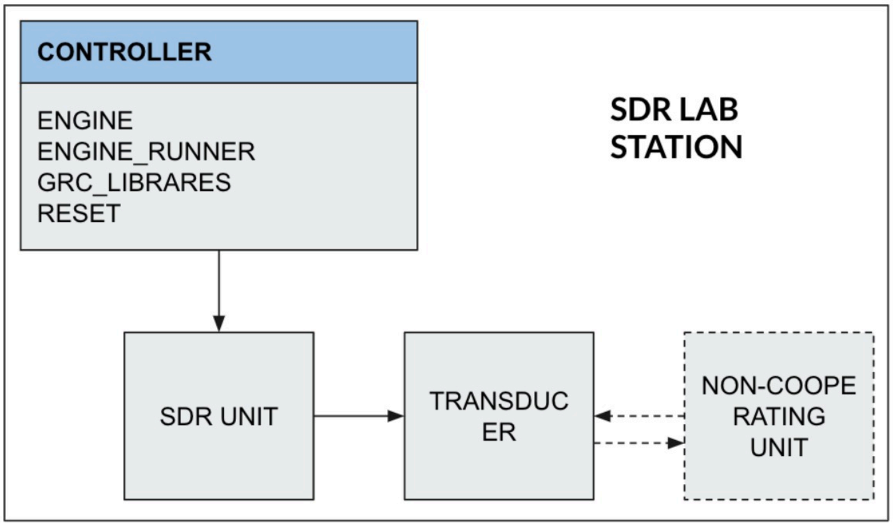

Figure 3.3: SDR Lab station - block of diagram

For instance, careful selection of appropriate SDR devices, antennas, and supporting hardware components is crucial to ensure optimal functionality and performance while avoiding data quality issues. Additionally, the development of software tools and platforms plays a vital role in facilitating data processing, visualization, and reliable data transfer to prevent any loss of information.

MELODY suggests to follow four guidelines when a SDR remote lab is going to be planed either to develop or to acquire. While these guidelines are technically optional, it is imperative to underscore that considerations such as the selection of Appropriate SDR Hardware and Scalability Concerns wield substantial influence over the overall cost associated with establishing a remote laboratory.

3.5.1 Choosing Appropriate SDR Hardware

Selecting the suitable SDR device empowers users to optimize their usage according to specific requirements. The selection of SDR devices for educational purposes hinges on variables such as the academic level (undergraduate or graduate) and the scope of the course. The SDR community provides an extensive array of devices, each differing in attributes such as bandwidth, transfer rate, channel count, external synchronization capabilities, dynamic range, and more [50].

3.5.2 Self Receiver Noise

Some SDR devices lack sufficient isolation to prevent transmitter (TX) leakage from causing internal interference or generating higher levels of noise. This issue can significantly impact the quality of received data, leading to a reduction in the minimum detectable signal and, consequently, affecting the signal-to-noise ratio (SNR) or signal-to-noise-plus-interference ratio (SNIR). A simple recommended solution is to disable the TX when it is not in use, a feature that most SDR devices offer.SDR allow this option.

3.5.3 Software Dependencies

Within an SDR application, users have the flexibility to set up their experiments through coding or by employing a graphical modeling and simulation environment. They can then analyze the outcomes by examining the streaming data generated. Such inputs and outputs might necessitate dedicated software, which could involve licensing prerequisites. At this juncture, developers need to deliberate on whether to utilize proprietary software or opt for open-source alternatives. For instance, SDR provides software like GRC (GNU Radio Companion), an open-source toolkit that grants users access to a wide array of SDR devices [35].

3.5.4 Platform Compatibility

When embarking on the development of an SDR remote lab, it becomes crucial to assess the technological tools available to users. Consequently, the choice of a system that ensures compatibility across diverse operating systems should be carefully deliberated.

3.5.5 Scalability Considerations

When making a decision about an SDR remote lab, it's essential to evaluate the projected user count. If there is a considerable user base, scalability options should be carefully considered. In this scenario, the concept of federated remote laboratories comes into play. This approach involves the interconnection and integration of multiple remote lab facilities, often located in diverse institutions or places, to form a cohesive system [48].

3.6 Datasets for standardized testing

Developers have the ability to perform unbiased performance assessments of SDR remote labs and to make meaningful comparisons with other implementations. SDR systems offer unique features that contribute to their performance capabilities and data quality. As a result, the datasets needed for testing and evaluating SDR applications may vary depending on the specific application or use case. MELODY suggests the following datasets for standardizing testing during the implementation of SDR in a remote laboratory.

By employing standardized evaluation methods and utilizing appropriate datasets, developers can assess the performance of their SDR remote lab in relation to others. This facilitates the identification of strengths and weaknesses, thereby fostering advancements in SDR technology and promoting its continuous improvement.

- Isolation. This refers to the mechanism and level of coexistence to ensure a proper qualitiy in data transmitted.

- Characterization. It referst to a characterization of the system in teh receiver.

- Lab scalability. It refers to the ability of a laboratory to increase the number of units. This might be measured by the numbers of users or adjusting the cost per unit to facilitate the creation of a larger network.

- Interoperatibility. It refers to the ability of the remote lab to operate with various SDR units within the same framework.

- Lab accessibility. This feature is developed in case study 3 (chapter 7), pertains to the method through which a user can access the remote laboratory.

- Lab usage session. It refers to the system provided by a laboratory to maximize the number of users who can access it simultaneously.

3.7 Classification Framework

The rating system of the classification framework ranges from 1 to 5 stars, reflecting the performance and quality of SDR remote labs. This rating system allows for a nuanced evaluation of various aspects of the labs, providing insights into their technical capabilities. According to the datasets for standardized testing the rubric is described as follow:

3.7.1 Isolation

MELODY establishes its own criteria for qualifying standards. Initially, a one-star rating is assigned for a SNIR value of 18 dB for BPSK communication or 20 dB for DPSK communication. Subsequently, each additional 3 dB exceeding this minimal threshold contributes an extra star to the evaluation. As a result, the rubric for isolation criteria is presented in Table 3.1, with the highest five-star rating extending from 27 dB for BPSK or 29 dB for DPSK to the point where the receiver reaches full scale (FS).

Table 3.1: Rubric Isolation Criteria - SNR levels

	1 star	**2 stars**	**3 stars**	**4 stars**	**5 stars**
BPSK	[0, 18[dB	[18, 21[dB	[21, 24[dB	[24, 27[dB	[27, FS] dB
DPSK	[0, 20[dB	[20, 23[dB	[23, 26[dB	[26, 29[dB	[29, FS] dB

3.7.2 Characterization

In accordance with the rubric, users must complete at least five out of six characterization tests to attain a five-star rating. These tests encompass assessments of linearity, receiver constancy, input and output noise power, minimum detectable signal, frequency stability, and receiver delay. Characterization procedures can be carried out either automatically or manually by users each time the system initializes. However, certain characterization steps may necessitate costly instrumentation. Therefore, MELODY implements a scoring system that assigns stars based on the completion of these procedures, as depicted in Table 3.2.

Table 3.2: MELODY's rubric - Characterization

Rubric	**Evaluation**
5 stars	5 or more characterization tests
4 stars	4 characterization tests
3 stars	3 characterization tests
2 stars	2 characterization tests
1 star	1 characterization test

3.7.3 Lab scalability

The scalability of the distributed remote lab will be evaluated based on the cost of each SDR and computer unit, a critical factor for determining the feasibility of expanding the setup with additional units. A literature review has revealed that the minimum cost for a single remote lab setup is $2400. Additionally, the integration of a federated remote lab feature in an SDR remote lab significantly enhances scalability, as it permits access by two or more institutions concurrently. The criteria for assessing scalability are outlined in Table 3.3.

3.7.4 Interoperability

Interoperability, within the context of MELODY, denotes the ability of a remote lab to support a wide variety of SDR devices. MELODY's rating system awards a five-star rating to labs that offer compatibility with five or more types of SDR, as outlined in Table 3.4.

3.7.5 Lab Accessibility

The accessibility of the remote lab will be evaluated based on the type of software required for user access and configuration. The level of accessibility will be assessed using a 5-star rating scale, as summarized in Table 3.5.

3.7.6 Lab Ussage sessions

The evaluation of Lab Usage will be based on the system provided by the lab to maximize the number of users. The rubric used to assess this metric is summarized in Table 3.7.

Table 3.3: MELODY's rubric - Lab Scalability

Rubric	**Evaluation**
5 stars	The laboratory provides units that are installed in shared institutions and the cost of each unit is below \$2000.
4 stars	The laboratory provides units that are installed in shared institutions and the cost of each unit exceeds \$2000.
3 stars	The laboratory provides units that are installed in one institution and the cost of each unit is below \$2000.
2 stars	The laboratory provides units that are installed in one institution and the cost of each unit exceeds \$2000.
1 star	The laboratory provides only one unit and is not scalable.

Table 3.4: MELODY's rubric - Interoperability

Rubric	**Evaluation**
5 stars	5 or more types of SDR
4 stars	4 types of SDR
3 stars	3 types of SDR
2 stars	2 types of SDR
1 star	1 type of SDR

3.8 Example of rubric - classification framework

The classification framework allows for quantitative comparisons between different remote laboratories, focusing on both their SDR features and general lab characteristics. Table 3.9 illustrates

Table 3.5: MELODY's rubric - Accesibility of the laboratory

Rubric	**Evaluation**
5 stars	The lab can be accessed remotely through a web browser, eliminating the need for software installation on the student's computer.
4 stars	Remote access is available through specialized software that requires installation on the student's computer.
3 stars	The lab can be accessed on-campus, enabling students to use it without installing any software on their computers.
2 stars	The lab consists of a kit of devices that students can take home, but it necessitates software installation on their computers.
1 star	Access to the lab is restricted to on-campus only, and students must install software and drivers on their computers to use it.

Table 3.7: MELODY's rubric - Lab usage session

Rubric	**Evaluation**
5 stars	The duration of each lab session is optimized to maximize throughput, regardless of the number of users.
4 stars	The duration of each lab session is short to ensure accessibility.
3 stars	The duration of each lab session is long without considering others' accessibility.
2 stars	Students must wait until others finish using the lab without time control.
1 star	Students must go Campus to access the laboratory.

these comparative results. The first five columns provide a summary of how the MELODY model's rubric was applied to the five laboratories discussed in Chapter 2. The last two columns introduce case studies that are explored in greater detail in the subsequent chapters.

Table 3.9: Classification framework rubric - Comparison of 7 SDR lab projects

	EMONA-TIMS	**Huazhong**	**Cluj-Napoca**	**Hyderabad**	**FORGE**	**RHL-RELIA**	**RHL-RADAR**
Isolation	★★★★★	Not known	☆☆☆☆☆	Not applicable	Not known	★★★★★	Not applicable
Characterization	Not applicable	Not known	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Interoperability	Not applicable	Not applicable	☆☆☆☆☆	☆☆☆☆☆	Not known	★★☆☆☆	Not applicable
Lab scalability	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★☆☆☆☆	★★☆☆☆	★★★★★	★☆☆☆☆
Lab Accessibility	★☆☆☆☆	★★★★★	★★★★☆	★★★★☆	★★★★☆	★★★★★	★★★★★
Lab Usage	★☆☆☆☆	★★☆☆☆	★★☆☆☆	★★☆☆☆	★★★☆☆	★★★★★	★★★★★

3.9 Conclusions of the Chapter

MELODY's creation was driven by the need to address technical challenges, promote interoperability, and enhance the modularity and flexibility of SDR systems. Through a layered approach and shared terminology, MELODY offers a comprehensive framework for developing, executing, and evaluating SDR projects. From four categories from MELODY architecture and shared terminology encompasses distinct components, including processes, services, platforms, and infrastructure, each playing a vital functionality of SDR remote labs. Creation guidelines provide developers with a structured set of rules and recommendations for designing successful SDR lab projects, ensuring compatibility, scalability, and optimal performance.

In standardized testing datasets and a classification framework, tests are described for objectively evaluating SDR remote labs. By utilizing suitable datasets and rating systems, developers can evaluate the performance and quality of their labs, pinpoint areas for enhancement, and contribute to the ongoing progress of SDR technology.

Chapter 4

MELODY - RUBRIC FOR CLASSIFICATION FRAMEWORK

This chapter is a modified version of Section IV in [22]:

- **Inonan**, M., and Hussein, R., ”MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology,” in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399.

4.1 Overview

Engineering metrics serve as quantifiable indicators that measure the level of quality and capabilities of remote lab designed. This classification framework gathers, categorizes, and organizes the diverse aspects and characteristics of SDR remote applications. MELODY employs a five-level classification system for quality assessment, encompassing isolation, characterization, scalability, availability, and usability with each one being rated on a scale of 1 to 5 stars according to the features it incorporates.

4.2 Isolation

Addressing isolation is crucial, especially when dealing with interference that arises when multiple SDR units operate simultaneously within the same or nearby bandwidth. This situation is common in scalable remote labs [51] or in confined lab spaces.

Current literature lacks standardized metrics for addressing interference concerns specific to SDR remote laboratories. However, insights from other radio networks can inform the analysis of this issue through coexistence strategies. These approaches ensure that multiple communication devices can operate concurrently without compromising data quality [52].

Effective techniques have been developed for wireless communication standards like WiFi and Bluetooth coexistence. For instance, Adaptive Frequency Hopping (AFH) enables Bluetooth devices to dynamically switch between frequency channels, preventing interference with WiFi transmissions. Conversely, Dynamic Frequency Selection (DFS) allows WiFi devices to detect and avoid radar signals and other interference, minimizing disruptions to Bluetooth devices [53,54]. To gain a deeper understanding of this issue, each concept will be defined before reviewing coexistence strategies.

4.2.1 Multi-radio network

In wireless networking, multi-radio networks can be classified into two categories: homogeneous and heterogeneous setups. In a homogeneous setup, all devices share similar characteristics, whereas in a heterogeneous setup, devices possess diverse capabilities, protocols, or technologies. For example, an SDR remote lab network can act as heterogeneous due to its flexibility in employing various modulation techniques and a wide range of frequencies.

4.2.2 Path loss

When an RF signal propagates, its strength decreases. Path loss (L_{pl}) describes signal strength as a function of distance. For Line-Of-Sight (LOS) communication in outdoor environments, free-space (L_{pl}) is used. An empirical path loss model at 2.4GHz [55] for indoor scenarios is defined as:

$$L_{pl} = \begin{cases} -40.0 - 20\log(d), & (d \leq 8) \\ -58.5 - 33\log(d/8), & (d > 8) \end{cases}$$

where L_{pl} is the path loss in (dB) and d is the distance in meters.

4.2.3 Coexistence Fundamentals

Coexistence occurs when multiple radio interfaces are collocated and operate simultaneously within a multi-radio platform, sharing the same or nearby frequency band in the same physical location without causing harmful interference to each other [56]. One of the key parameters used to assess the performance of a multi-radio system is the signal-to-interference-plus-noise ratio (SINR) [57].

Maximizing SINR is desirable in a multi-radio platform. However, three potential interference mechanisms—receiver blocking, transmitter noise, and inter-modulation—can degrade SINR [55]. Understanding these interference phenomena is crucial for designing robust wireless systems that can coexist effectively in shared frequency bands.

4.2.3.1 Receiver Blocking (D)

Receiver blocking occurs due to the limited dynamic range of the power amplifier and A/D converter in the receiver. It happens when a transmitting antenna (interferer) is near a collocated antenna. If the interfering signal strength surpasses a certain threshold, it can drive the receiver's Low Noise Amplifier (LNA) to its compression point, resulting in a reduction in gain and potentially increasing the LNA's noise figure [58]. If the cumulative input power at the receiver exceeds the blocking threshold P_{3dB}, it leads to degradation in the received signal strength [59].

For example, in simultaneous communication between systems A and B, the degradation that system B's transmitter causes in system A's receiver can be represented as:

$$D(P_B) = \max\big\{0, (P_{in,A} - P_{A,3dB})\kappa + 3\big\} \tag{4.1}$$

Where $P_{in,A}$ indicates the power input in receiver A, $P_{A,3dB}$ is the blocking threshold of A's receiver, and κ is the dB value of the degradation of the received signal strength for every dB increase of input power [60]. In a generalized network with M radio systems, as illustrated in Figure 4.1, Equation 4.2 can be formulated to estimate the degradation produced by the system in receiver A:

$$D(P_{B,C,\ldots,M}) = \max\big\{0, \Big(\sum_{n=1}^{M} P_n - L_A - P_{A,3dB}\Big)\kappa + 3\big\} \tag{4.2}$$

$P_{A,3dB}$ is estimated experimentally. In Bluetooth applications, it is calculated by receiving the desired signal with a power of 3 dB above the reference sensitivity level. Then, an interfering signal (a continuous wave) is applied until the BER is $\leq$ 0.1%. The power of this interfering signal represents the blocking threshold [61]. Following a similar approach, MELODY proposes to calculate this value by conducting a BPSK transmission with a receiver power twice the receiver noise level. Subsequently, an interfering signal is inserted until the BER reaches 10^{-2} or less. Alternatively, parameters such as Packet Reception Ratio (PRR) can also be utilized until it reaches less than 99% [62].

The degraded signal power $P_{A,RX}$ in the receiver A can be represented as:

$$P_{A,RX} = P_{TX_A} - L_{pl,A} - D(P_{B,C,\ldots,M}) \tag{4.3}$$

Where P_{TX_A} represents the power transmitted by transmitter A and $L_{pl,A}$ signifies the free-space propagation loss of A's receiver.

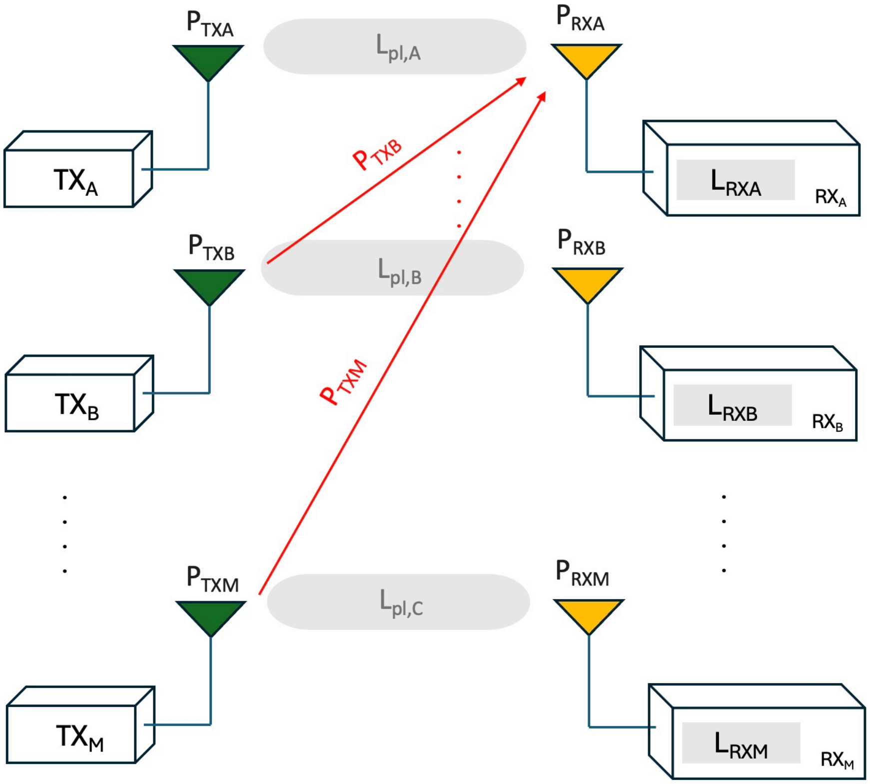

Figure 4.1: SDR Distributed network

4.2.4 Transmitter Noise (I_{OOB})

Also known as adjacent channel selection (ACS), this phenomenon refers to the out-of-band emissions detected by receivers in close proximity to a transmitter. These emissions occur due to imperfect filtering at the transmitter antenna. The transmitter generates out-of-band (OOB) emissions denoted as I_{OOB} [59].

4.2.5 Inter-modulation Interference (I_{IM})

Represented as I_{IM}, this interference is caused by non-linearity in the signal path of radio components, such as amplifiers that generate harmonics. These interference can be clasified by the order of inter-modulation. Second-order are generated by integer multiples of the fundamental frequency of signals and the sum and difference of them. In the case of two frequencies, f_1 and f_2 (referred to as first-order inter-modulation products) these two frequencies mix together produce $f_1 + f_2$, $f_2 - f_1$, $2f_1$, $2f_2$, $f_1 + f_2$, and $f_2 - f_1$. An example is shown in Figure 4.2.

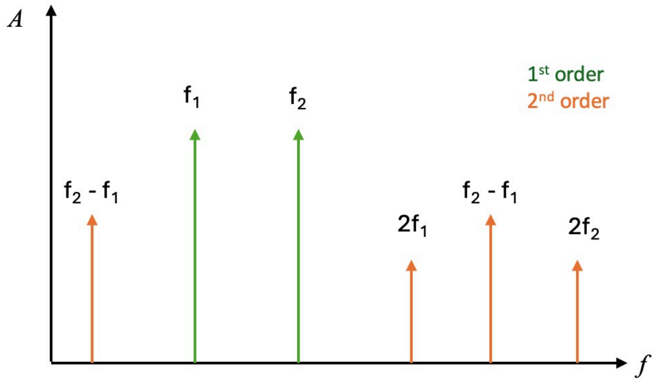

Figure 4.2: 1st and 2nd order inter-modulation frequency

The third order is the result of combining the second-order products, $2f_1$ and $2f_2$, with the first-order products, f_1 and f_2. This combination yields new frequencies, two of which are $2f_1 - f_2$ and $2f_2 - f_1$. The third-order products are the most problematic because they appear near the input frequencies, f_1 and f_2, as shown in Figure 4.3, making them difficult to filter out.

In a multi-radio system, inter-modulation interference occurs when the inter-modulation bandwidth, resulting from a pair of concurrent and nearby transmissions, overlaps with the receiver channel bandwidth. For example, if two systems A and B have carrier frequencies f_A and f_B respectively, each transmitting a signal where $f_A < f_B$, third-order intermodulation interference will occur at $f_A - (f_B - f_A)$ and $f_B + (f_B - f_A)$. Its power can be expressed as a function of the power of the input signals $P(f_A)$ and $P(f_B)$ [55].

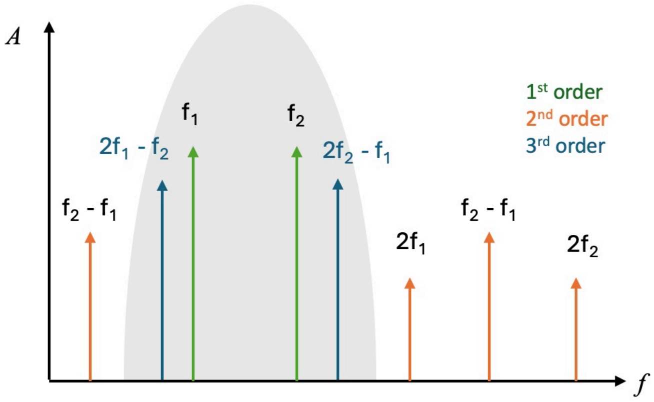

Figure 4.3: 3rd order inter-modulation frequency

$$I_{IM}(f_A - (f_B - f_A)) = 2P(f_A) + P(f_B) - 2IP3 + 10\log_{10}(f) \tag{4.4}$$

$$I_{IM}(f_B + (f_B - f_A)) = 2P(f_B) + P(f_A) - 2IP3 + 10\log_{10}(f) \tag{4.5}$$

Where f indicates the overlapping ratio obtained between the separation of $(f_B - f_A)$ and the IM bandwidth of the signal. $f = 0$ indicates that there is no overlapping, so IM is negligible. As for $IP3$, it is the imaginary point where the four frequency components f_A, f_B, $2f_B - f_A$, and $2f_A - f_B$ will be at the same power level and $f = 1$. This method must be generalized in a multi-radio system, as shown in Figure 4.1, by calculating the inter-modulation between receiver A and every other receiver.

4.2.6 Self-reception interference (I_{SR})

Certain SDR devices are equipped with both TX (transmit) and RX (receive) outputs, boasting full-duplex capabilities. However, this setup presents a challenge known as self-interference. When a radio transmits a signal, a leakage occurs, causing a portion of that energy to be captured by its own receiver. This can potentially overpower the desired received signal. Despite being a recognized issue in radio design, this challenge remains unresolved, leading radios to operate in either transmit or receive mode on a given frequency but never both simultaneously [63].

Coexistence in a multi-radio system is deemed successful when the power of the desired signal surpasses that of the interfering signals. This assessment is typically conducted using the SINR, a metric in telecommunications and signal processing for evaluating signal quality amidst noise and interference. The SINR metric is frequency-dependent, meaning that its value can differ for different frequency values within the communication system. Therefore, the SINR assessment is typically conducted for specific frequencies or frequency ranges of interest to evaluate signal quality amidst noise and interference. Zhu et al. [55] defined SINR for heterogeneous devices, where a receiver “x” is interfered with by transmitter “y,” defined as follows:

$$SINR = \frac{S/10^{D/10}}{N_0 + (I_{OOB} + I_{IM})/10^{D/10}} \tag{4.6}$$

Where S represents the received signal strength in receiver “x” without coexistence, D is the Receiver blocking of receiver “x”, N_0 is background noise of receiver “x”, and $I_{OOB,n}$ and $I_{IM,n}$ represent the transmitter noise and intermodulation interferences generated by transmitter “y” in receiver “x” respectively.

In the same vein, in a multi-radio system comprising M transmitter-receiver units, and including the self-receiver interference, SINR in a receiver “x” the preceding equation can be modified as follows:

$$SINR_x = \frac{S/10^{D/10}}{N_0 + \left\{I_{SR,x} + \sum_{i=1,i\neq x}^{M}(I_{OOB,n} + I_{IM,n})\right\}/10^{D/10}} \tag{4.7}$$

Where $I_{OOB,n}$ and $I_{IM,n}$ denote the interference arising from transmitter noise and transmitter ”n” intermodulation, respectively, and $I_{SR,x}$ denotes the self-receiver interference in receiver “x”

considered only for the energy that falls within the band-pass of desired signals

4.2.7 Faraday Cage Isolation

In a distributed SDR remote lab, SDR devices are typically grouped in TX-RX pairs and exclusively communicate with one another. However, simultaneous access by multiple users to the remote lab, particularly when they work on the same frequency due to shared lab materials, can degrade signal transmission, resulting in a lower SINR. A practical solution to mitigate this issue is to enclose each pair of devices with electro-textile metallization material, forming a Faraday cage. With an efficient enclosure, Equation 4.7 simplifies to:

$$SINR_x = \frac{S/10^{D/10}}{N_0 + \{I_{SR,x} + I_{OOB,y} + I_{IM,y}\}/10^{D/10}} \tag{4.8}$$

This equation shares similarities with Equation 4.6, where interference is only caused by the adjacent transmitter unit, but it incorporates I_{SR}, representing the self-receiver interference.

An example of such material is the RadioScreen A1240, composed of nickel/copper-coated polyester, offering high transparency (important for remote labs requiring a camera to focus on the SDR device). It has a surface resistance of $\leq 0.1\ \Omega/sq$, a thickness of 0.09 mm, and according to its manufacturer, an isolation of 50 dB between 10 MHz and 3 GHz [64, 65].

4.2.8 Estimating SINR through observation

Estimating SINR is inherently dependent on frequency and typically requires specialized equipment that can operate across a wide range of frequencies. An alternative approach involves conducting the test through observation in the frequency domain. Insights from similar experiments in various engineering contexts can provide valuable guidance. For example, manufacturers of Analog Digital Converters (ADCs) often provide detailed technical specifications, including information about interference within their products. One crucial metric in this regard is the Spurious Free Dynamic Range (SFDR), which evaluates the converter's ability to differentiate between the desired signal and any extraneous spurious signals in the output [66]. Figure 4.4 illustrates this concept. However, it's important to note that the reliability of this method is limited, as it may show results outside the linear region.

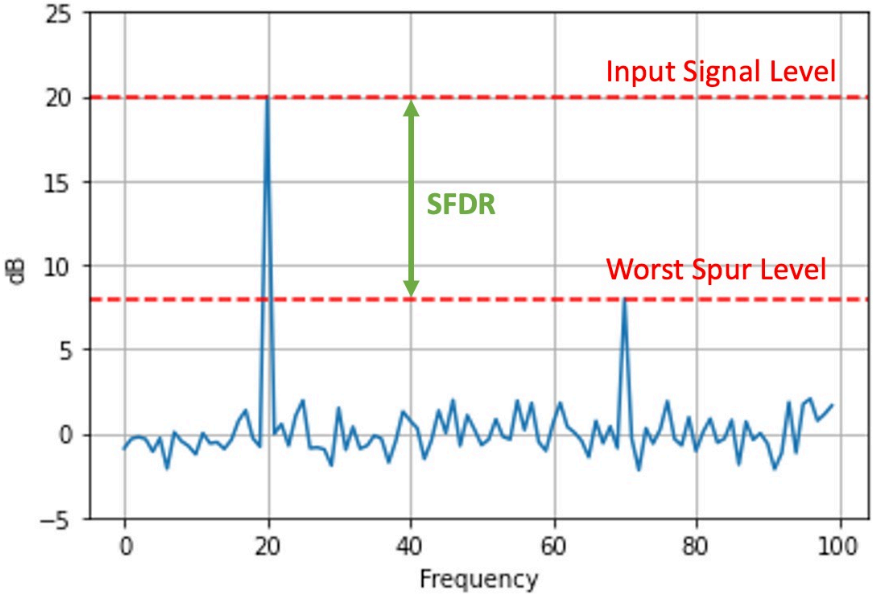

Figure 4.4: Spurious Free Dynamic Range (SFDR)

4.2.9 Analysis of BER and SINR

The higher the SINR, the better the quality of the received signal. The success of this can be assessed through an analysis of the Bit Error Rate (BER), which is defined as the rate at which errors occur in a transmission system. This can be directly translated into the number of errors that occur in a string of a specified number of bits [67]. The definition of bit error rate can be expressed using a simple formula:

$$BER = \frac{\text{Number of Bit Errors}}{\text{Total Number of Bits Transmitted}} \tag{4.9}$$

Efforts have been made to mathematically link BER with SINR for specific wireless protocols. However, this task is challenging due to the absence of an exact function to directly convert SINR to BER. The complexity arises from factors such as the protocol's multiple access scheme, synchronization algorithm, packet format, and error control coding. For example, [68] obtained a relation between them through simulations using the QualNet simlator [69] shown in Figure 4.5. They are called mapping functions to approximate the conversion.

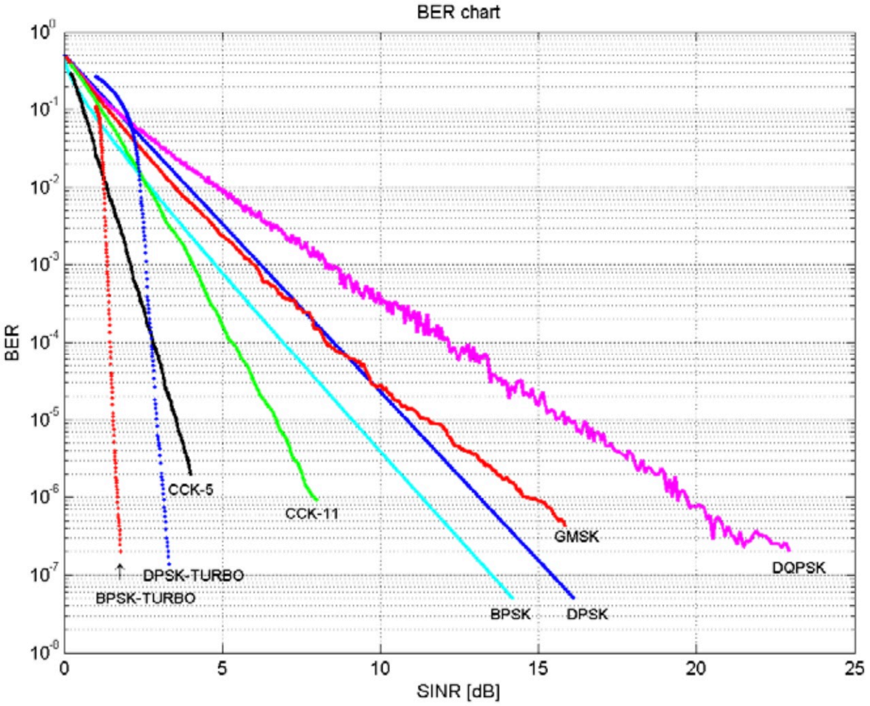

Figure 4.5: The conversion map of the SINR to BER using Qualnet at 2.4GHz. Source: Adapted from [68].

The relationship between BER and SINR for Differential Phase Shift Keying (DPSK) communication at 2.4GHz was derived by Go et al. [68] as follows:

$$BER_{DPSK} \approx 0.5 \times \left(10^{\mathrm{SINR}/10}\right)^{-4.3429} \tag{4.10}$$

Similarly, an equation for Binary Phase Shift Keying (BPSK) from the data shown in Figure 4.5 can be derived as follows:

$$BER_{DPSK} \approx 0.074 \times \left(10^{\mathrm{SINR}/10}\right)^{-4.3478} \tag{4.11}$$

In wireless communication systems, a common standard for the maximum acceptable bit error rate is 10^{-9}. This implies that the receiver can produce a maximum of 1 error in every 10^9 bits of transmitted information [70]. Substituting this value of BER into equations 4.10 and 4.11 we obtain the results shown in Table 4.1.

Table 4.1: SNIR for to achieve a BER = 10^{-9}

SNIR$_{BPSK}$	18.10 (dB)
SNIR$_{DPSK}$	20.03 (dB)

4.3 Characterization

Characterization of RF devices ensures that the receiver provides accurate measurements and readings. This is crucial in various wireless applications, such as communication systems and radar applications, where precise data is essential for proper signal processing and analysis. Within the MELODY framework, five essential engineering methods (Linearity, Receiver Constant, Input and Output Noise Power, Minimum Detectable Signal, and Frequency Stability) are introduced for proper characterization.

4.3.1 Linearity of the Receiver

A receiver is considered linear when there exists a constant proportion between the input and output, inclusive of any associated noise. This test determines whether the receiver operates in a linear manner. Linearity is expressed in equation 4.12 as presented in [71].

$$S_{out}(t) + N_{out}(t) = G_{RX}(S_{in}(t) + N_{in}(t)) \tag{4.12}$$

where:

S_{in} = Input Signal Power.

S_{out} = Output Signal Power.

N_{in} = Input Noise Power.

N_{out} = Output Noise Power.

G_{RX} = Power Gain of the receiver.

Ideally, linearity should be maintained within a certain range. However, this doesnt keep at the minimum and maximum levels. Near the maximum level there is a portion where the input signal exceeds a certain level, the output signal begins to exhibit soft-limiting or compression. A critical parameter to consider in this context is the 1 dB compression point. This point signifies the level at which the output signal becomes compressed by 1 dB compared to an ideal input/output transfer function. The compression phenomenon is depicted in Figure 4.6, where the transition from the ideal (dotted) to the actual response curve (solid) indicates the onset of compression.

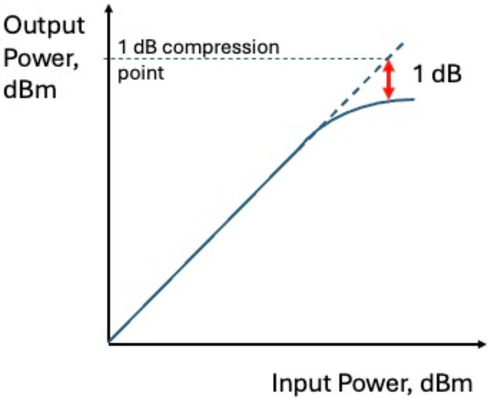

Figure 4.6: 1 dB compression point

In digital receivers, the output is not measured in dBm as it can be in the input; instead, Arbitrary Digital Units (ADU) are used. Therefore, the 1 dB compression point must be redefined, where the output no longer follows linearity and begins attenuating by 80%, which is equivalent to a 1 dBm compression in power units.

At the lower limits of a receiver, linearity is less accurate due to the influence of internal noise levels, which can distort the input signal. This can be seen in Figure 4.7.

Typically, the 1 dB compression point varies with frequency, with distortion becoming more pronounced at higher frequencies [72]. Therefore, it is advisable to conduct the test at a frequency

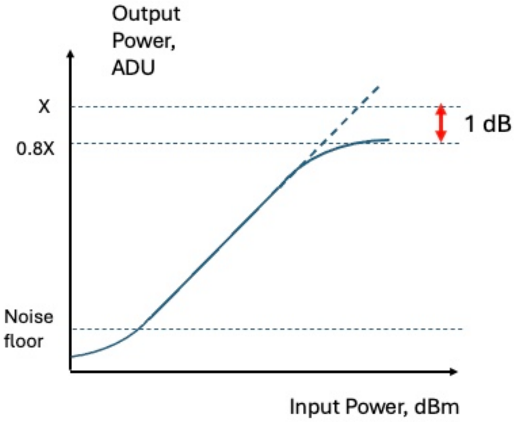

Figure 4.7: 1 dB compression point for digital receivers

recommended for typical receiver operation. While the input power can be easily calculated from a test signal, determining the output power requires considering both the in-phase (V_{out_I}) and quadrature (V_{out_Q}) components of the acquired I/Q signal:

$$P_{out} = \sqrt{V_{out_I}^2 + V_{out_Q}^2} \tag{4.13}$$

where $Vout_I$ and $Vout_Q$ are the components of the I/Q signal acquired.

4.3.2 Receiver Constant

Once it's established that the receiver operates linearly, the Receiver Constant (RC) can be calculated. RC is a parameter that quantifies the relationship between the input and output power of the receiver. This input power of the receiver is sourced from a Signal Generator or Function Generator device, which produces a Test Signal Power in watts. It's crucial that this generator can be precisely calibrated and adjusted in milliwatt increments.

On the other hand, the measured output power of the receiver depends on the receiver bits resolution and it will be tested in ADU. Consequently, RC is mathematically represented as:

$$RC = \frac{Test\ Signal\ Power\ [W]}{Measured\ Output\ Power\ [ADU]} \tag{4.14}$$

Experimentally, the RC coefficient can be modeled using linear regression estimation. Therefore, with the array of inputs and outputs from the measurements, the RC can be accurately estimated as follows:

$$RC = \frac{N \sum_{i=1}^{N} P_{in,i} P_{out,i} - \sum_{i=1}^{N} P_{in,i} \sum_{i=1}^{N} P_{out,i}}{N \sum_{i=1}^{N} P_{in,i}^2 - (\sum_{i=1}^{N} P_{in,i})^2} \tag{4.15}$$

where N is the number of measurements, $P_{in,i}$ and $P_{out,i}$ denote the input power and output power measurements in watts, respectively. Additionally, to assess the precision of linearity, the coefficient of linear regression can be calculated using the inputs and outputs measurements, employing the following expression:

$$R = \frac{\sum_{i=1}^{N} (P_{in,i} - \bar{P}_{in})(P_{out,i} - \bar{P}_{out})}{\sqrt{\sum_{i=1}^{N} (P_{in,i} - \bar{P}_{in})^2 \sum_{i=1}^{N} (P_{out,i} - \bar{P}_{out})^2}} \tag{4.16}$$

Where $\bar{P}_{in}$ and $\bar{P}_{out}$ represent the mean input and output power, respectively.

To ensure reliable measurements, the Test Signal Power must surpass the receiver noise by at least twice its power or 3dB more in order to disregard the noise term. The constancy of RC is pivotal for maintaining precise calibration, as emphasized in [73]. Ideally, this value should be set to one. Nonetheless, if it deviates, the RC value is utilized to transform the detected output power of an actual signal back to its corresponding input power.

4.3.3 Input and Output Noise Power

The input and output noise power of a digital receiver are critical factors that impact its performance in various communication systems. When a receiver's input is properly terminated with a matched load, the input noise can be expressed by the equation:

$$N_{IN} = T_0 k_B B \tag{4.17}$$

where:

N_{IN} = Input Noise Power in Watts.
T_0 = Temperature of the environment in Kelvin.
k_B = Boltzman constant ($1.38 \times 10^{-23} J/K$)
B = System Bandwidth in Hz

Regarding the calculation of output power noise, it can be estimated as the product of the measured noise power and the previously calculated RC:

$$N_{OUT} = Measured\ Noise\ Power\ [ADU] \times RC \tag{4.18}$$

where:

N_{OUT} = Output Noise Power in Watts.
ADU = Arbitrary Digital Units.
RC = Receiver constant.

For comprehensive insights into both N_{IN} and N_{OUT}, along with the derivation of these equations, refer to [74].

4.3.4 Minimum Detectable Signal

Minimum Detectable Signal (MDS) defines the sensitivity of a receiver. It denotes the starting point of the linear region, and it can be considered as equal to N_{OUT} . In some applications, MDS is typically defined as twice the value of N_{OUT} or with an additional 3dB margin. Measurement of this parameter is detailed in [75].

4.3.5 Frequency Stability

Another examination conducted on SDR devices, particularly those without an external clock enabled, is the frequency stability test. This test evaluates the device's ability to maintain a specific frequency consistently without experiencing drift over time. Digital transceivers operate at their frequency based on an internal oscillator, which is sensitive to external parameters such as temperature, voltage supply, and aging [76].

Transceiver manufacturers provide the frequency along with the ppm (parts per million) value, indicating the potential deviation of the crystal's frequency from the nominal value. There are several methods to assess this statistical stability. One intuitive method involves using a spectrogram, which plots the spectrum of frequencies of a signal as it varies over time. Conducting this experiment requires access to a Signal Analyzer equipment with a lower ppm [77].

4.3.6 Delay of a receiver

In certain applications, calculating the delay caused by receiver's sytem is crucial. This is particularly significant in radar applications, where measurements such as height or range are determined based on the time taken for the transmitted signal to return. The delay has both analog and digital components, as illustrated in the simplified diagram in Figure 4.8 and represented by the following equation:

$$\tau_{total} = \tau_{analog} + \tau_{digital} \tag{4.19}$$

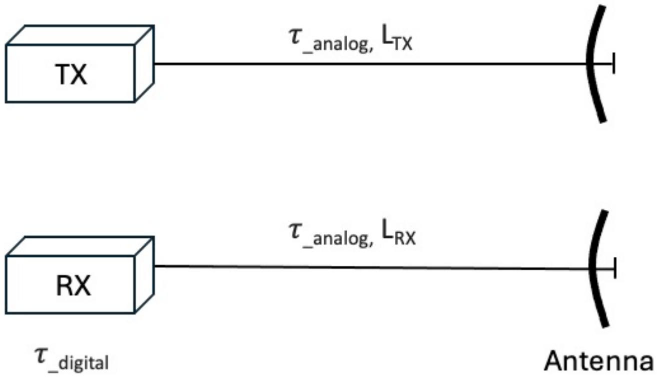

Figure 4.8: Radio System

The analog delay primarily stems from the wires used to connect the transmitter or receiver to the antenna, especially when antennas are positioned far from the operational center. While electromagnetic waves in air travel at the speed of light, their velocity is reduced within coaxial cables due to a factor known as the velocity factor. For instance, in coaxial cables, this factor is approximately $\frac{2}{3}c$, where c represents the speed of light [78]. The delay caused by cables can be calculated in microseconds using the following expression:

$$\tau_{analog} = \frac{(\text{velocity factor})(\text{Lc})}{c} \tag{4.20}$$

where c represents the speed of light and L_c is the total length of cables that connect transmitter and receiver with antennas.

The digital delay is caused by to the Digital receiver integrated circuit which has a latency produced by its different internal stages (registers and filters). Normally each digital filter has a latency that depend on the filter order and sampling Frequency, it can be calculated

$$\tau_{digital} = \sum_{i=1}^{L} \frac{N_i}{2} \times \frac{1}{f_{s,i}} \tag{4.21}$$

where L is the number of filters blocks, N_i is the filter order or number of taps of filter i and $f_{s,i}$ is the input sampling clock frequency (before any decimation) of each filter i.

Digital receivers typically incorporate filters to decimate the sampling rate, with the final stage often featuring a Finite Impulse Response (FIR) filter with multiple taps. The delay of the FIR filter dominates due to its numerous taps and lower sampling frequency. Therefore, for a rough estimation, the delay can be approximated considering only the contribution of the FIR filter delay [79]. Then equation 4.21 will be simplified to:

$$\tau_{digital} = \frac{N_{Taps}}{2} \times \frac{1}{f_{s,FIR}} \tag{4.22}$$

Where N_{Taps} and $f_{s,\text{FIR}}$ represent the number of taps used and the sampling frequency at the input of the FIR filter, respectively.

4.4 Lab Scalability

The scalability of a lab is closely tied to its affordability, particularly concerning the prices of SDR devices and computers. Higher prices for these components can pose financial challenges when attempting to scale up the lab by adding more stations. This aspect is particularly relevant in the comparison between remote and traditional laboratories, where cost influences are a significant trend.

Remote laboratories offer a distinct advantage in terms of cost savings compared to conventional laboratories. This advantage is highlighted by Heradio et al. (2016) [80], emphasizing the constrained physical spaces within which remote labs are established. These cost savings are crucial in enabling the scalability of remote labs, as they allow for more stations to be deployed within a given budget.

One strategy to enhance scalability without requiring additional resources is the implementation of federated remote labs. This cooperative approach integrates multiple remote laboratory installations into a cohesive system, as described by Fernandez et al. (2013) [81]. Federated remote labs provide users with access to resources from diverse configurations, effectively increasing the number of available units without incurring additional costs. Components such as servers, cameras, and software licenses are also essential in remote labs.

In the context of MELODY, scalability is evaluated based on the cost of SDR devices and computers. By considering the affordability of these components, MELODY assesses the lab's scalability and its ability to expand in a cost-effective manner.

4.5 Lab Interoperability

Rating interoperability based on the types of SDR devices used in the lab acknowledges the importance of providing users with a diverse, flexible, and collaborative environment while ensuring the lab's relevance and adaptability in an ever-changing technological landscape [82].

A greater variety of SDR devices allows users to experience different hardware capabilities, interfaces, and features, catering to diverse research needs and preferences. For instance, certain SDR devices may excel in specific applications or frequency bands, enabling users to select the most suitable hardware for their experiments. This versatility promotes more exploration of SDR technology.

Moreover, interoperability fosters collaboration among researchers and institutions using different equipment, data exchange, and collaborative projects. By supporting multiple types of SDR devices, the lab encourages interdisciplinary collaboration and enhances the potential for innovation and discovery.

Furthermore, the field of SDR technology is continuously evolving, with new devices and advancements being introduced regularly. By accommodating a diverse range of SDR devices, the lab ensures that it remains relevant and adaptable to emerging technologies, thus future-proofing its infrastructure. MELODY acknowledges the importance of interoperability by awarding ratings based on the number of distinct types of SDR devices supported by the lab, reflecting its commitment to providing users with a versatile and inclusive environment for research and experimentation.

4.6 Lab Accessibility

Lab accessibility is an aspect of remote laboratories, reflecting how users can effectively utilize the available resources. Insights from Case Study #3 on Digital Inequalities highlight the importance of the interface's familiarity and ease of use in determining the lab's accessibility.

Adopting a web-based interface for accessing remote labs ensures equitable access for all users, irrespective of their technological background or resources. Moreover, this approach allows students to continue using their existing computers, eliminating the need to purchase new ones that support specific software. This aspect is particularly crucial for students from low-income families, as it reduces financial barriers to accessing remote laboratory resources.

Given these benefits, MELODY awards remote labs with a five-star rating when they provide a graphical user interface accessible through a web browser.

4.7 Lab usage sessions

The availability of scheduling and time distribution options in the remote lab is of utmost importance for various reasons. First and foremost, it ensures equitable access to lab resources, allowing all users to utilize them fairly and efficiently [83].

The MELODY rubric for lab usage sessions serves as a quality measure to ensure that SDR remote labs meet specific performance standards. Optimizing the duration of each session to maximize throughput regardless of the number of users can lead to more effective lab operations.

A straightforward yet impactful approach is to allocate users a brief window during which they can execute the lab while preparing their configurations offline on their local computers. While this strategy does restrict the time each student has to access the hardware, its benefits lie in minimizing queueing time, ultimately enhancing the learning experience for a larger number of students [51].

4.8 Conclusions of the Chapter

Addressing tests of isolation, characterization, lab scalability, lab accessibility, and lab usage sessions in remote laboratories cover all essential aspects necessary to evaluate and compare SDR remote labs comprehensively.

In remote laboratories employing multiple SDR units simultaneously, addressing isolation is crucial to mitigate interference issues effectively. This involves implementing coexistence strategies aimed at reducing interference and analyzing various types of degradation. Three primary types of interference—receiver blocking, transmitter noise, and inter-modulation—affect the SINR, thus impacting signal quality. Receiver blocking occurs when the receiver's components' limited dynamic range is surpassed by the strength of the interfering signal, leading to a reduction in gain and potential degradation of the received signal. Transmitter noise refers to out-of-band emissions detected by nearby receivers due to imperfect filtering at the transmitter antenna. Inter-modulation interference arises from non-linearities in the signal path, such as those introduced by amplifiers generating harmonics. These interference mechanisms collectively contribute to the reduction of SINR, posing challenges to signal quality and reliability in SDR systems operating in close proximity.

The implementation of Faraday cage covers is a solution for tackling external interference in distributed SDR remote labs. This method is effective in counteracting interference originating from units positioned at a far distance. By encasing each pair of devices with electro-textile metallization material, a Faraday cage cover forms a shield against external interference, ensuring optimal performance and reliability of the SDR units.

Characterizing RF devices is essential to ensure accurate measurements and reliable performance. To achieve this, six fundamental engineering methods are employed for comprehensive characterization: Linearity, Receiver Constant, Input and Output Noise Power, Minimum Detectable Signal, and Frequency Stability. These methods form the basis for calibrating devices to perform across various conditions and applications.

The Linearity of the receiver test involves injecting an input signal from a Test Signal Generator (TSG) and measuring the power of the output within the dynamic range of the receiver. The goal is to ensure that the conversion factor remains constant, which is denoted as the Receiver Constant (RC). RC is evaluated separately, and its proximity to a linear region is assessed by estimating the correlation factor. However, it's anticipated that the receiver may not exhibit linearity across the entire range, particularly at very low and high levels. At low levels, weak signals within the noise level may not follow a linear trend, indicating a threshold where the receiver shows linear behavior. Conversely, at high levels, the system may deviate from linearity near the Full Scale (FS) of the receiver.

Input and Output Noise Power are factors affecting receiver performance. Input noise power is influenced by the system's temperature and bandwidth, representing the inherent noise present within the system. On the other hand, output noise power is calculated using the measured noise power and the Receiver Constant (RC). This calculation accounts for the conversion factor between input and output, providing insights into the level of noise present in the received signal.

Minimum Detectable Signal (MDS) is a parameter that defines the sensitivity of a receiver. It represents the minimum signal strength that the receiver can detect reliably above the noise floor. MDS is equivalent to the output noise power, indicating the threshold at which a signal becomes distinguishable from background noise. This value serves as the starting point of the linear region of the receiver's operation and is essential for accurate signal detection and interpretation.

Frequency Stability assesses how well a device can maintain a consistent frequency output over time. This parameter is especially crucial for digital transceivers that rely on internal oscillators for frequency generation and lack an external clock source. Fluctuations in frequency can lead to inaccuracies and instability in signal transmission and reception, affecting the overall performance of the system.

Understanding and quantifying the delay introduced by the receiver system is crucial, particularly in radar applications where accurate range measurements depend on precise timing. This delay comprises both analog and digital components. Analog delay predominantly arises from the lengths of cables connecting the transmitter or receiver to the antennas. Conversely, digital delay stems from internal stages within the digital receiver circuitry, notably the Finite Impulse Response (FIR) filter.

Lab interoperability is a feature that enables the extended use of SDR devices while also serving as a gauge of the lab's relevance over time, as it offers flexibility for future incorporations. Moreover, it serves as a demonstration of the adherence of development protocols to the standards commonly applied by most SDR devices.

Lab scalability can be evaluated from a cost-saving perspective by comparing the expenses associated with the SDR-computer setup. Meanwhile, the rubrics of Lab accessibility and Lab usage focus on ensuring equitable access for users and assessing how easily users can utilize the lab resources. These aspects evaluate how users access the lab and the level of ease provided by the lab for their usage.

Chapter 5

CASE STUDY #1 - IMPLEMENTING THE MELODY MODEL: RHL-RELIA

This chapter is a modified version of [22], [62], [84] and [85]:

- [22] M. **Inonan** and R. Hussein, ”MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology,” in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399

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5.1 Overview

RHL-RELIA (Remote Engineering Lab for Inclusive Access) is the first deployment based on the MELODY model. Developed within the Remote Hub Lab (RHL), it comprises a distributed network of SDR stations aimed at establishing a wireless communication laboratory. The main goal of this initiative is to furnish students with a remote laboratory experience that mirrors hands-on engagement with tangible SDR kits.

5.2 Requirements

RELIA's objectives were to facilitate engineering education experiments via a distributed network of SDR solutions at the lowest feasible cost. These experiments include:

- Amplitude and Frequency Modulation
- Digital modulation BPSK and QPSK
- Frame synchronization

Table 5.1 outlines the bandwidth requirements for each experiment. The budget-friendly ADALM-Pluto can effectively meet these demands, employing one unit for transmission and another for reception (as recommended by MELODY-creation guidelines). Each unit can be managed by an affordable embedded system such as the Raspberry Pi 4B, capable of handling the maximum throughput of the sample rate. Another reason for choosing the ADALM-Pluto is its widespread use in engineering communication classes. Beyond its utility in laboratory experiences, ADALM-Pluto SDR offers extensive capabilities. Its manufacturer, Analog Devices, provides a package for demonstration designs that span from simple to complex, showcasing the versatility and potential of the device [86].

Table 5.1: Minimum bandwidth requirements for the modulations utilized in RHL-RELIA

Modulation type	Minimum Bandwidth
Amplitude Modulated	30 KHz
Frequency Modulated	180 KHz
BPSK Modulated (T=10us)	200 KHz
QPSK Modulated (T=10us)	200 KHz

Traditionally, students program the ADALM-Pluto by connecting its USB interface to their local computer. Then, users install GRC (GNU Radio Companion), a graphical interface that overlays the standard GNU Radio programming environment [87]. Within this environment, they prepare their RF prototypes, identifying signal sources, filters, and ADALM-Pluto Tx and ADALM-Pluto-Rx as blocks and connecting them.

5.3 System Design

To fulfill these requirements, RHL-RELIA was composed following the MELODY model architecture that as illustrated in Figure 5.1. These components are organized into blocks on university servers and instances, as illustrated in Figure 5.2.

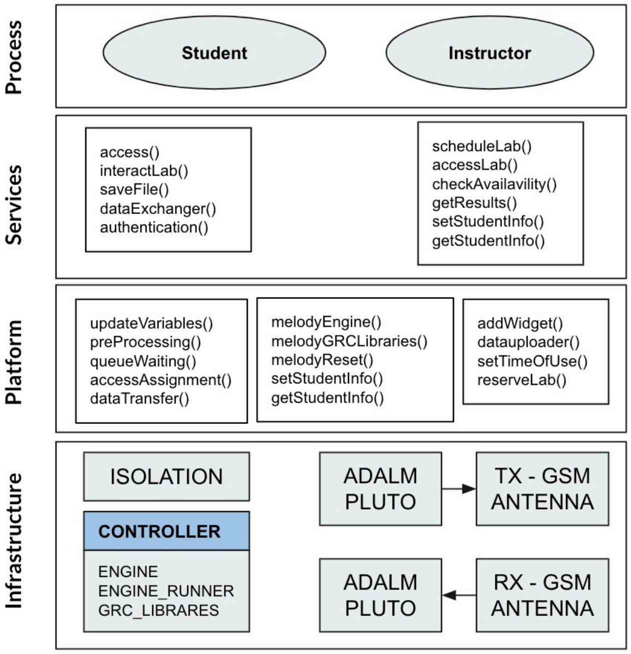


Figure 5.1: Components of RHL-RELIA derived from the MELODY model

5.3.1 University Server

The University Server is tasked with providing access, managing, and receiving data. It is built using Flask, which is a Python web application framework enabling rapid development [88], and

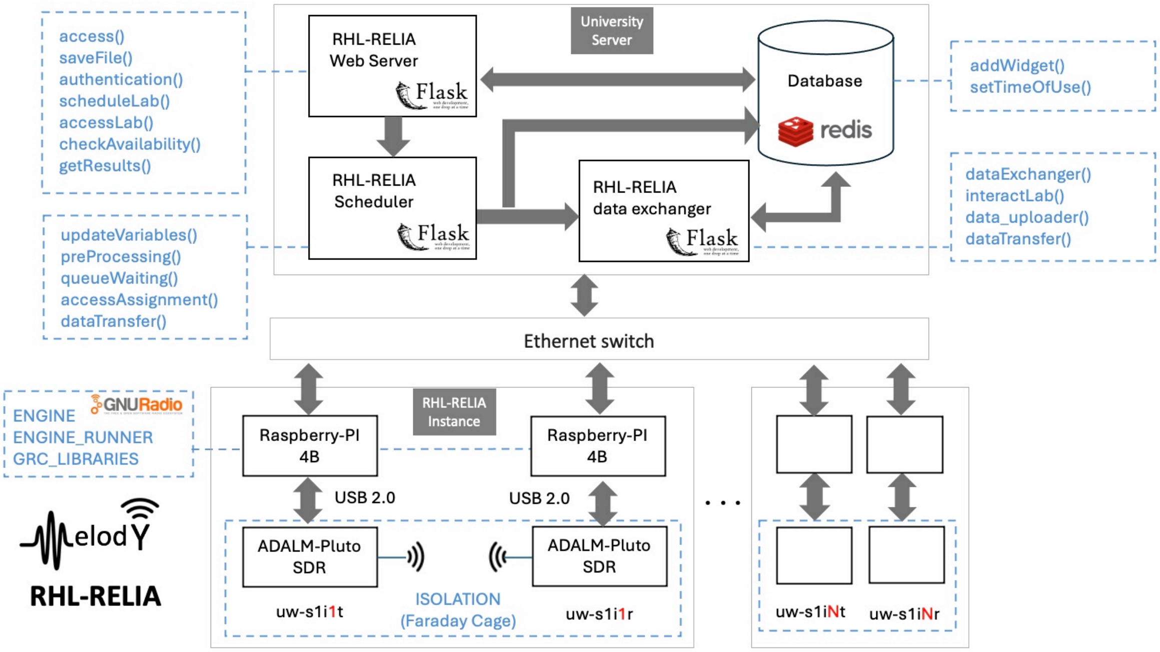


Figure 5.2: RHL-RELIA architecture.

Redis, an open-source in-memory data store known for its high performance [89]. The server comprises four main blocks:

- Web Server: This block facilitates user interaction and grants access if an instance is available. Upon user identification, it forwards the GRC files to the Scheduler block for temporary access allocation. Additionally, it receives streaming data from the database and visualizes it using independent widgets.

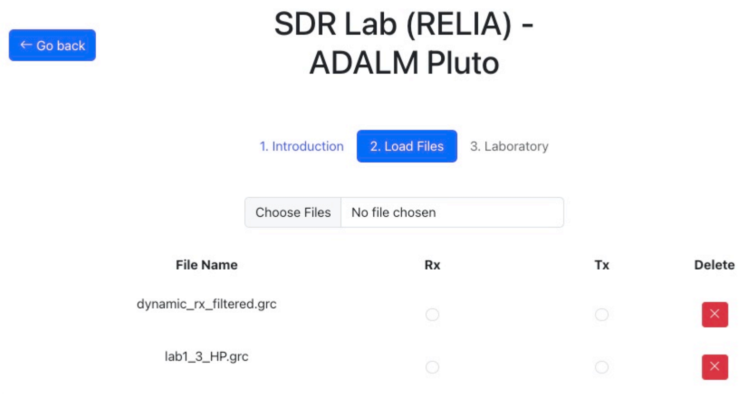
- Scheduler: This component reserves available instances and communicates with the Raspberry Pi to transmit SDR configuration information. Additionally, it interacts with the data exchanger and database to provide metadata for upcoming data.

- Database: This block allows to receive data from one or more instances, where some signal processing is applied.

- Data exchanger: This component receives data transmitted from the Raspberry Pi and interacts with the Lab system.

5.3.2 RHL-RELIA instances

Each RHL-RELIA instance consists of a pair of ADALM-Pluto devices, each controlled by a Raspberry Pi 4B. Each ADALM-Pluto device is dedicated to either transmission (TX) or reception (RX), while the Raspberry Pi hosts the GRC libraries and engines for signal processing. To operate RHL-RELIA, users first prepare two GRC files on their local computer, one for TX and the other for RX as it is shwon in Figure 5.3.



File Name	Rx	Tx	Delete
dynamic_rx_filtered.grc	○	○	✕
lab1_3_HP.grc	○	○	✕

Figure 5.3: RHL-RELIA Web interface to load GRC files

In RHL-RELIA, each receiver instance provides digital I/Q data in a Complex Float 32 format, representing a 64-bit word. The affordability of RHL-RELIA enables extensive scalability, allowing multiple stations to operate in a single room. However, due to the potential for interference when multiple instances work simultaneously, a mechanism of isolation is necessary to ensure optimal operation and minimize interference.

5.4 User Interface

RHL-RELIA incorporates a web graphical interface that empowers users to visualize and interact with streaming data through dynamic variables and widgets. This interface enhances accessibility and interaction with applications running in GNU Radio. Its development leveraged Google Charts, enabling the creation of charts and reporting applications from structured data and seamlessly integrating them into the local computer environment.

5.4.1 Dynamic Variables and Widgets

Dynamic variables, serving as inputs, allow for the adjustment of parameters even after the experiment has commenced. Widgets, acting as output windows, display streaming data online, presenting results across various domains such as time and frequency. Additionally, widgets incorporate dynamic inputs that facilitate visualization tasks such as zooming in/out, toggling grid visibility, and setting minimum and maximum vertical axis values. These widgets, integrated within GRC, enable users to visualize GNU Radio plots based on the QT framework. In RHL-RELIA, widgets are developed to showcase diverse plots through HTML, utilizing graphical libraries sourced from Google Charts. The dynamic inputs and widgets developed in RHL-RELIA include adjusting parameters during experiments, displaying streaming data, and presenting results in time and frequency domains. They also support visualization tasks such as zooming, grid toggling, and setting axis values. Examples of these widgets are listed below and shown in Figure 5.4.

1. Autocorreltion Sink (Widget)
2. Checkbox (Input Variable)
3. Chooser (Input Variable)
4. Constellation Sink (Widget)
5. EyePlot Sink (Widget)
6. Frequency Sink (Widget)
7. Histogram Sink (Widget)
8. Number Sink (Widget)

9. Push Button (Input Variable)
10. Range (Input Variable)
11. Time Sink (Widget)
12. Vector Sink (Widget)

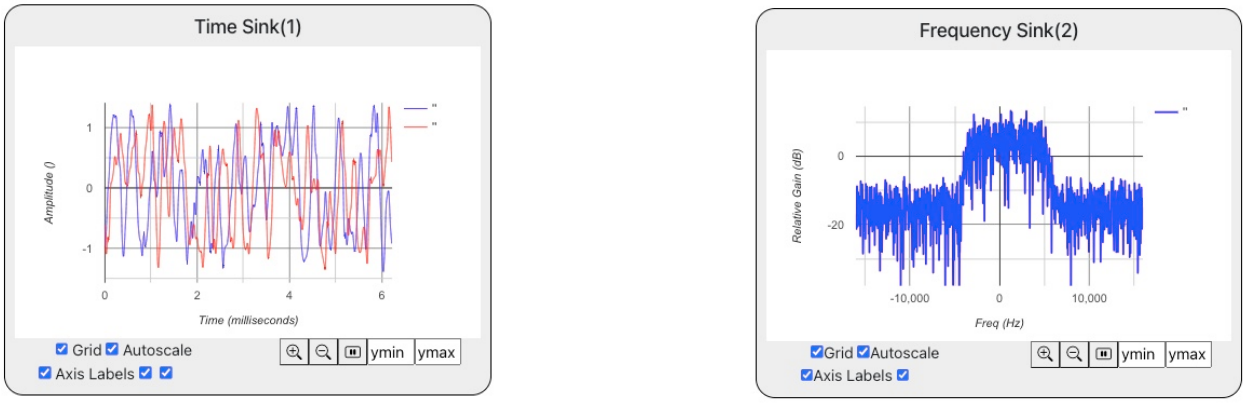
5.4.2 Creation of Widgets and Input Variables

To create a widget or input variable within the RHL-RELIA architecture, three essential files need to be created and inserted. Here is a structured flow for the process:

1. Insert RHL-RELIA Libraries:
   - Include the RHL-RELIA libraries in the header of the YAML files, which compile from GRC to Python. This YAML file is located in the `ENGINE_RUNNER` block, as depicted in Figure 5.2.
2. Create Python Script:
   - Develop a Python script to initialize variables and a function that connects user dynamic input and hardware instances.
3. Develop User Interface in Java:
   - Design the user interface in Java using Google Charts libraries. Every widget or variable requires a new file. All of them are located on the RHL-RELIA Web Server.

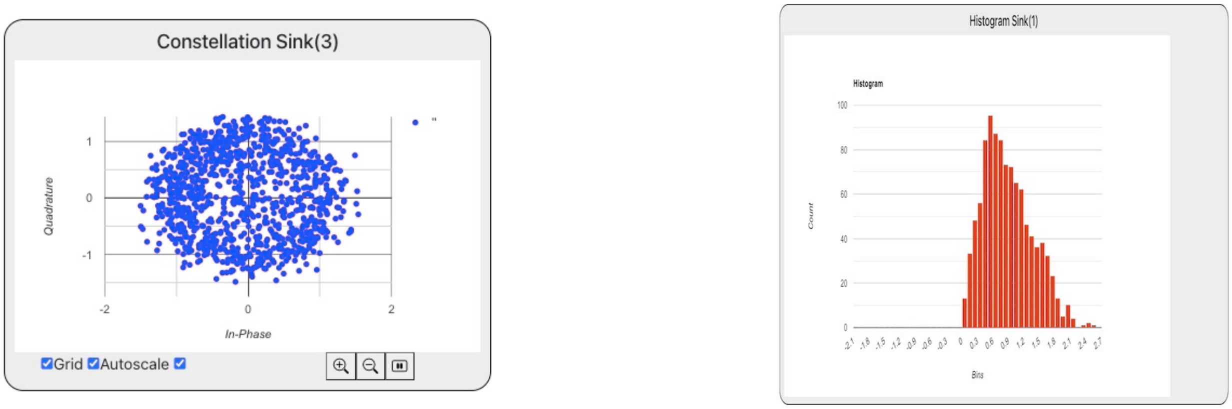
Once the widget creation process is complete, the workflow is as follows:

1. The user compiles the GRC file locally.
2. On the server, access the linked YAML file containing all the IDs and parameters.



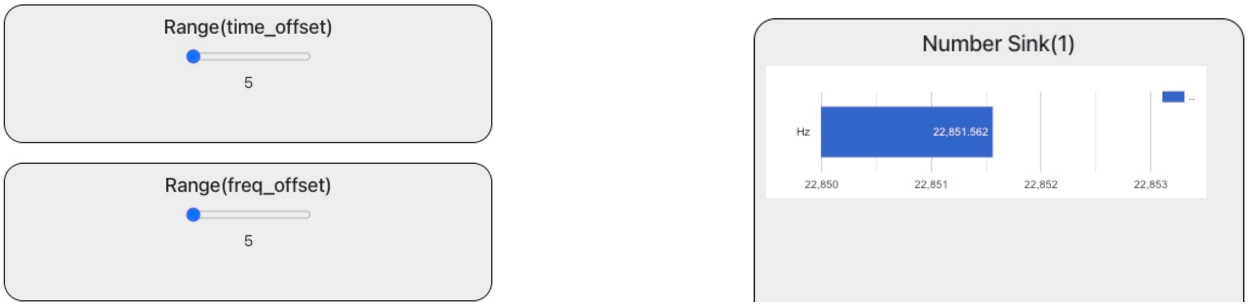
(a) Time Sink Widget

(b) Frequency Sink Widget



(c) Constellation Sink Widget

(d) Histogram Sink Widget



(e) Range Variables

(f) Number Sink Widget

Figure 5.4: RHL-RELIA web widgets and variables

3. Modify the QT headers to RELIA headers.

4. Compile the modified GRC file.

5. Initialize the Python scripts on the server, merging them with the RELIA libraries.

6. Export the result to HTML, merging it with the RELIA graphic libraries developed with Google Charts.

7. Process, display, and update the inputs and plots in a loop until the timeframe ends.

Figure 5.5 illustrates the sequence of steps comparing the QT libraries used for visualization in GRC (left) and RHL-RELIA (right).

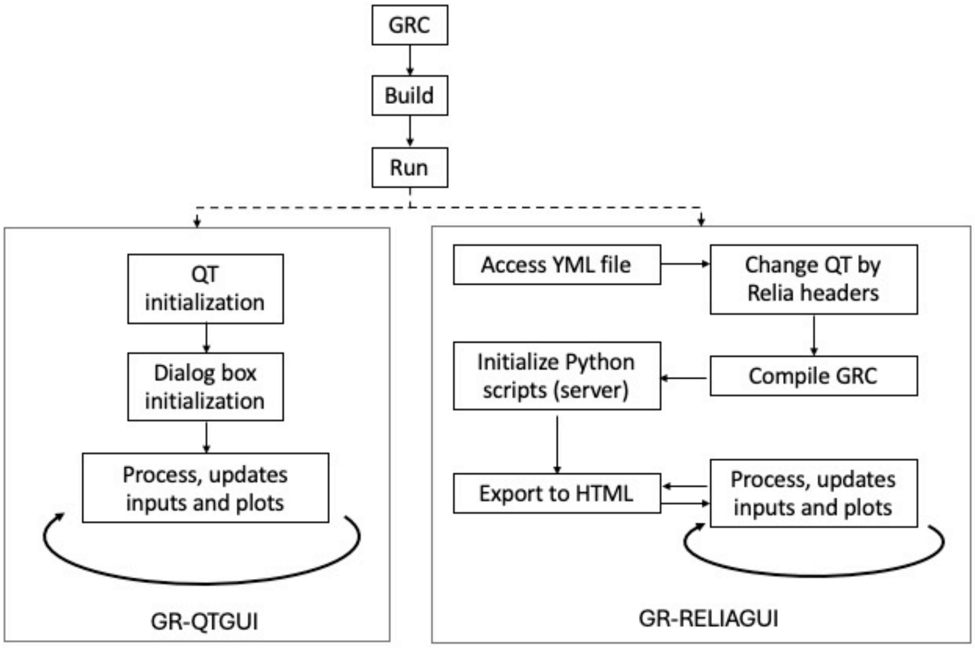


Figure 5.5: Comparison of gr-qtgui with gr-reliagui.

5.5 RHL-RELIA interoperability

An enhancement of RHL-RELIA involves integrating an additional SDR device into the framework, a concept known as interoperability. This expansion provides students with a greater degree of diversification in their learning experience.

5.5.1 Requirements

The goal of this project was to integrate an additional SDR device with alternative operating capabilities while maintaining similar benchmarks than ADALM-Pluto, allowing it to be operated by low-cost embedded systems.

After considering various options, the RedPitaya SDRlab 122-16 was chosen due to its different operating frequency range compared to the ADALM-Pluto SDR, as well as its provision of two independent inputs and outputs. Table 5.3 presents a comparison of features between the ADALM-Pluto and Red Pitaya 122-16.

Table 5.3: Red Pitaya SDRlab 122-16 vs ADALM-PLUTO

	SDRlab 122-16	ADALM-PLUTO
SoC	Zynq Z-7020	Zynq Z-7010
Transceiver	AD9767 & LTC2185	AD9363/94
Transmitter Channels	2	1
Receiver Channels	2	1
Transmitter RF Range (Hz)	300k - 60M	70M - 3.8G
Receiver RF Range (Hz)	300k - 550M	
Output Resolution (bits)	14	12
Input Resolution (bits)	16	
Connectivity	1Gb Ethernet	USB 2.0
SD Card Port	Yes	No
Digital IOs	16	No

Moreover, its open-source nature facilitates exploration, learning, and the development of various applications [90]. Additionally, its internal FPGA/ZYNQ capability makes it an appealing option for functionalities such as partial reconfiguration [91]. Red Pitaya has garnered widespread popularity as a versatile learning platform since its introduction, embraced by amateurs, educators, and professionals alike for diverse project creations [92–95].

5.5.2 System Design

The interoperability mode architecture of RHL-RELIA is crafted to support a range of SDR devices. Typically, the interconnection for SDR devices necessitates a USB 2.0, USB 3.0, or Gigabit Ethernet interface, leveraging the available ports of the Raspberry Pi 4B. A detailed block diagram is depicted in Figure 5.6, showcasing users' remote access to the RHL-RELIA system via a server. Through this interface, students have the flexibility to choose their preferred SDR station.

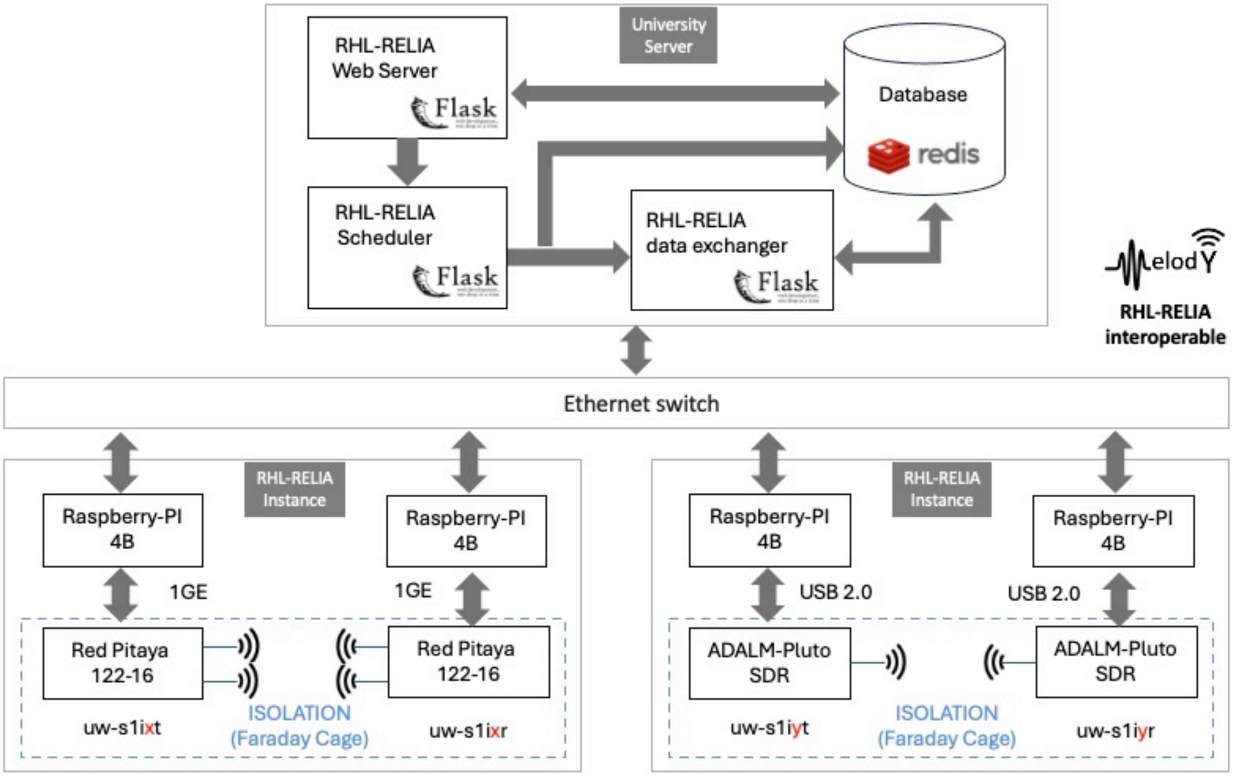


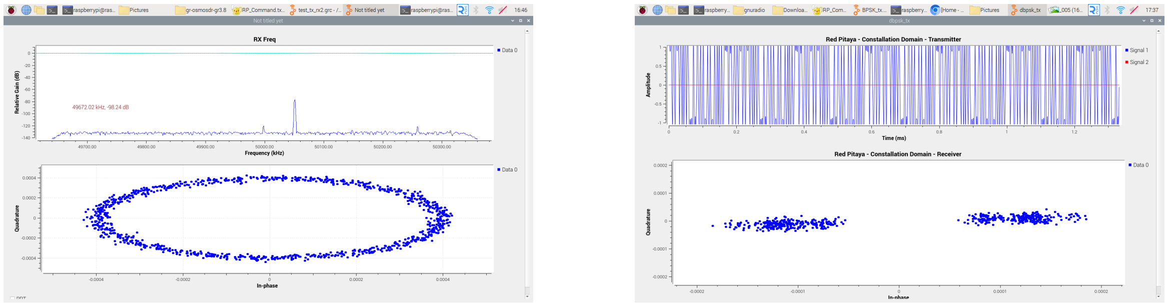
Figure 5.6: RHL-RELIA general interoperability architecture.

5.5.3 Interoperability results

The initial results were obtained from two types of experiments conducted between two Red Pitayas, each one controlled by a Raspberry Pi 4B. The first involved a single-tone transmission aimed at assessing the accuracy of the transmitted frequency. Due to the inaccuracy of the internal oscillator in each Red Pitaya, slight frequency variations are expected. While these discrepancies may be insignificant in certain scenarios, accurately gauging their magnitude is crucial for more complex experiments. Parameters of the experiment are shown in Table 5.4 and results of this experiment are shown in Figure 5.7a. The second experiment revolves around BPSK. Figure 5.7b showcases the outcomes of the experiment, which entail the random transmission of 1's and 0's.

Table 5.4: Red Pitaya Test Parameters

Frequency of Operation	50 MHz
Bandwidth	800 KHz
Noise Level Power	-130 dB
BPSK Modulated (T=10us)	200 KHz



(a) Single tone transmission test.

(b) BPSK transmission test

Figure 5.7: RHL-RELIA Red Pitaya First Results

5.6 Rubrics - MELODY classification framework

RHL-RELIA, modeled as a multi-radio system in Figure 5.8, consists of five stations, each hosting two instances of SDR. These instances are identified in the $UW - sxiy$ format, where 'x' represents the station number (1 to 5), and 'y' indicates the instance number (1 or 2). Stations 1-4 utilize ADALM-Pluto SDR, while station 5 is equipped with Red Pitaya SDR. The isolation measurements were conducted using ADALM-Pluto, chosen for its higher number of instances in the system. The measurement procedure and the corresponding values are elaborated below. Figure 5.9 depicts the actual setup of the RHL-RELIA system, where each unit is enclosed within a metal box."

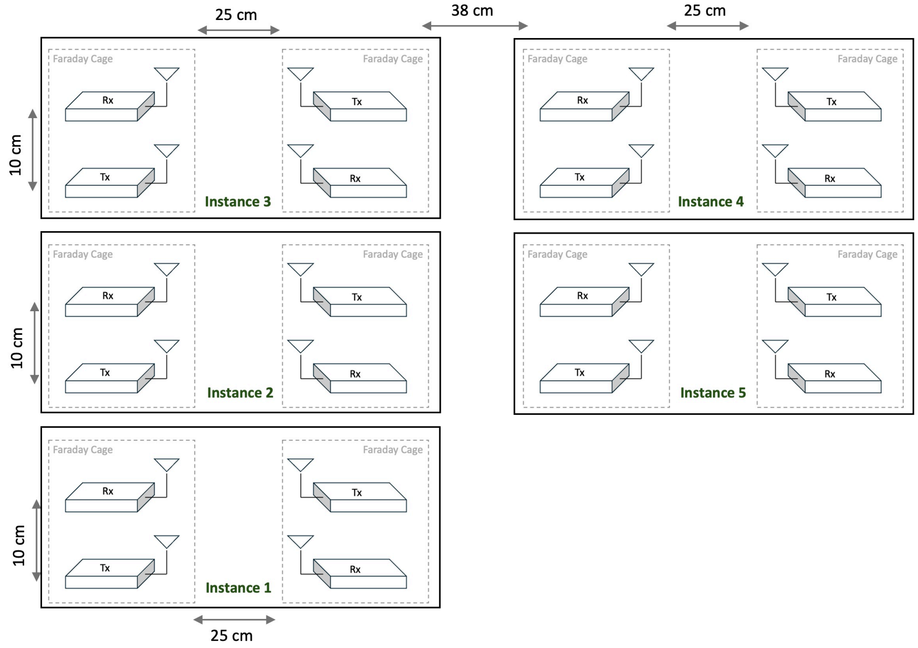


Figure 5.8: RHL-RELIA graphical representation.

5.6.1 Isolation

The isolation metric is determined by the Signal-to-Interference-plus-Noise Ratio (SINR), as described in Equation 4.7. The parameters needed to compute this metric include the degradation caused by the blocking receiver (D) and the intermodulation interference (I_M), and transmitter

Figure 5.9: RHL-RELIA Remote Laboratory.

noise interference (I_{OOB}).

5.6.1.1 Faraday Cage isolation

A Faraday Cage is employed in every instance of RHL-RELIA by covering every TX-RX pair to minimize external. This approach simplifies analysis by concentrating on interference from next instance in the unit, while interference from distant other instances are negligible. Proof of efficiency of Faraday Cage are show in Figure 5.10. where two instances are transmitting without Faraday Cage.

In the initial experiment, two transmitters operating at 2.4 GHz with identical power levels were tested without any isolation mechanisms. The spectrum analysis, as shown in Figure 5.11a, displays frequencies from both transmitters. Notably, the power from the external transmitter exhibited an attenuation of 8 dB compared to the power from the transmitter in the same instance. This observed attenuation is consistent with the path loss estimates from the same instance and external instance, calculated to be approximately 20 dB and 28 dB, respectively, as derived from equation 4.2.2. Subsequent experiments repeated the same setup but with the addition of isolation

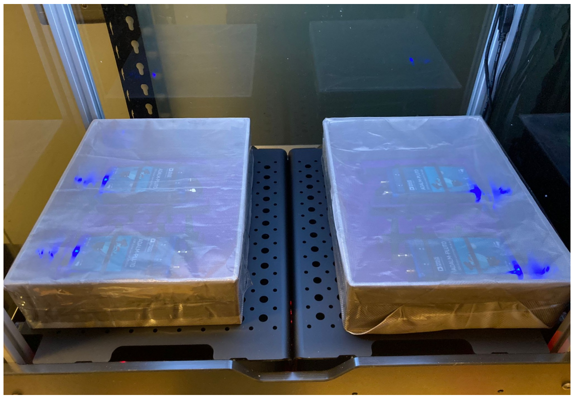
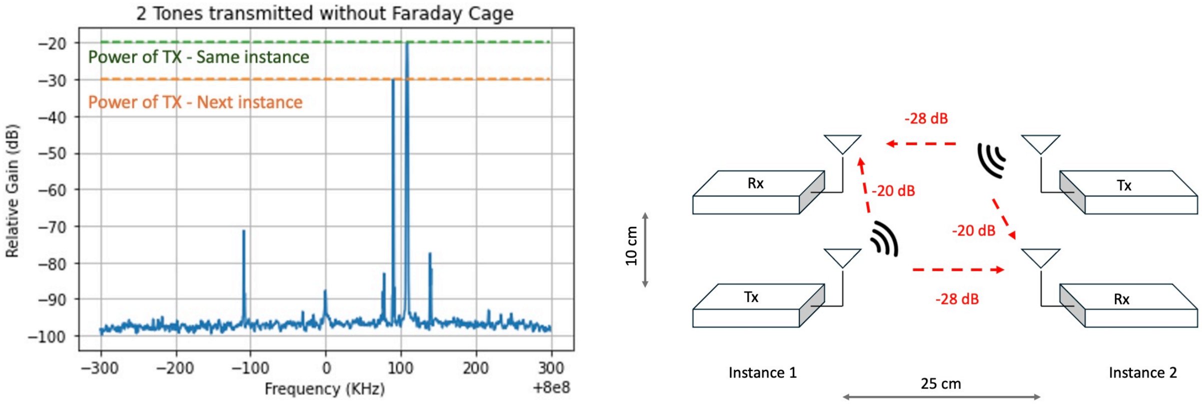


Figure 5.10: Isolation mechanism of one RHL-RELIA Tx/Rx module.

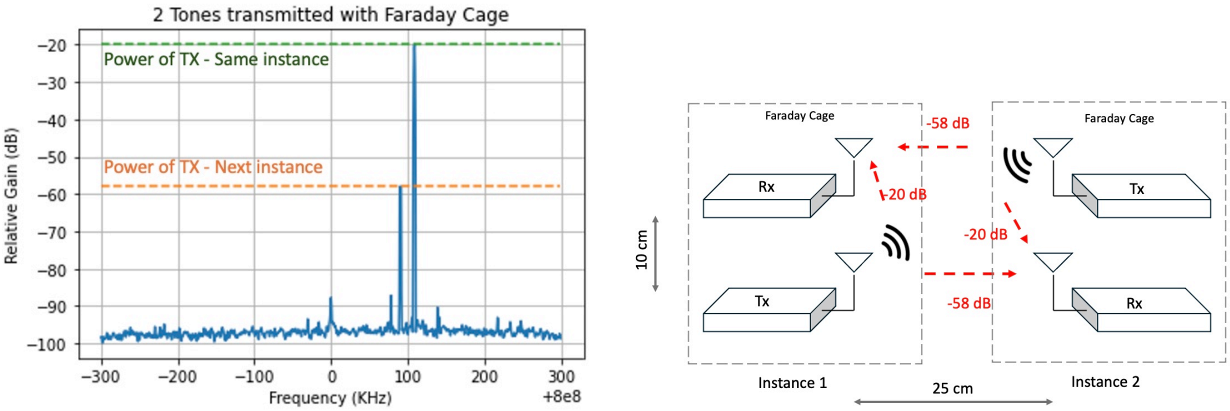
between the two instances. This modification led to a significant reduction in the detected tone from the other instance, dropping to about 58 dB as depicted in Figure 5.12a, effectively demonstrating an isolation improvement of 30 dB.



(a) Spectra of 2 tones transmitted.

(b) Block diagram of 2 units of RHL-RELIA

Figure 5.11: Power Spectra and block diagram of 2 units of RHL-RELIA without Faraday Cage



(a) Spectra of 2 tones transmitted.

(b) Block diagram of 2 units of RHL-RELIA

Figure 5.12: Power Spectra and block diagram of 2 units of RHL-RELIA without Faraday Cage

5.6.1.2 Blocking Receiver

To estimate the blocking receiver parameter (D), the initial step involves experimentally determining the blocking threshold (P_{3dB}). This process begins with the transmission of a BPSK-encoded message, 'hello world', from the instance under study, while ensuring all other instances remain inactive to eliminate coexistence interference. The parameters of this experiment are summarized in Table 5.6.

The aim of this experiment is to assess the efficiency of transmission packages. With a Packet Reception Ratio (PRR) efficiency of 99.6% observed in a transmission of 100,000 words, a spectrum of the $s1i1$ instance (our device under test (DUT)) is plotted in Figure 5.13. This allows for the determination of the signal power, estimated to be approximately at -20 dB, and the noise floor power, measured at -98 dB.

Table 5.6: BPSK configuration parameters

Sample Rate	600 KHz
Frequency of operation	2.4 GHz
Transmitter attenuation	10 dB
Receiver gain	50 dB
Distance between 2 ADALM-Pluto	10 cm

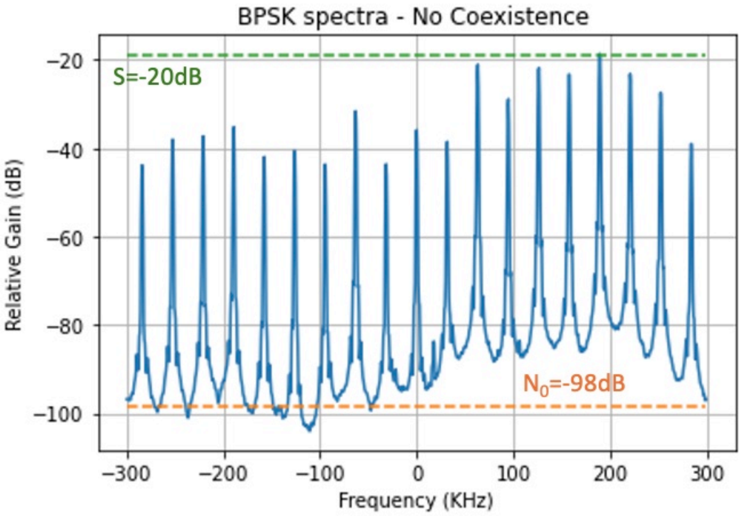


Figure 5.13: Spectra of BPSK transmission within a single RHL-RELIA unit without coexistence

The next step is to conduct a simultaneous BPSK transmission experiment in every system while adjusting each transmitter gain (excluding the DUT). The objective is to interfere DUT until decrease the Packet Reception Ratio (PRR) efficiency in our DUT 99%. Figure 5.14 illustrates the distorted power spectra observed by our DUT's receiver when it reaches to that efficiency.

The estimation of the threshold interference power at the DUT's receiver can be determined by measuring the power in the adjacent DUT's receiver. Figure 5.15 displays how the DUT's power level distorts due to external interference. It can be observed that when the adjacent DUT's receiver

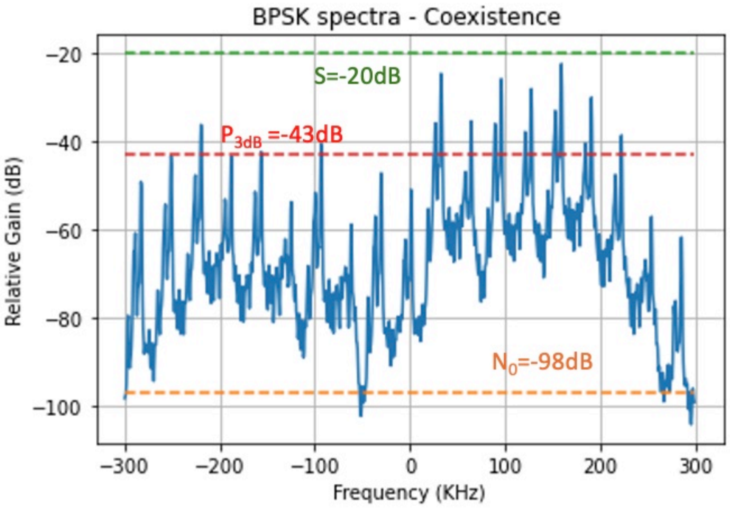


Figure 5.14: Spectra of BPSK transmission within a single RHL-RELIA unit with coexistence.

detects a power level of -5 dB, the power at the DUT's receiver begins to degrade. Considering the path loss due to distance and the shielding provided by the Faraday Cage, it can be inferred that the power at the DUT's receiver is approximately -43 dB. Furthermore, this figure allows for the estimation of the value of κ, which is determined to be 0.5.

$$D = \max\Big\{0, (-20 - (-43))\kappa + 3\Big\} = 14.5dB \tag{5.1}$$

5.6.1.3 *Inter-modulation interference (I_{IM})*

In order to assess this form of interference, it is essential to determine the level of the third-order intercept point (IP_3). This is achieved by utilizing a Test Signal Generator (TSG), which introduces two tones into the band-pass and measures the power of the intermodulation products. According to International Telecommunication Union (ITU) recommendation [96], the IP_3 value can be estimated using the following equation:

$$IP_3 = P_{in} + \frac{a}{2} \tag{5.2}$$

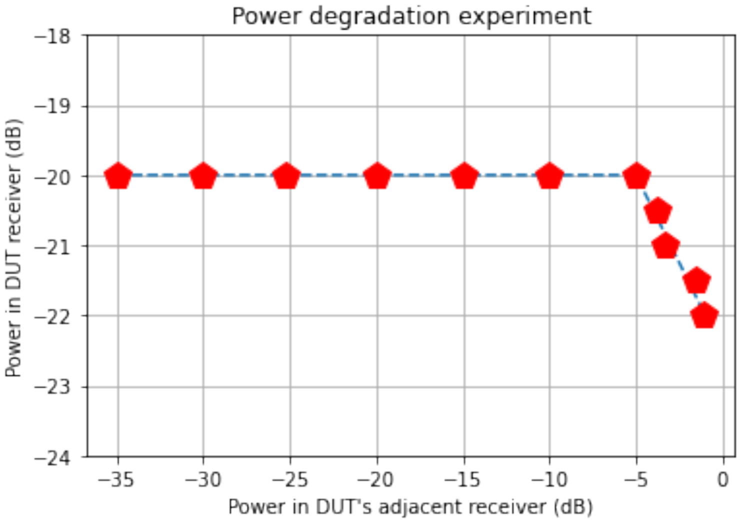


Figure 5.15: Spectra of BPSK transmission within a single RHL-RELIA unit with coexistence.

Analysis is done though the power spectra where it can be seen the components and harmonics that is common in a phase modulation.

where P_{in} represents the root mean square (r.m.s.) power measured for each of the two test signals inserted (in dBm), and a denotes the difference (in dB) between the levels of the inserted test signals and the levels of the intermodulation products at the measurement point. If the intermodulation products have different levels, the higher one should be taken into account.

Features of the measurement and equipment used is listed in Table 5.8

Table 5.8: Intermodulation Test Experiment parameters

TSG	AWG420 Arbitrary Waveform Generator
Center Frequency	100 MHz
Frequecny Tone 1	100.09 MHz
Frequecny Tone 2	100.11 MHz
Power of Tone 1	-30dBm
Power of Tone 2	-30dBm

The parameter a can be obtained from Figure 5.16 by subtracting the average input tones from the maximum power of any intermodulation product, resulting in $a = 32$ dB in this instance. Consequently, the value of IP_3 is calculated as $-30+16 = -14$ dB. Additionally, from Figure 5.16, it can be observed that both the input tones and the intermodulation products occupy approximately 400 kHz out of a bandwidth of 600 kHz, yielding a factor of $f = 0.666$. Replacing these values in equation 4.4 we can get the I_{IM}.

$$I_{IM} = 2 \times (-30) + (-30) - 2 \times (-14) + 10 \log_{10} 0.666 = -63.7dB \tag{5.3}$$

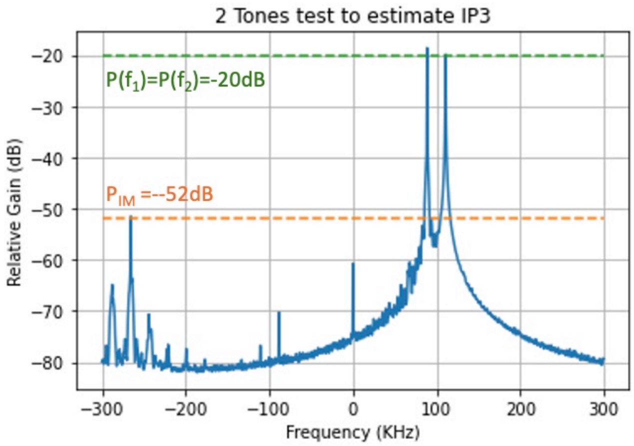


Figure 5.16: Power Spectra of IP3 Test.

5.6.1.4 Transmitter Noise (I_{OOB})

For RHL-RELIA, this type of external interference is negiglible. This is because power noise if ADALM-Pluto is around -157dBm/Hz [97] and it also is attenuated by the Faraday Cage isolation.

5.6.1.5 Self Receiver Interference (I_{SR})

Self-receiver interference can pose a significant challenge as it can be hundreds of thousands of times stronger than the desired signal. For instance, Figure 5.17 illustrates the reception of a receiver with a tone and replicas with power up to 40 dB over the floor noise, leading to a significant reduction in the sensitivity and SINR of the receiver. While techniques such as Self-Interference Cancellation (SIC) exist to mitigate self-interference [98,99], simpler recommendations are available. Most SDRs provide the option to disable the TX when it is not in use. This feature can be accessed in the ADALM-Pluto's Phy layer. Figure 5.18 demonstrates the result when the TX is disabled and interference is eliminated.

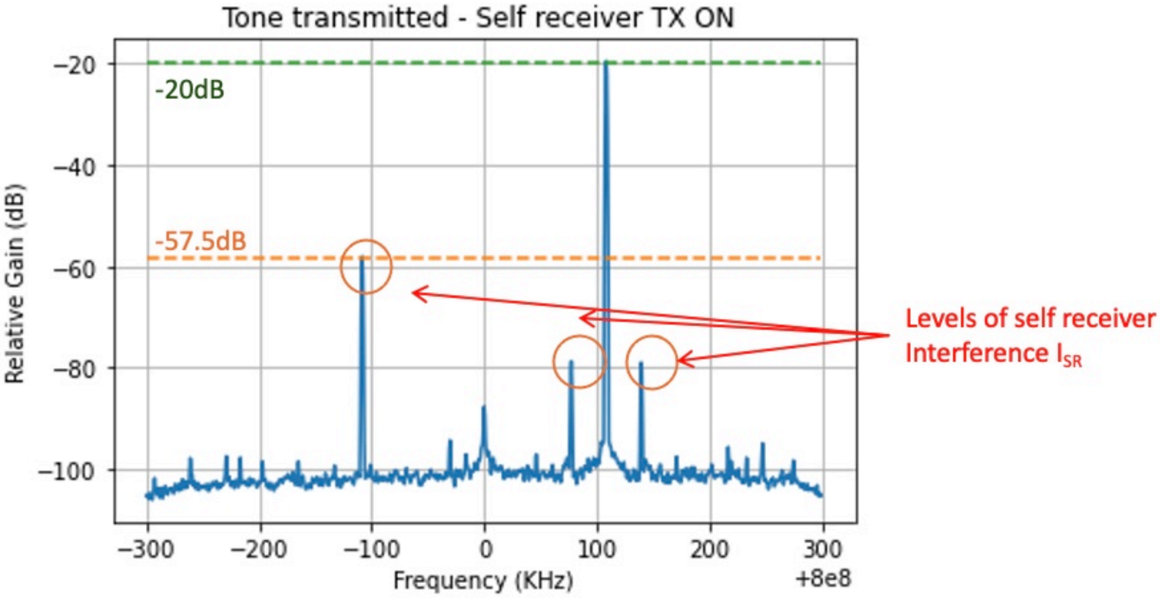


Figure 5.17: Power Spectra of a tone with self Tx ON

Therefore, equation 4.8, to estimate SNIR is simplified to:

$$SINR_x = \frac{S/10^{D/10}}{N_0 + I_{IM,y}/10^{D/10}} \tag{5.4}$$

Since $I_{SR,x}$ and $I_{OOB,y}$ are negligible, the values of SINR in each instance and the parameters required to calculate it are compiled in Table 5.10.

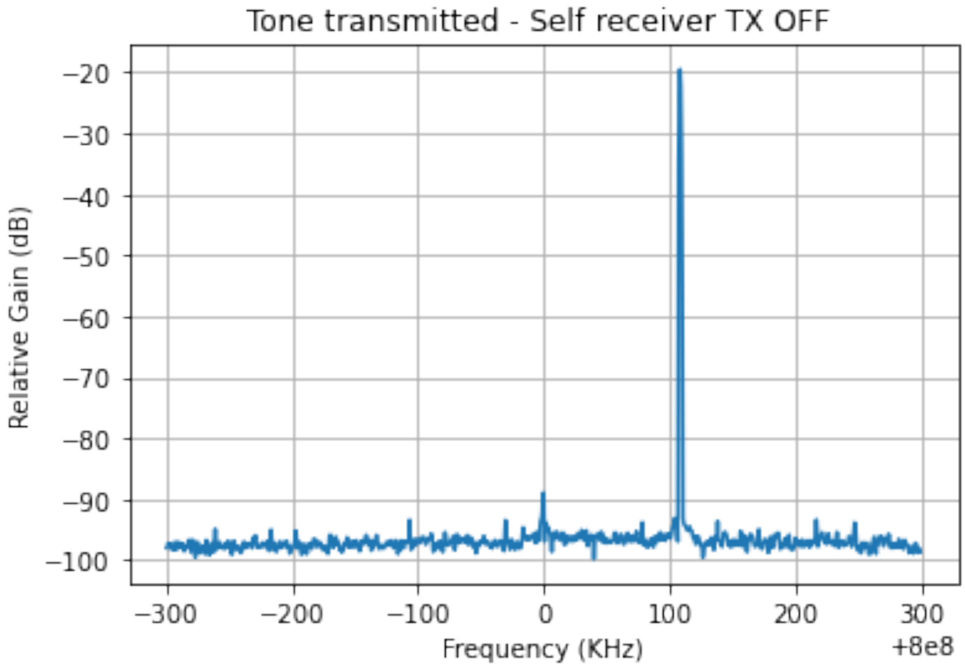


Figure 5.18: Power Spectra of a tone with self Tx OFF

Table 5.10: Measurements for every instance of RHL-RELIA

RHL-RELIA instance	P_{3dB} (dB)	I_{IM} (dB)	N_0 (dB)	S (dB)	SINR (dB)
s1i1	-43.0	-63.7	−98.0	-20.0	43.65
s1i2	-41.0	-60.1	−94.0	-21.0	39.06
s2i1	-45.0	-62.9	−100.0	-22.0	40.88
s2i2	-40.0	-64.2	−99.0	-18.0	46.16
s3i1	-42.0	-62.2	−95.0	-17.0	45.12
s3i2	-39.0	-66.9	−99.0	-19.0	47.85
s4i1	-45.0	-68.1	−92.0	-21.0	46.57
s4i2	-40.0	-63.5	−94.0	-19.0	44.41

Therefore, in terms of isolation test results, as detailed in Table 3.1, RHL-RELIA exhibits an average SINR of 44 dB. Consequently, according to MELODY's isolation rubric, RHL-RADAR is deemed **5 stars** ★★★★★.

5.6.2 Characterization

In the subsequent lines, a comprehensive examination focusing on Isolation, Calibration, Lab Scalability, Lab Accessibility, Lab Usage, and Interoperability will be scrutinized in detail.

5.6.2.1 Linearity

The linearity test entails injecting a signal into the digital receiver (ADALM-Pluto) input at varying levels, with increments of 2 dB, using a Test Signal Generator (TSG). The experiment's specifications are outlined in Table 5.12. From Figure 5.19, it is evident that the receiver exhibits a linear trend across most of the dynamic range, spanning approximately from -80dBm (corresponding to 4×10^{-8} ADU) to -4dBm (equivalent to 1.3 ADU), with exceptions noted at the lower limit (minimum detectable region) and upper limits (saturation region). The 1dB compression point is observed at an input level of -4 dBm or 2 ADU.

Table 5.12: Linear experiments specifications

TSG	AWG420 Arbitrary Waveform Generator
Center Frequency	100 MHz
Frequency of input signal	100.09 MHz
Max Input	2.5 dBm
Min Input	-77 dBm
Step	2 dB

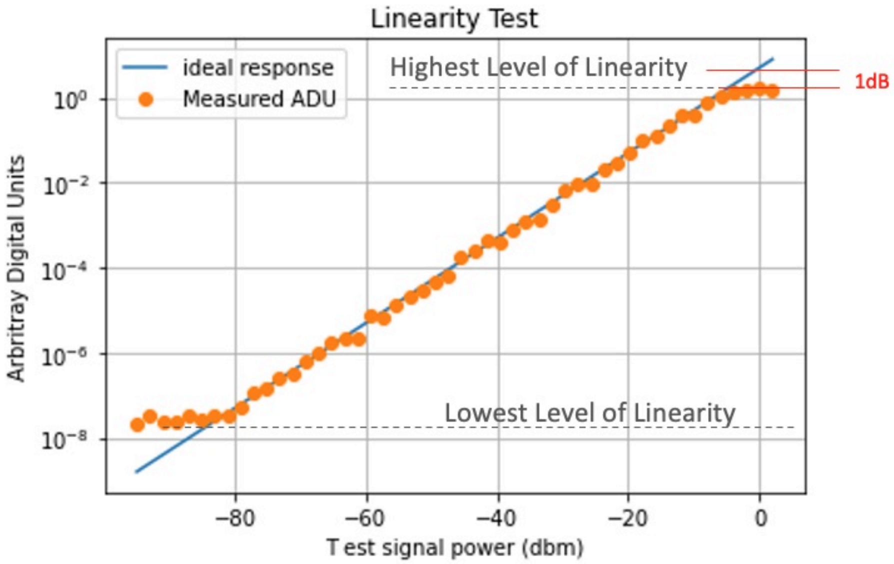


Figure 5.19: ADALM-Pluto Linearity Test.

5.6.2.2 Calibration of Receiver Constant

The calibration of the receiver constant was conducted utilizing the previous linearity test. By employing the array of power input and output measurements and substituting them into Equation 4.15, the RC constant was estimated. Since the input power is in dBm units, it is necessary to convert it to the linear scale using the following equation:

$$P_W = 10^{\frac{P_{dBm-30}}{10}} \tag{5.5}$$

This constant serves as a conversion factor from input power to ADU. The calculated value for RC is:

$$RC = 2.26 \times 10^{-4} dBm/ADU \tag{5.6}$$

Moreover, the coefficient of linear regression can be estimated using Equation 4.16.

$$R = 0.969 \tag{5.7}$$

5.6.2.3 Input and Output Noise Power

To calculate the input noise power, it is determined using equation 4.17, considering that the receiver operates at a room temperature of 22°C (295.15 K) and a bandwidth of $BW = 600$ kHz, where most experiments were conducted.

$$N_{IN} = 10\log_{10}(295.15 \times 1.38 \times 10^{-23} \times 600 \times 10^3) = -146.12dB \tag{5.8}$$

When it comes to the Output Noise Power, it's derived by either examining the Output Noise Power at the lowest linearity level in Figure 5.19 or utilizing Equation 4.18. Therefore, N_{OUT} is:

$$N_{OUT}(dBm) = -80dBm \tag{5.9}$$

5.6.2.4 Minimum Detectable Signal measurement

It can be obtained from Figure 5.19 where N_{OUT} is extracted.

$$MDS = N_{OUT} + 3 = -80 + 3 = -77dBm \tag{5.10}$$

5.6.2.5 Delay of a receiver

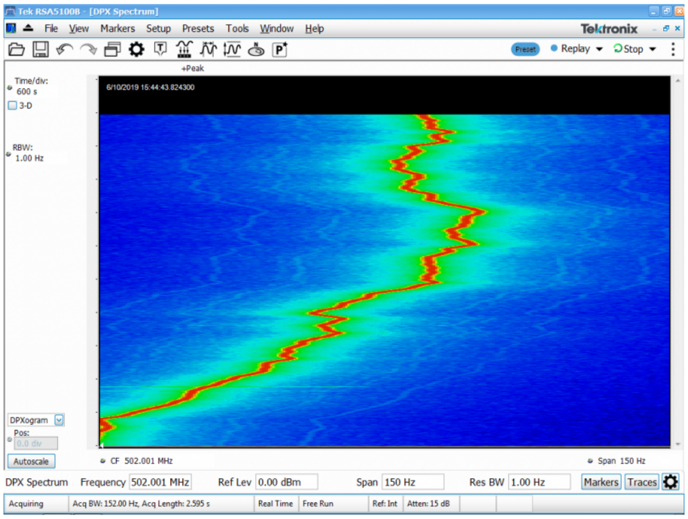
The digital receiver in ADALM-Pluto utilizes the AD9363/AD9364 chipset. It comprises three Half-Pass (HP1, HP2, and HP3) filters in cascade and a Finite Impulse Response (FIR) filter with 128 taps at the end. The HP1 and HP2 filters have a decimation factor of 2, while HP3 has a decimation factor of 2 or 3. The FIR filter supports decimation factors of 1, 2, or 4 [100].

For calibration, the operation is set to 1 MHz. For this purpose there is cable between ADALM-Pluto output and the antenna. To obtain the status of the FIR filter, the command line $ad9361\_set\_rx\_fir\_config$ is used, which provides the number of taps used and the decimation factor. In this case, the values are 128 for the number of taps and 2 for the decimation factor. Therefore, according to Equation 4.21, the delay is calculated as:

$$\tau \approx \frac{128}{2} \times \frac{1}{2 \times 1M} = 32\mu s \tag{5.11}$$

5.6.2.6 Frequency stability

Analog Devices, the manufacturer of the ADALM-PLUTO SDR, conducted a test on the device and found that its oscillator exhibited a drift of 100 Hz within a 10-minute time frame. It's important to note that the level of frequency stability can vary among different SDR devices, as each device has its own unique characteristics and performance specifications [77]. The results of this test are illustrated in Figure 5.20.



6/10/2019 15:44:43.824300

Time/div: 600 s

RBW: 1.00 Hz

Pos: 0.0 div

CF 502.001 MHz

Span 150 Hz

DPX Spectrum Frequency 502.001 MHz Ref Lev 0.00 dBm Span 150 Hz Res BW 1.00 Hz

Acquiring | Acq BW: 152.00 Hz, Acq Length: 2.595 s | Real Time | Free Run | Ref: Int | Atten: 15 dB

Figure 5.20: ADALM-Pluto Frequency Stability Test. Taken from [77].

Therefore, in terms of calibration test results where 6 calibration tests were performed, MELODY's calibration provides a rubric of **5 stars** ★★★★★.

5.6.3 Interoperatibility

According to the MELODY rubric, one star is provided for every distinct SDR device that is incorporated. In the case of RHL-RELIA, it has 2 SDR devices (ADALM-Pluto and Red Pitaya SDR). Therefore, RHL-RELIA receives a rating of **2 stars** ★★☆☆☆ in this category.

5.6.4 Lab Scalability

For its architecture, RHL-RELIA can handle 8 instances, and its low cost represents $560 per instance, which includes 2 ADALM-Pluto and 2 Raspberry Pi 4B devices. Therefore, according to the Lab Scalability rubric of MELODY, RHL-RELIA receives **5 stars** ★★★★★.

5.6.5 Lab Accessibility

As a technology-agnostic platform with its interface development based on widgets using Google Chart libraries, RHL-RELIA can be accessed through a web browser. Therefore, according to the Lab Availability rubric of MELODY, RHL-RELIA receives **5 stars** ★★★★★.

5.6.6 Lab Usage Sessions

According to the MELODY rubric for lab sessions, the maximum rating is given if the system employs a method to maximize the number of users. This feature is offered by RHL-RELIA, which democratizes usage sessions by allotting each user 20 seconds to utilize the system. Therefore, RHL-RELIA receives a rating of **5 stars** ★★★★★.

5.7 Preliminary Evaluation of RHL-RELIA Post-Development

In the initial phase, RHL-RELIA underwent testing by three engineering students with no prior experience in SDR topics. The purpose was to collect preliminary feedback before the system undergoes a more comprehensive evaluation in a classroom setting. The students were tasked with solving two lab assignments using both RHL-RELIA and traditional ADALM-Pluto SDR Kits to compare their experiences and the effectiveness of each system [85].

5.7.1 Evaluation

This section's evaluation focused on examining both the operational intricacies of the system and its educational implications across the following categories:

5.7.1.1 Operational intricacies

- User interface: Ensuring that the user interface enables students to navigate and interact with the lab platform easily, thereby enhancing the efficiency of conducting experiments.

- Technology dependence: Assessing the degree of dependence on technology to evaluate the accessibility of the remote lab. Additionally, ensuring compatibility with various devices and operating systems is crucial.

- Lab availability: Referring to the accessibility of the remote lab at different times and from various locations. Furthermore, assessing lab availability involves understanding how resources such as equipment and simulation tools are managed.

5.7.1.2 Educational implication

- Time Efficiency: This explores the time-related aspects of using RHL-RELIA, focusing on efficiency and the learning curve. It's crucial to understand how long it takes students to complete assignments and become familiar with the system to assess its practicality in an educational context.

- Learning Independence: This measures the autonomy students have when using RHL-RELIA. Determining the balance between independent work and the need for external assistance offers insights into the lab system's user-friendliness and intuitiveness.

- This assesses students' interest in wireless communication, especially as they start as novices, and their overall satisfaction with the learning experience after using RHL-RELIA.

5.7.2 Results

The results of this initial evaluation were categorized into three groups, comparing the outcomes between the RHL-RELIA and ADALM-Pluto kits.

5.7.2.1 User Interface

RHL-RELIA features a web interface, offering a user experience distinct from the traditional GRC utilized for controlling ADALM-PLUTO within the SDR community. Additionally, its provision of a 20-second access window for each user is advantageous in scenarios where resource demand exceeds supply, demonstrating RHL-RELIA's capability to serve a larger user base. The students' feedback on this functionality is summarized in Table 5.14.

Table 5.14: Students' Impression Over the User Interface

	RHL-RELIA	Traditional
Student 1	*"The interface is friendly, but it would be more effective with prolonged use for manipulating signal graphs".*	*"The configuration process was complex, and it doesn't function on certain operating systems".*
Student 2	*"A timer of how long it is used will be helpful".*	*"Access to a more robust user interface for signal analysis and readability".*
Student 3	*"It simplifies the process but is difficult handle long period results".*	*"I can use it for as long as I need".*

5.7.2.2 Technology Dependence

RHL-RELIA is engineered to reduce reliance on specialized components. This approach contrasts with traditional labs that require users to install specific software on their computers. The results of student feedback on this aspect are detailed in Table 5.16.

5.7.2.3 Availability and Accessibility

Students provided their perspectives on the accessibility of both RHL-RELIA and traditional lab setups. RHL-RELIA is noted for its 24/7 availability, though each user's access is time-limited to allow more students to use the system and to decrease wait times. In contrast, traditional labs

Table 5.16: Students' Impression on the Technology Dependence

	RHL-RELIA	Traditional
Student 1	*"Requires only a device compatible with GNURadio and later any device with internet access can be used".*	*"A computer that has USB ports is needed".*
Student 2	*"Operates through the web, eliminating the need for expensive devices and dealing with varying connections to different computers. It is straightforward and accessible on all devices".*	*"GNURadio poses a challenge in terms of usage across different devices. Traditional labs, with actual hardware, add an extra layer of work".*
Student 3	*"Requires only a device compatible with GNURadio and internet access".*	*"A device with USB support is needed, and modern devices often lack USB ports, necessitating extensions".*

offer full and unrestricted access to individual students, who have direct and personal access to the hardware. The feedback from students on this difference is summarized in Table 5.18.

5.8 Comprehensive Pedagogical Evaluation of RHL-RELIA

To conduct a comprehensive assessment of the RELIA lab's effectiveness in educational settings, the lab was utilized by 37 students enrolled in the Embedded Systems Capstone courses ECE/CSE 475 and EE 542 at the University of Washington during the Winter quarter of 2024.

The author of the dissertation developed three lab assignments, established an evaluation methodology, and created questions for pre-survey, post-survey, and focus group sessions. These materials were submitted to the University of Washington's Office of Educational Assessment (OEA). The OEA, acting as an independent consulting body, was responsible for administering the evaluation of the RHL-RELIA lab. This included conducting the pre-survey and post-survey questionnaires and facilitating a focus group session.

Table 5.18: Students' Impression Over the Availability and Accessibility

	RHL-RELIA	Traditional
Student 1	*"Accessible from anywhere once configured".*	*"Allows playing, pausing, and taking one's time but requires carrying hardware at all times".*
Student 2	*"Accessible from any device, ability to save and load previous files".*	*"Lack of features like saving files, requires connection to specific devices".*
Student 3	*"No need to carry devices, access anytime but 30-second limit can be pressuring for analysis".*	*"Allows taking time, despite the burden of carrying devices".*

5.8.1 Laboratory materials

Students participated in the "Exploratory Challenge," which involved completing three lab assignments using RHL-RELIA. For Labs 0 and 2, the entire group used the RHL-RELIA remote lab. However, for Lab 1, participants were randomly divided into two groups: the control group (utilizing the Traditional Lab Kit, n=18) and the intervention group (utilizing the RHL-RELIA remote lab, n=18). Each lab assignment included the following components:

- Lab 0. This laboratory session involved configuring an ADALM-PLUTO SDR and conducting a basic experiment with RHL-RELIA.

- Lab 1. Students explored the importance of signal processing in wireless communication by applying digital filters and analyzing the resulting quality.

- Lab 2. Focused on the calibration of a Digital System, where students learned how to calibrate a real digital system by estimating the Sample Frequency Offset (SFO).

5.8.2 Pre-survey, post-survey and focus groups

The evaluation process involved administering pre- and post-online surveys to assess students' satisfaction with RHL-RELIA, gather suggestions for improvement, and evaluate its impact on skills and learning. According to the OEA, all 37 students enrolled in the class completed the pre-survey, while 34 students completed the post-survey. The pre-survey featured questions on a scale from 1 to 5 about students' backgrounds in topics related to RF communications and SDR. The post-surveys, completed after each of the three labs, asked students to rate their overall experience on a scale from 1 to 5. Key questions from the pre- and post-surveys are detailed in Table 5.20 and Table 5.21 respectively.

Table 5.20: Pre-Survey questions

	Question
Q1	Have you ever completed a lab assignment by controlling real hardware remotely as opposed to using physical lab kits?
Q2	Please indicate how confident you are, at this point, in your understanding of the following concepts: - Python - Radio-frequency devices - GNU Radio Companion - Software Defined Radio - Fourier Transform - Synchronization - Sample Frequency Offset - Constellation Domain - Digital Modulation - Noise
Q3	Please indicate how likely it is that you will do the following in the next 12 months: - Take part in design, build and test competitions - Explore Software Defined Radio technology - Be a radio amateur

Table 5.21: Post-Survey questions

	Question
Q1	Please rate your satisfaction with the following aspects of: Lab “X” - Introduction to the lab - Usefulness of Quick Start Guide of RELIA - Usefulness of Installation Guide - Availability of the Remote SDR/Wait Time - Usability of the system - Support from RELIA team - The amount you learned - Overall experience
Q2	Please indicate how much you agree or disagree with the following statements about your experience with the RHL-RELIA lab assignments: - I liked the flexibility offered by the remote lab assignments- Lab 0 and Lab 2 (i.e., able to complete anytime and anywhere) - The remote lab was interesting and kept me engaged - Particularly, in Lab “X”, the remote lab gave me the opportunity to experiment more by trying out different scenarios as many times as I want - I may access the remote lab after the course is over (e.g., to reinforce concepts)
Q3	What, if anything, did you find valuable about completing the RHL-RELIA labs?
Q4	What challenges, if any, did you face in completing the RHL-RELIA labs?
Q5	What, if anything, could be improved based on your experience with the RHL-RELIA labs?

As anticipated, over 80% of students indicated that they did not have prior experience in these areas, which aligns with expectations given that the class primarily focuses on embedded systems.

OEA reported that the focus group session lasted for one hour and thirty minutes, conducted online with a group of ten students. The aim was to delve deeper into their experience using RHL-RELIA, its influence on their learning, and their perspectives on its applicability in engineering education. Table 5.22 outlines the questions posed during the focus group session.

Table 5.22: Focus groups questions

1	Have you completed a remote lab in the past? If yes, how many?
2	Overall, how would you describe your experience with the RHL-RELIA assignment(s)?
3	Did you have prior experience with Software Defined Radio (SDR) before completing the assignments? If not, do you think that you learnt about SDR after completing the assignments?
4	To what extent did you feel like you received enough of an introduction as to how remote labs operate?
5	What did you think of the user interface? To what extent did you feel like you were controlling real equipment?
6	What, if anything, made it easy to use? What, if anything, was challenging? (e.g., wait time, glitches, debugging)
7	Have you used the Physical PLUTO Kit in Lab 1? If so, how was your experience compared to using the RHL-RELIA in Lab 2 (i. e. ease of use, drivers installation, external connectors/adapters, etc.)
8	What Operating System (OS) do you have in your computer? Did you have a problem using the Physical PLUTO Kit with your OS? Did you have a problem using RHL-RELIA with your OS?
9	How, if at all, do you think that completing the assignment via a remote platform instead of with physical hardware impacted your learning? - To what degree was the lab effective in teaching you key concepts? - What skills, if any, did you learn while completing the RHL-RELIA lab assignment(s)? - To what extent did you feel engaged while completing the assignments?
10	Given this format, did you receive enough support to successfully complete the assignments?
11	Do you think that RELIA is a platform that promotes equitable access to engineering education?
12	Compared to how you thought about remote labs before completing the RHL-RELIA lab assignment(s), what, if anything, has changed?
13	What, if anything, was the most valuable aspect of using the remote lab platform?
14	How, if at all, do you think the remote lab platform could be improved?
15	Do you have any additional comments?

5.8.3 Preliminary Findings: Focus Group

The results of the evaluation were centered around several key themes, including the level of satisfaction among users, the user interface experience, comparisons with the physical ADALM-Pluto kit, and considerations regarding equitable access.

5.8.3.1 General satisfaction with RHL-RELIA labs

Preliminary findings from the focus group and post-survey show in students a positive experience with RHL-RELIA, explaining that the platform was easily accessible, straightforward to learn and use, and the experience was similar to using a physical hardware kit. One student commented on the benefits of RHL-RELIA:

> *"With physical labs when I found a new solution I had to power up a board and connect it to my laptop and wait for it to reboot . . . now when I have a new idea I can just go to the website, upload it there, and I will see the result immediately- I don't need to set up any hardware."*

Another student underscored the convenience of RHL-RELIA

> *"I would say accessibility [was the most valuable aspect] as long as you have a stable internet connection and a computer to work from you can access those labs in a fairly easy and simple to use way."*

5.8.3.2 User interface experience

Under the 'User interface experience' heading, students conveyed that the RHL-RELIA interface functioned effectively, providing them with a sense of operating physical equipment. A student shared their perspective:

> *". . . it takes the aspects of working with your hands with hardware and puts it on a screen. . . you don't get to move all of the knobs but it doesn't detract from the experience as much as I anticipated it would and I felt like it was a good representation of what it would be like if whatever hardware was in front of you."*

5.8.3.3 Comparison with physical ADALM-Pluto kit in Lab 1

Students who utilized a physical ADALM-Pluto kit in Lab 1 encountered greater difficulties compared to RHL-RELIA. Multiple students highlighted challenges in getting both ADALM-Pluto devices to function simultaneously, with one student resorting to RHL-RELIA to ensure proper functionality. In their own words:

> *"I did appreciate being able to see 'here's the receiver. here's the transmitter in front of me.' I'm typically more of a mechanical learner but in the end I ended up using RELIA just to double-check everything was working properly. . . overall I enjoyed using RELIA more than the hardware."*

5.8.4 Equitable access

All students unanimously agreed that the RHL-RELIA platform fosters equitable access to engineering education, attributing this to two primary factors: 1) accessibility, allowing usage anywhere and anytime as long as an internet connection is available, and 2) reduced cost, as departments are not obligated to acquire and maintain expensive physical kits. Two students specifically outlined the advantages:

> *"Imagine if you were running a class and you had 50 of these lab kits and you had to maintain them. That in and of itself seems like it needs an additional employee. . . "*
>
> *"[The benefit is] not just for individual users, let's say less well-funded departments and institutions could benefit from this. They might not need to buy their own, they can tap into other RELIA servers."*

5.8.5 Conclusions of the OEA report

The initial findings from the evaluation indicate that students expressed satisfaction with the user experience, noting various advantages such as flexibility, ease of use (including the user interface and wait times), and cost-effectiveness. Additionally, students indicated that they received adequate introduction and ongoing support to effectively fulfill the RHL-RELIA assignments.

Although students indicated somewhat lower satisfaction with the knowledge gained in Lab 0 and Lab 2 (with means ranging from "neutral" to "satisfied"), initial analyses propose that this stemmed from the lack of alignment between the lab content and the course material rather than any shortcomings with RHL-RELIA. To support this assertion, two students stated:

> *"If you were to use this platform to do a more meaningful assignment that was more related to what was talked about in class or something similar, I think it would be a really useful tool."*
>
> *". . . the fact that students were able to complete the lab with little background [knowledge] is a testament to how user friendly RELIA is."*

5.9 Conclusions of the Chapter

The development and implementation of RHL-RELIA, based on the MELODY model, have provided a comprehensive system characterization, facilitating a thorough understanding of it. MELODY's architecture has been instrumental in structuring each block layer during the development process, enabling RHL-RELIA to be open-source, technology-agnostic, low-cost, and conducive to fulfilling engineering education experiments.

In terms of accessibility, RHL-RELIA's user interface allows for the display of independent widgets, enabling manipulation of streaming data. The framework within Google Charts libraries can seamlessly integrate with SDR signal processing engines, supplanting the QT libraries. This enables users to access RHL-RELIA in a technology-agnostic manner, eliminating the need for specialized software. Additionally, it provides scalability for future growth through the addition of more widgets or customization for more intricate systems.

Integrating Red Pitaya SDR into RHL-RELIA enhances the efficiency of sharing diverse SDR applications within a unified framework. This integration fosters scalability and cost-effectiveness, facilitating expansion and opening up new avenues for incorporating additional SDRs.

The isolation rubric gauges interference within a multi-radio system, accounting for degradation and intermodulation interference. Notably, transmitter noise is minimal due to the low power output of ADALM-Pluto SDR and the use of Faraday Cage isolation which reduces external interference by approximately 29 dB. Additionally, self-receiver noise is minimized by disabling the transmitter within the receiver unit. Consequently, RHL-RELIA achieves an average SINR of 37 dB for BPSK communication, earning a five-star rating.

In terms of characterization, tests indicate that the system exhibits linearity across most of its dynamic range. These tests also enable the calculation of the Receiver Constant, providing insight into how the receiver responds to its input. Furthermore, this factor facilitates the estimation of other parameters such as output noise N_{OUT} and Minimum Detectable Signal (MDS). Alongside other tests, this comprehensive evaluation earns RHL-RELIA a top rating of five stars.

The combination of features such as affordability, technology agnosticism, and maximizing user accessibility has earned RHL-RELIA top ratings in scalability, availability, and usage within the lab environment, each receiving five stars. This reflects a fine balance between quality and cost efficiency. Furthermore, interoperability could be further enhanced by incorporating additional SDRs with diverse characteristics.

Chapter 6

CASE STUDY #2 - IMPLEMENTING THE MELODY MODEL: RHL-RADAR

This chapter is a modified version of [22] and [101].

- [22] M. **Inonan** and R. Hussein, ”MELODY: A Platform-Agnostic Model for Building and Evaluating Remote Labs of Software-Defined Radio Technology,” in IEEE Access, vol. 11, pp. 127550-127566, 2023, doi: 10.1109/ACCESS.2023.3331399

- [101] M. **Inonan**, M. Reynolds, and R. Hussein, ”RHL Radar Remote Laboratory,” in Proc. 21st International Conference on Smart Technologies & Education (STE), Helsinki, Finland, Mar. 6-8, 2024.

6.1 Overview

RHL-RADAR is a lab that involves the creation of a remotely controllable Radar system prototype designed to estimate the rotational velocity of a fixed structure. This educational tool is oriented toward to supplement Radar courses by actively engaging in real-world Radar problem-solving exercises. Radar, a device that utilizes electromagnetic waves, is employed to detect various physical parameters of objects, including distance, velocity, and more. It finds common applications in tracking ships, airplanes, vehicles, spacecraft, missiles, and natural phenomena like cyclones, weather patterns [102]. Specifically, this dissertation explores the implementation of a bi-static Continuous Wave (CW) radar to estimate the rotational velocity from micro-doppler signatures.

6.2 Requirements

In contrast to RHL-RELIA, where typically two cooperating entities handle transmission and reception, radar applications involve a non-cooperative entity known as the target. This presents additional challenges in terms of features, configuration, and processing stages, requiring elements such as powerful antennas and digital signal processing. In the case of RHL-RADAR, the objective was to provide experimentation with a Continuous Wave radar capable of estimating the rotational velocity of a stationary structure.

6.3 System Design

For RHL-RADAR, MELODY proposes changes, particularly in the infrastructure layer. This includes the adoption of a single SDR transceiver paired with a suitable antenna. By utilizing a single SDR, the aim is to reduce costs and address synchronization issues and timing jitter, which can complicate signal processing. Additionally, given the capability of ADALM-Pluto to function as a full-duplex device in radar applications, it can effectively act as a bistatic radar by utilizing separate antennas for transmission and reception.

As for the antenna selection, the preference was for one that primarily emits radio waves in a specific direction, facilitating efficient energy transmission along that path. In this experiment, the Log Periodic Antenna was chosen. This antenna type is characterized by its directional radiation pattern, providing significant gain ranging from 9 to 10 dBi. Additionally, it demonstrates excellent versatility across a wide frequency range. Further specifications can be found in [103]. A visual representation of components derived from the MELODY model can be seen in Figure 6.1 and these components are organized into blocks on university servers and instances, as illustrated in Figure 6.2.

6.3.1 Continuous Wave Radar and micro-doppler effects

Continuous Wave (CW) Radar emits a RF continuous wave energy at a fix frequency without any interruption. This type of Radar is able to estimate the velocity of a target by measuring a portion of the signal reflected back to the Radar receiver. The receiver then analyzes the frequency shift, known as the Doppler shift, between the emitted signal and the received signal [104].

CW radar is commonly used in applications like speed detection. However, it lacks the ability to estimate range resolution due to its reliance on continuous transmission without pulse timing for distance measurement. Despite this limitation, CW radar serves in specialized roles, such as estimating the rotational velocity of objects [105]. CW radar estimates the velocity of a target

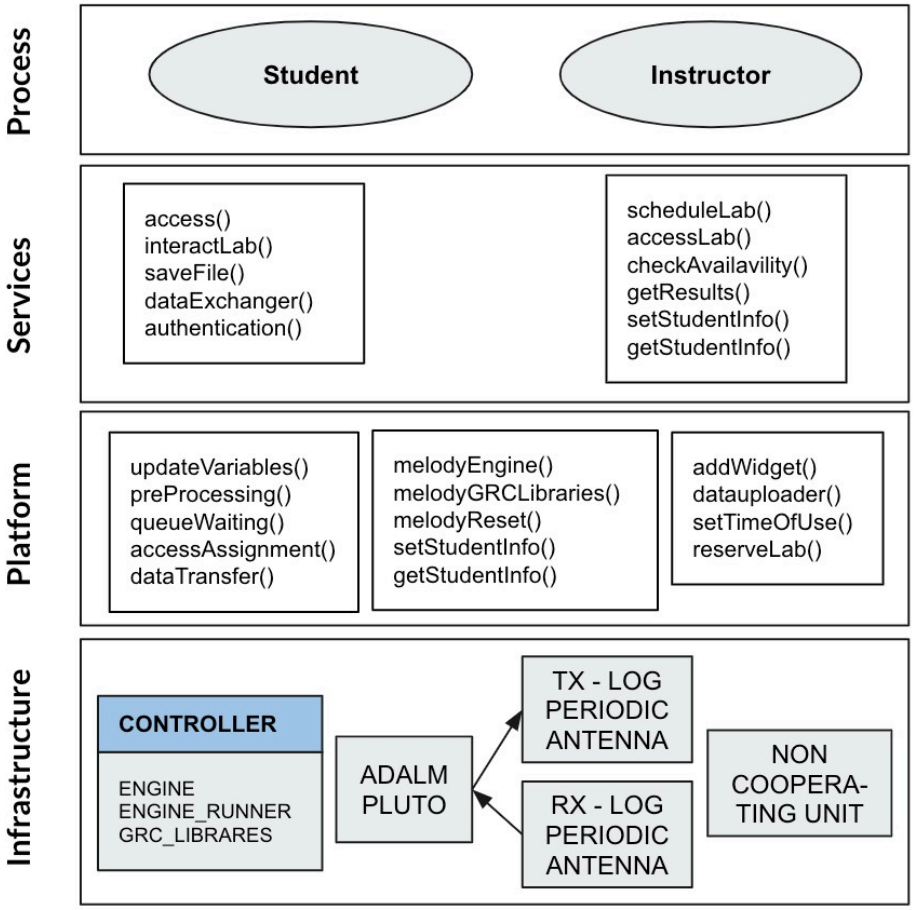


Figure 6.1: CW Doppler Radar experiment diagram.

by detecting a frequency shift that is proportional to the velocity and direction of the target with respect to the transmitting source, thanks to the Doppler effect [106]. However, not every target is a rigid object; therefore, they have other movements such as vibrations and rotations in different directions that produce additional Doppler shifts known as micro-Doppler [107]. One example of this effect occurs when a helicopter flies; its blades' rotations generate micro-Doppler signatures in radar receiver [108]. In this thesis, a CW radar system tailored for estimating the velocities of a rotating structure at various speed levels by detecting the micro-Doppler signatures is presented. Figure 6.3 shows the components that compose a bistatic CW radar system tailored for such purposes.

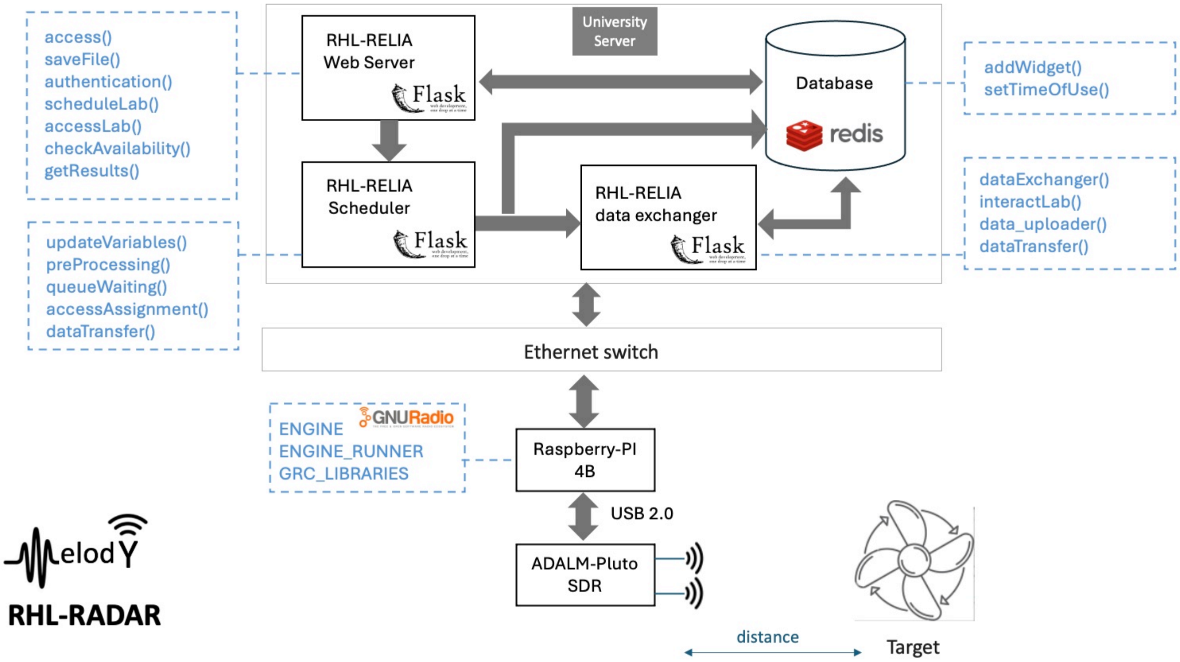


Figure 6.2: CW Doppler Radar experiment diagram.

6.3.2 Modeling of The Rotating Structure

The mathematical analysis of the received signal in Doppler Radars encountering a rotating structure with blade length L involves complex modeling due to the requirement of azimuth and pitch angles of the incident wave. However, in the case of a fixed rotating structure where the Radar is aligned with the center, the analysis can be simplified. In this scenario, at time $t = 0$, a scattering point P_0 positioned at an initial rotation angle ϕ_0 begins rotating counterclockwise with an angular velocity of Ω. The movement is depicted in Figure 6.4.

At a given time t, the point P undergoes rotation and is denoted as $P(t)$, with the rotation angle represented as $\phi_t = \Omega t + \phi_0$. The distance from the Radar to the point P can be expressed as:

$$R_p(t) = \sqrt{(R_0 + x_t)^2 + y_t^2} \tag{6.1}$$

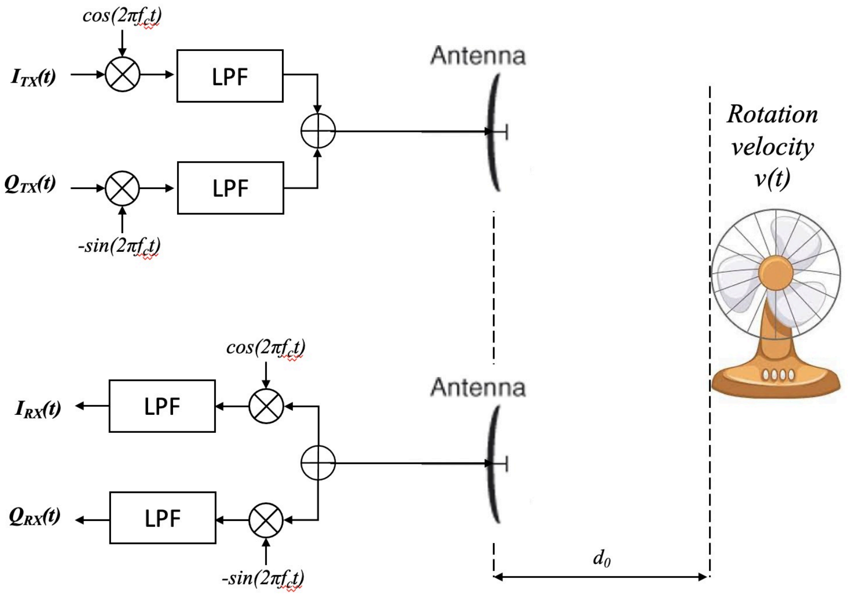


Figure 6.3: CW doppler radar diagram

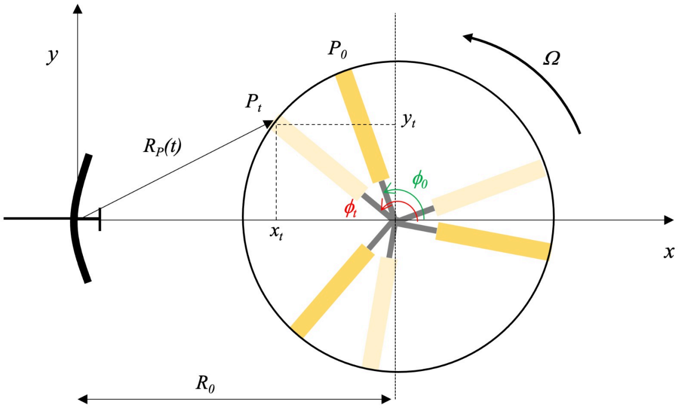


Figure 6.4: Rotating structure diagram.

$$R_p(t) = \sqrt{(R_0 + L\cos\phi_t)^2 + (L\sin\phi_t)^2} \tag{6.2}$$

$$R_p(t) = \sqrt{R_0^2 + L^2 + 2R_0L\cos(\phi_t)} \tag{6.3}$$

$$R_p(t) = \sqrt{R_0^2 + L^2 + 2R_0 L \cos(\Omega t + \phi_0)} \tag{6.4}$$

In the far field distance can be reduced to:

$$R_p(t) = R_0 + L \cos(\Omega t + \phi_0) \tag{6.5}$$

According to the Radar theory, the echo of a scattering is attenuated and delayed. The is delayed is represented by:

$$\tau(t) = \frac{2d_0}{c} + \frac{2v(t)}{c} \tag{6.6}$$

where d_0 is the distance between the Radar and the target and $v(t)$ is the velocity of the target. However, because it is a static infrastructure then $v(t)$ is 0. Therefore for this specific case the echo returned is:

$$s(t) = A_r \exp\{-j2\pi f_{TX}(t - \tau(t))\} \tag{6.7}$$

Where A_r is the amplitude of the received signal and f_{TX} is the frequency of transmission. Replacing

$$s(t) = A_r \exp\{-j2\pi f_{TX}(t - \frac{2R_p(t)}{c})\} \tag{6.8}$$

$$s(t) = A_r \exp\{-j2\pi f_{TX} t + j\frac{4\pi R_p(t)}{\lambda}\} \tag{6.9}$$

$$s(t) = A_r \exp\{-j2\pi f_{TX} t + j\frac{4\pi[R_0 + L\cos(\Omega t + \phi_0)]}{\lambda}\} \tag{6.10}$$

Thus, the base-band signal at the scattering point P_t is:

$$s_p(t) = A_r \exp\{j\frac{4\pi R_0}{\lambda}\} \exp\{j\frac{4\pi L \cos(\Omega t + \phi_0)}{\lambda}\} \tag{6.11}$$

For a fan with N blades, the initial rotational angle of each blade is:

$$\phi_k = \phi_0 + \frac{2k\pi}{N} \qquad k = 0, 1, \ldots, N-1 \tag{6.12}$$

The expression for the phase function of the echo at the tip of the blade k is as follows:

$$\phi_k(t) = \frac{4\pi L}{\lambda} \cos(\Omega t + \phi_0 + \frac{2\pi k}{N}) \tag{6.13}$$

As it is know the frequency features of the blade are represented by the Doppler frequency shift is the derivative of the phase:

$$f_{D,k}(t) = \frac{1}{2\pi} \frac{d\phi_k(t)}{dt} \tag{6.14}$$

Then resolving equation 6.14 taking from equation 6.13

$$f_{D,k}(t) = -\frac{2\Omega L}{\lambda} \sin(\Omega t + \phi_0 + \frac{2\pi k}{N}) \tag{6.15}$$

From Equation it can be deducted that the rotational speed modulates the instantaneous Doppler frequency as a sinusoidal curve [109]. Therefore, the maximum Doppler is when

$$f_{Dmax} = \frac{2\Omega L}{\lambda} = \frac{2v}{\lambda} \tag{6.16}$$

Figure 6.5 illustrates the simulation of micro-Doppler characteristics for rotating 5 blades at a speed of 900 RPM, which simulates real maximum velocity $v3$ of the fan.

The radial velocity (v_r) of a target can be determined by measuring the frequency shift (f_d) [110]. This provides information about the target and its components. Hence, estimating the RPM (rotations per minute) of a rotating structure, like rotating blades, can be achieved by observing the micro-Doppler effect generated by the rotational motion. The relationship between the observed frequency shift and the RPM of the rotating structure can be expressed as:

$$f_d = \frac{RPM_{fan} \times N}{60} \tag{6.17}$$

where f_d is the frequency shift and N is the number of blades of the fan.

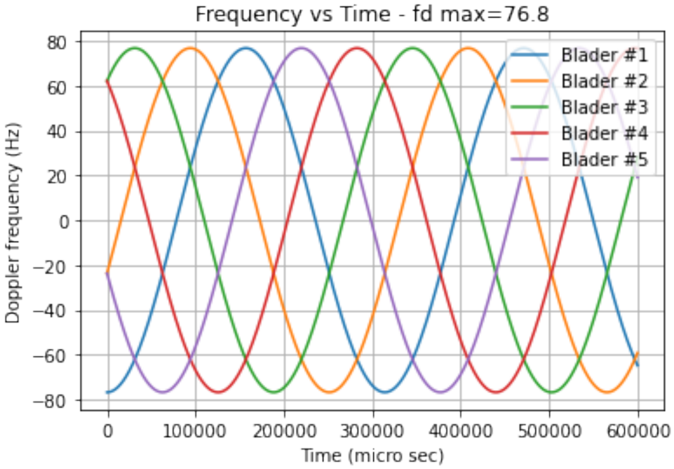


Figure 6.5: The micro-Doppler features of a fan with 5 blades.

6.4 Implementation

In radar applications, it's crucial to utilize an antenna that predominantly emits radio waves in a specific direction, enabling concentrated transmission of energy in that particular direction. For this experiment, a Log Periodic Antenna is chosen due to its directional radiation pattern, high gain (typically ranging from 9 to 10 dBi), and its capability to operate across a wide range of frequencies. The specific antennas employed are the HG72710LP-NF models from L-com, which cover the frequency range of $698 - 960$ MHz and $1710 - 2500$ MHz. These antennas feature a horizontal beam width of $78°$ and a vertical beam width of $56°$. Additional specifications can be found in [103].

The area where the radiation pattern achieves stability and predictability is termed the far field. Within this domain, electromagnetic waves propagate as near-planar wavefronts, and the intensity weakens proportionally to the inverse square of the distance from the antenna [111]. For log-periodic antennas, the far field relies solely on the operating frequency, as depicted by the subsequent equation:

$$\text{Far Field} = \frac{c}{2\pi f} \tag{6.18}$$

where c represents the speed of light in vacuum, and f stands for the frequency of operation of the antenna.

Figure 6.6 illustrates the Radar prototype system. The experiments entailed employing a fan as the target object, with three different velocities ranging from the lowest (v1) to the highest (v3). The distance between the transmitter/receiver (TX/RX) and the target was set at 50 cm, positioned within the far-field region, which at 800 MHz begins approximately at 6 cm. Additionally, to augment reflectivity, the blades of the fan were coated with aluminum. Moreover, the configuration parameters are detailed in Table 7.2.

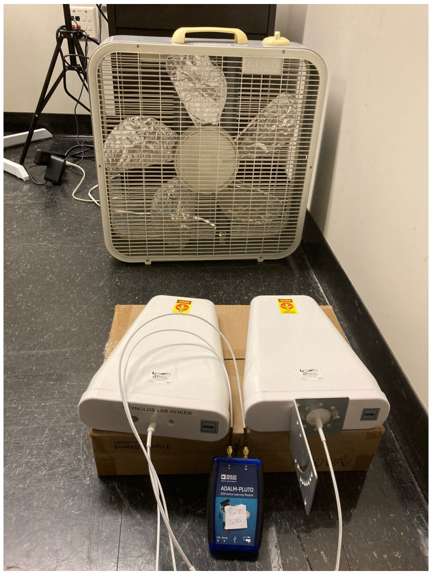


Figure 6.6: CW Radar system installed.

6.4.1 DSP in receiver

One significant advantage of SDR technology is its capability to perform the mixing process for signal conversion to baseband digitally. Additionally, the conjugate multiplication can be executed during data acquisition, presenting a notable advantage over its analog counterpart. Consequently, this accelerates the development time of RF prototypes. However, a limitation of ADALM-PLuto SDR is that the minimum sample rate is 600 kHz. Therefore, an additional block for downsampling and/or filtering data must be added if a narrow bandwidth is required. The user can apply this filter stage during the acquisition, or they can acquire raw data and then apply this signal processing offline. The DSP process is illustrated in Figure 6.7.

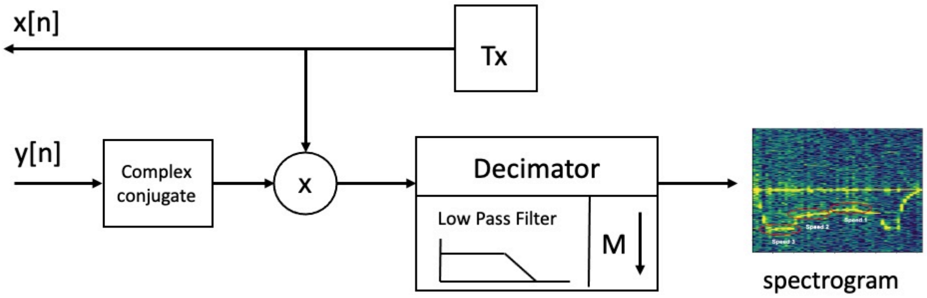


Figure 6.7: CW Radar DSP block diagram.

Table 6.1: CW Radar Configuration.

Parameter	Value
Frequency	800 MHz
Tx Gain	0dB
Rx Gain	60dB
Sample Rate	2MHz
Data Type and Resolution	I/Q 64bits
Low Pass Filter cut-off frequency	500 Hz

6.5 Results

The outcomes derived from the Radar experiment are depicted in Figure 6.8, showcasing a spectrogram. A spectrogram visually represents the spectrum of frequencies in a sound or signal, illustrating how they change over time [112].

Initially, the velocities may not be clearly visible in the Spectrogram. However, after applying a low-pass rectangular window filter, the Spectrogram in Figure 6.9 reveals three distinct velocities: $v3$, $v2$, and $v1$. The corresponding spectra and RPM measurements for these velocities are presented in Figures 6.10, 6.11, and 6.12, respectively.

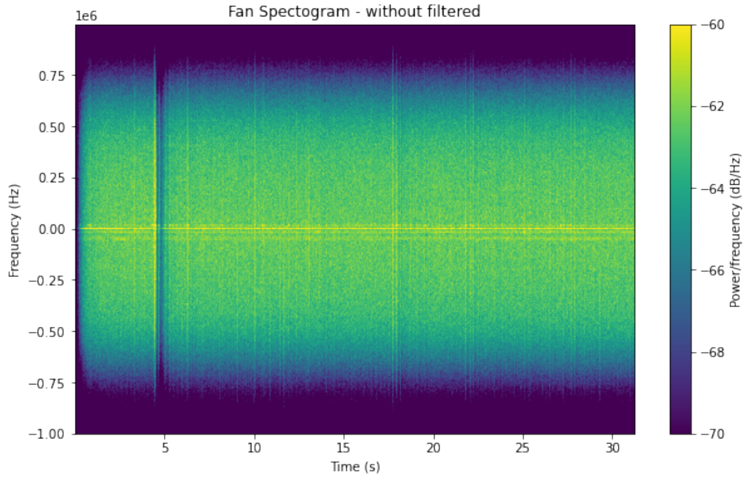


Figure 6.8: Raw data Spectrogram of the rotating structure experiment.

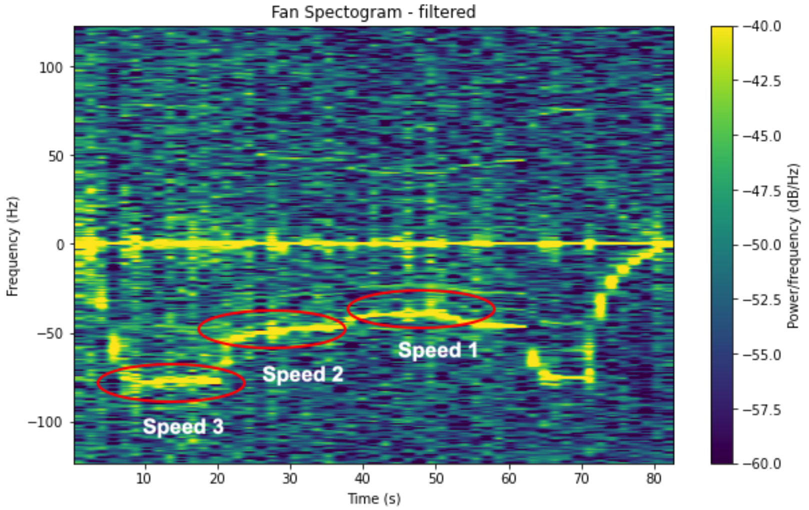
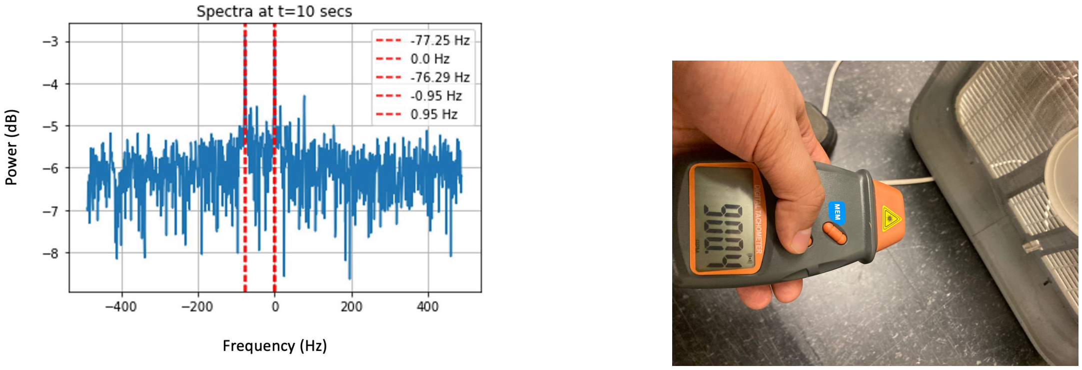


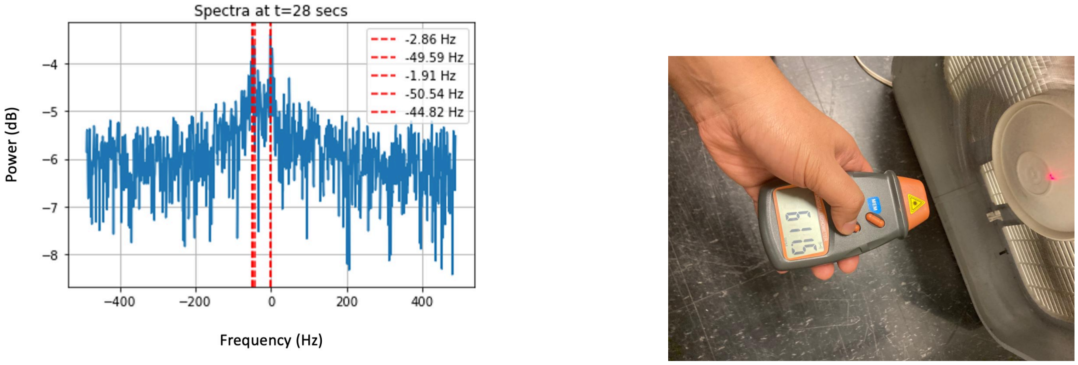
Figure 6.9: Filtered data Spectrogram of the rotating structure experiment.



(a) Spectrum of the fan - v3.

(b) RPM of Fan's speed - v3.

Figure 6.10: Spectra and tachometer's measurement of velocity - v3.

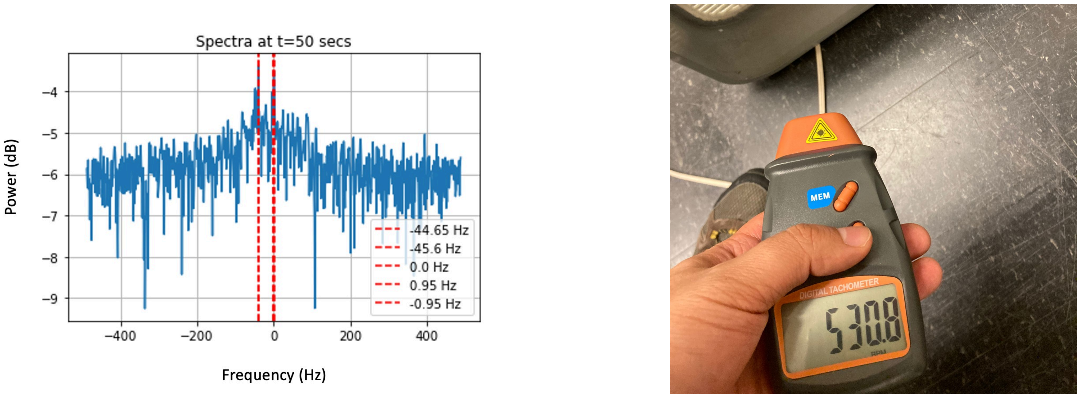


(a) Spectrum of the fan - v2.

(b) RPM of Fan's speed - v2.

Figure 6.11: Spectra and tachometer's measurement of velocity - v2.

By extracting a specific time slice from the data, it becomes possible to obtain a more precise estimate of the Doppler frequency, which can then be compared with the measurements obtained from the tachometer. The comparison between the two values can be performed using Equation 6.17, allowing for a quantitative assessment of their agreement. The results demonstrate a strong correlation between the two measurements, as indicated by the low error values ranging between 1-3%. Table 6.2 provides a summary of the three measurements obtained.



(a) Spectrum of the fan - v1.

(b) RPM of Fan's speed - v1.

Figure 6.12: Spectra and tachometer's measurement of velocity - v1.

Table 6.2: Comparison of results from Radar and Tachometer's measurement.

Tachometer (RPM)	Radar (Hz)	Error (%)	Std Dev	Power (dB/Hz)
900.4 (v3)	76.29 - 77.25	1.57 - 2.92	4.92	-3dB
611.5 (v2)	49.59 - 50.54	0.74 - 2.68	3.88	-3dB
530.8 (v1)	44.18 - 45.57	0.94 - 3.08	3.44	-3dB

6.6 Rubrics

RHL-RADAR consists of one ADALM-Pluto SDR station. The procedure for each measurement and the corresponding values obtained are detailed below.

6.6.1 Isolation

MELODY does not include an isolation mechanism in RHL-RADAR, as it is designed to operate with either a single instance or in ultra-concurrent mode. Additionally, the limited space characteristic of remote labs makes coexistence unfeasible in this radar setup. However, in this application, the ADALM-Pluto functions as a full-duplex transceiver, resulting in self-receiver interference that was to calculated $37dB$ less than peak in Figure **??** so it will decrease the dynamice raange. Therefore, according to MELODY's isolation rubric, RHL-RADAR is deemed **Not applicable**.

6.6.2 Characterization

In the case of characterization, RHL-RADAR utilizes Characterization-Pluto, yielding the same results as RHL-RELIA. Therefore, according to MELODY's characterization rubric, RHL-RADAR is deemed **5 stars** ★★★★★.

6.6.3 Interoperatibility

Since RHL-RADAR operates with only one unit, the interoperability is considered **Not applicable**.

6.6.4 Lab Scalability

Regarding lab scalability, the system is currently limited to supporting a single module. To accommodate additional modules, a transition to the ultra-concurrent mode is necessary. Therefore, according to MELODY's Lab Scalability rubric, RHL-RADAR receives **1 star** ★☆☆☆☆.

6.6.5 Lab Availability

In this section, RHL-RADAR receives a full rubric. RHL-RADAR and RHL-RELIA share the same Server University platform, thus accessible through a web browser. Therefore, according to MELODY's Lab Availability rubric, RHL-RADAR receives **5 stars** ★★★★★.

6.6.6 Lab Usage Sessions

In terms of lab usage, the system allocates a 30-second window for each user to utilize the lab, ensuring efficient rotation. Therefore, according to MELODY's Lab Availability rubric, RHL-RADAR is deemed **5 stars** ★★★★★.

6.7 Conclusions of the Chapter

RHL-RADAR serves as an adjunct to radar theory in engineering courses. Understanding the micro-Doppler effect offers a sophisticated level of mathematical insight that enhances students' grasp of radar principles and their practical applications. Additionally, students gain a deeper understanding of radar signal processing, target characterization, and detection techniques, thereby enriching their educational experience for real-world challenges in radar engineering.

Despite its low cost (approximately $600) and lack of external synchronization within the system, RHL-RADAR demonstrates the capability to deliver precise measurements of rotational velocity, with a maximum margin of error compared to a tachometer of 3%.

While RHL-RADAR shares several features with RHL-RELIA, a significant distinction is its configuration for a single station, employing the ADALM-Pluto in full duplex mode. This decision is influenced not only by cost-effectiveness but also by the physical constraints of remote labs, which often operate within limited spaces. Additionally, RHL-RADAR utilizes a transmitter approximately six times more powerful than RHL-RELIA, rendering its isolated use impractical. However, to accommodate multiple users, RHL-RADAR seamlessly transitions into an ultraconcurrent mode, allowing simultaneous access for several individuals. In this mode, users can access pre-recorded data containing various radar parameters, optimizing resource usage while maintaining the integrity and functionality of the radar system.

More complex radar experiments can be performed with the versatility of SDR devices, which offer a range of capabilities beyond traditional Continuous Wave (CW) radar systems that solely capture Doppler information. Integrating RedPitaya further enhances interoperability, enabling the implementation of diverse experiments and expanding the scope of data acquisition from targets. This synergy enables researchers and students to delve deeper into radar theory and applications, fostering innovation and exploration in the field of radar technology.

Chapter 7

CASE STUDY #3: MELODY'S EQUITABLE ACCESS APPROACH WITH DIGITAL INEQUALITIES

This chapter is a modified version of [21], [113] and [114].

- [21] M. **Inonan**, P. Orduna, and R. Hussein, "Adapting a remote SDR lab to analyze digital inequalities in wireless communications education in Latin America," Revista Innovaciones Educativas, vol. 25, no. SPE1, pp. 31-44, 2023.

- [113] M. **Inonan**, A. Paul, D. May, and R. Hussein, "RHLab: Digital Inequalities and Equitable Access in Remote Laboratories," in Proc. 2023 ASEE Annual Conference & Exposition, June 2023.

- [114] M. **Inonan**, A. Paul, D. May, and R. Hussein, "RHLab: Digital Inequalities and Equitable Access in Remote Laboratories," in Proc. 2023 ASEE Annual Conference & Exposition, June 2023.

7.1 Overview

The literature has classified digital inequalities into three levels, each influenced by different factors depending on the specific circumstances of various regions. This research aims to delve into the nuances of challenges faced by students, examine the impact of remote labs on these three levels of inequalities, and propose potential solutions and interventions to incorporate equitable access into the MELODY model. A comprehensive review of existing research, along with surveys and focus groups involving students from the United States, has been conducted. Additionally, adaptations of RHL-RELIA have been customized to explore these issues within the context of Latin America.

7.2 Levels of Digital Inequalities

According to Katz's definition [115], digital inequality refers to limited access to the internet and internet-connected devices. Initially, this issue was framed as a "digital divide," dividing the population into those who have access to technology and those who do not. However, recent research has shown that digital inequality is more complex than a simple binary classification [115], and it has been classified into three levels:

7.2.1 First level

The initial tier pertains to unequal internet access, where access to the network is primarily dictated by demographic characteristics [116]. This category encompasses individuals who lack access due to financial constraints, have slow or unreliable connections, share devices, or primarily rely on smartphones or tablets for connectivity [117].

7.2.2 Second Level

The second level is more nuanced and focuses on individuals' proficiency and utilization of internet technology. This tier distinguishes between active content creators and passive content consumers [118].

7.2.3 Third Level

Lastly, the third tier can be seen as an extension of the first two [119]. It encompasses individuals capable of leveraging internet access to generate wealth, such as by converting their access into monetary gains [120]. In the educational realm, directly evidencing the digital divide at this level is challenging, as assessing students' incomes is complex. Nonetheless, it is noteworthy that research has demonstrated how digital access and skills can enhance job prospects through successful engagement with online resources [121]. Table 7.1 summarizes the three levels of digital inequalities identified by researchers and describes their relevant characteristics.

Table 7.1: Summary of digital inequalities factors

	Level 1	Level 2	Level 3
Digital inequality factors	• Cannot afford internet service. • Have slow or unstable connections. • Share devices. • Primarily use smartphones or tablets for connectivity.	• Have difficulties adjusting settings and using internet platforms to their full capacity. • Encounter issues in communication through internet tools or when seeking assistance. • Are not prepared to generate content in digital environments.	• Can limit job opportunities

7.3 Digital Inequalities in USA

In the United States, digital disparities persist even in states hosting numerous major technology companies. A study conducted by the California Emerging Technology Fund (CETF) and documented in their 2020 report revealed that approximately 9.6% of California residents still lack access to a computer at home or remain disconnected [122]. Rural areas in California also experience a digital divide. Currently, 89.9% of them have access to 10/1 megabits per second (Mbps) internet connections, according to a report by the CPUC for the year 2022 [123]. However, there is an improvement trend, as in 2018 only 71.5% of rural households had access to broadband infrastructure that allows for 10/1 Mbps service offerings [124].

In another US state, Washington, data from the American Community Survey (ACS) conducted between 2015 and 2019 reveals that 84.5% of high school students and graduates have access to high-speed internet [125]. Additionally, the same study indicates that 95% of these students possess a computer or other electronic device for accessing the internet. However, disparities become evident when examining access by racial groups. For instance, while high-speed internet access at home is reported at 85% for Asian and White students, this percentage drops to approximately 72% for Hispanic and Native American/Alaska Native students.

In rural US areas, inequality percentages are higher [126].A survey of 56 district-level technology directors in Minnesota revealed significant geographical disparities. For instance, nearly half of the districts reported lacking connectivity, either due to internet service providers not reaching them or families being unable to obtain a strong enough signal to support distance learning. The primary obstacle to addressing this issue is the cost of installation in rural areas, which requires significant investments such as excavations over considerable distances, often in challenging terrain.

Additionally, rural communities often lack the population density necessary to ensure high levels of demand. This presents an economic challenge for companies involved, as they often struggle to achieve financial returns sufficient to cover implementation costs [127]. However, it is worth noting that the gap in internet connectivity has been gradually narrowing over the years. According to the Federal Communications Commission (FCC), the entity responsible for regulating and overseeing communications in the United States, the disparity between urban and rural areas nationwide was 30% at the end of 2016 and decreased to 16% by the end of 2019 [128].

These digital inequalities have become starkly apparent in the educational sector during the COVID-19 pandemic. University students have encountered challenges in maintaining reliable internet connectivity, ensuring the operational functionality of their technological devices, and establishing effective communication with faculty and teaching assistants [115].

This overview of digital disparities in the United States encompasses both geographical and ethnic factors. Despite some improvements, significant obstacles persist in accessing digital technology. Now, it is essential to delve into the specific scope of these digital divides in the context of remote labs, as they necessitate a high level of technological infrastructure, including material resources and knowledge.

7.3.1 Survey and Focus Groups insights into Digital Inequalities

A comprehensive study was undertaken through surveys and focus groups to investigate the perspectives of US students who utilized a remote lab as part of their digital circuit course in 2022. This research methodology adopted mixed methods, combining quantitative and qualitative responses, and utilized thematic analysis to comprehend the implications of remote labs in terms of equitable access.

In the survey, opinions were gathered from 83 out of 85 participating students regarding the factors deemed important when considering equitable access based on their Remote Laboratory experience. These responses were systematically coded, and the resulting highlighted themes are outlined in Table 7.2. Furthermore, the frequency of these themes in students' responses is visually represented in Figure 7.1.

Table 7.2: Factors of Equitable Access

Code	**Associated Phrases, Mentions, and Ideas**
Accessibility	24/7 availability, Offering equal opportunities for everyone, Reliability
Quality of Internet	Internet is all you need, Off-line options, Importance of Internet quality in academic success
Affordability	Free, Cost, Lab fee
Ease of Use	Functional, Usability, Quality of web interface, Not browser or OS-specific, Ease of Access
Convenience	Convenient, Schedule Flexibility (Anytime), Location Flexibility (Anywhere), Didn't require transport, No need to worry about damage
Other factors	Free to user's choice

Regarding the focus groups, a total of five sessions, each lasting 60 minutes, were conducted online via Zoom. These round-table sessions aimed to delve into various topics related to equitable access. Ten students, specifically chosen to represent minority groups, including individuals from low-income backgrounds and racial or ethnic minorities. The sessions revolved around questions pertaining to Diversity, Equity, and Inclusion (DEI) topics, accessibility, and digital inequalities. Through their responses, students articulated their perspectives on the impact of remote labs on accessibility, internet quality, and content creation. Here is a summary of the most significant interventions gleaned from the focus groups:

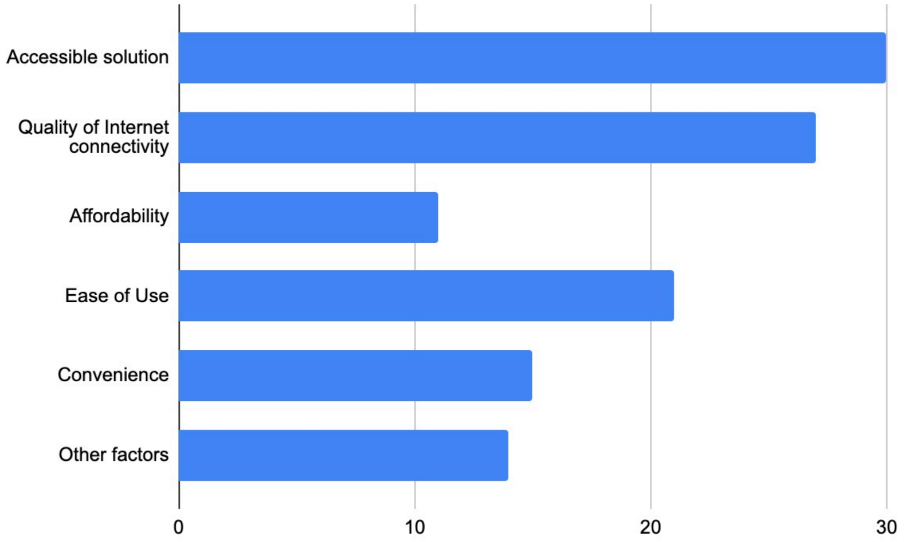


Figure 7.1: Student-mentioned Factors of Equitable Access vs. number of mentions in free response

7.3.2 Survey and Focus groups results

Results from both the survey and focus groups can be organized as follows:

Analyzing "Internet quality" as a factor of equity access:

Theme 1: Importance of Internet quality in academic success

> *"Students who are not fortunate to have consistent internet access may be unfairly disadvantaged in an online academic setting."*

The responses underscore the critical role of internet speed in ensuring the accessibility of remote labs. Students emphasize that the quality of internet connection directly impacts their ability to effectively utilize the lab resources.

Theme 2: Off-line & alternative options

> *"Get free internet access or rent a computer from my university if I need it."*

In the reflections provided by students, a key point highlighted was the financial obstacles linked to internet access and owning devices connected to the internet. One student proposed solutions such as providing free internet access or offering the option to borrow or rent university computers to guarantee equal access for all students. Another student pointed out the financial strain of paying for internet services, particularly for those living farther from campus due to financial limitations. These responses from both themes confirm that internet quality is indeed a factor that exacerbates level one of digital inequalities.

Importance of Remote Labs in Creation of Content

Theme 1: Facilitation of Creation Process

> *"Remote lab was nice in the creation because since it was so controlled, you knew that if any errors were happening it was usually on your side or most likely was on your side."*

Students emphasize that remote labs streamline the creation process by offering a controlled environment where errors are more likely to be attributed to the user, enabling easier troubleshooting and experimentation with both code and hardware.

> *"I'm often curious to learn if there's a more efficient way to solve a problem than the workaround I've implemented. It would be beneficial if there were opportunities to explore alternative problem-solving approaches. Incorporating peer solutions into the learning process could provide valuable insights into optimizing engineering solutions."*

Here, respondent expresses a desire for opportunities to explore alternative problem-solving approaches and incorporate peer solutions into the learning process. They see remote labs as platforms that could provide valuable insights into optimizing engineering solutions.

> *"Yes, absolutely. Like as an engineer to like help drives your creativity or like to improve on your quality you collapse with other people you work in a theme setting or like you work with other people to know what you're missing or what you need or what you already have your skill set. And I feel like remote lab is like a perfect collaborative tool for that aspect of engineering because again like physical lab can only like provide access to so many people."*

Remote labs in driving creativity and collaboration among engineers. They emphasize how remote labs serve as collaborative tools that allow for teamwork and exploration of different skill sets, fostering creativity in engineering projects. An important conclusion drawn from these reflections is that remote laboratories have the potential to bridge the gap of level two digital inequalities.

Analyzing "Accessibility" as a factor of equity access:

Theme 1: Technology as an Equalizer:

> *"I believe technology plays a crucial role in acquiring new knowledge. Being exposed to computers and accessing new technology from a young age has given me an advantage, particularly in learning about new topics."*
>
> *"I believe the remote lab offers the most accessible option for using FPGAs because it can be accessed from home or any system. In contrast, purchasing an FPGA is expensive, creating a financial barrier. Additionally, borrowing FPGAs from the lab may not be feasible due to limited availability, especially considering the large number of users."*

This excerpt provides insights into how remote technology levels the playing field, enabling students to overcome barriers and gain a competitive edge in learning about diverse topics. This perspective was emphasized by a significant portion of students, with 30% expressing it in the survey and 20% articulating it during the focus groups.

Theme 2: Financial Considerations and Commuting Costs:

> *"Commuting to school during peak hours can cost around $15-$16 a day in gas alone. While I don't consider myself from an underprivileged background, needing to work is just a reality based on my age. However, if you're someone like a younger student with additional responsibilities like childcare, reducing trips to campus can be a financial relief since transportation costs can add up."*
>
> *"I prefer the remote lab, especially considering my background in Thailand, where limited monetary resources often mean a lack of access to materials, particularly in rural areas where I grew up."*

In this theme, students highlight how remote labs help save money on things like transportation, making it a more affordable choice, especially for students with other expenses like childcare.

Theme 3: Simplifying Remote Lab Usage:

> *"I like using a website to use the remote lab because I don't need to worry about special software or what kind of computer I have. It works on my tablet, so I can use it anywhere."*
>
> *"I prefer using the website for the remote lab because it's more intuitive and user-friendly. Unlike software that you have to install on your computer, the website is light and doesn't require any updates. It's just easier to use overall."*

In this theme. students remark that using a website for remote lab access offers greater accessibility, flexibility, and ease of use compared to traditional software installations.

7.3.3 Survey and Focus groups - Discussion

Results from both the survey and focus groups can be summarized in Table 7.3, where a comparison is made between the categorization of the three levels of digital inequality and the survey responses contextualized within that framework. However, it's important to note that the limitations of the survey and focus groups may hinder the identification of third-level digital inequalities, as their focus primarily revolves around the advantages that proficiency in internet tool usage can offer.

7.4 Digital Inequalities in Latin America

Latin America is characterized by its vast territory and population, where urban overcrowding, population dispersion, unequal access to technology, and various demographic dynamics shape diverse realities [129]. Furthermore, several studies refer to a digital transformation that has impacted education, so its evaluation is not limited solely to a technological perspective but encompasses a systemic vision that considers social and institutional aspects [130]. This is of paramount importance because, despite sharing cultural aspects, countries in the region face unique situations and challenges.

An exemplary country that stands out for maintaining one of the lowest levels of digital inequality in the region is Uruguay. With an urban predominance of 95% [131], the country has promoted state projects since the 2000s to reduce the digital divide [127]. Among these projects are the telecenters of Digital Inclusion Spaces, in collaboration with the state-owned company ANTEL, which provides equipment, programs, and furniture, internet access, training, and maintenance of

Table 7.3: Comparison of Digital Inequalities (Literature vs. Remote Laboratories Survey & Focus group) in the U.S.

Digital Inequality Level	Literature Review	Survey and Focus group
First level	Limited access to the Internet and connected devices.	- Students inquire remote labs that do not rely on an Internet connection. - Students prefer access it from a web browser
Second level	Difficulties in adjusting settings and using platforms to their full capacity.	Students point out that remote lab fosters their creativity.
Third level	More job opportunities for those who have successful participation in online resources.	X

computer devices [132].

In Peru, a different reality exists, where a considerable rural population is more exposed to structural poverty. Rural populations face fewer economic opportunities and access to educational services. Furthermore, considering their status as linguistic minorities speaking indigenous languages instead of Spanish (the language used by the Peruvian state for its services), inequality with these populations becomes even more complex [127].

To understand this dynamic in the Peruvian context, Huanca-Arohuanca [133] conducted a study involving university students. The main objective was to explore the relationship between students' place of origin and their internet access. The results revealed that those from provinces and rural areas face greater obstacles compared to their counterparts residing in urban areas.

Similarly, in other countries, variations in mobile phone subscriptions have been observed according to population density. For example, nations with a lower proportion of rural population, such as Brazil, Mexico, and Argentina, have a higher number of subscriptions, while countries like Guatemala, Ecuador, Peru, Paraguay, and Panama show a lower number of subscriptions [134].

In this regard, researchers argue that strategies and programs should be specifically targeted at communities with limited access, simultaneously addressing essential needs in social, economic, and political domains. An ideal approach would involve close and active collaboration with members of these communities. This would ensure that digital solutions are conceived inclusively, respecting the diversity of contexts. In this way, not only material deficiencies would be addressed, but also efforts to alleviate the sense of social or territorial isolation that may arise due to insufficient access to digital and educational resources [135].

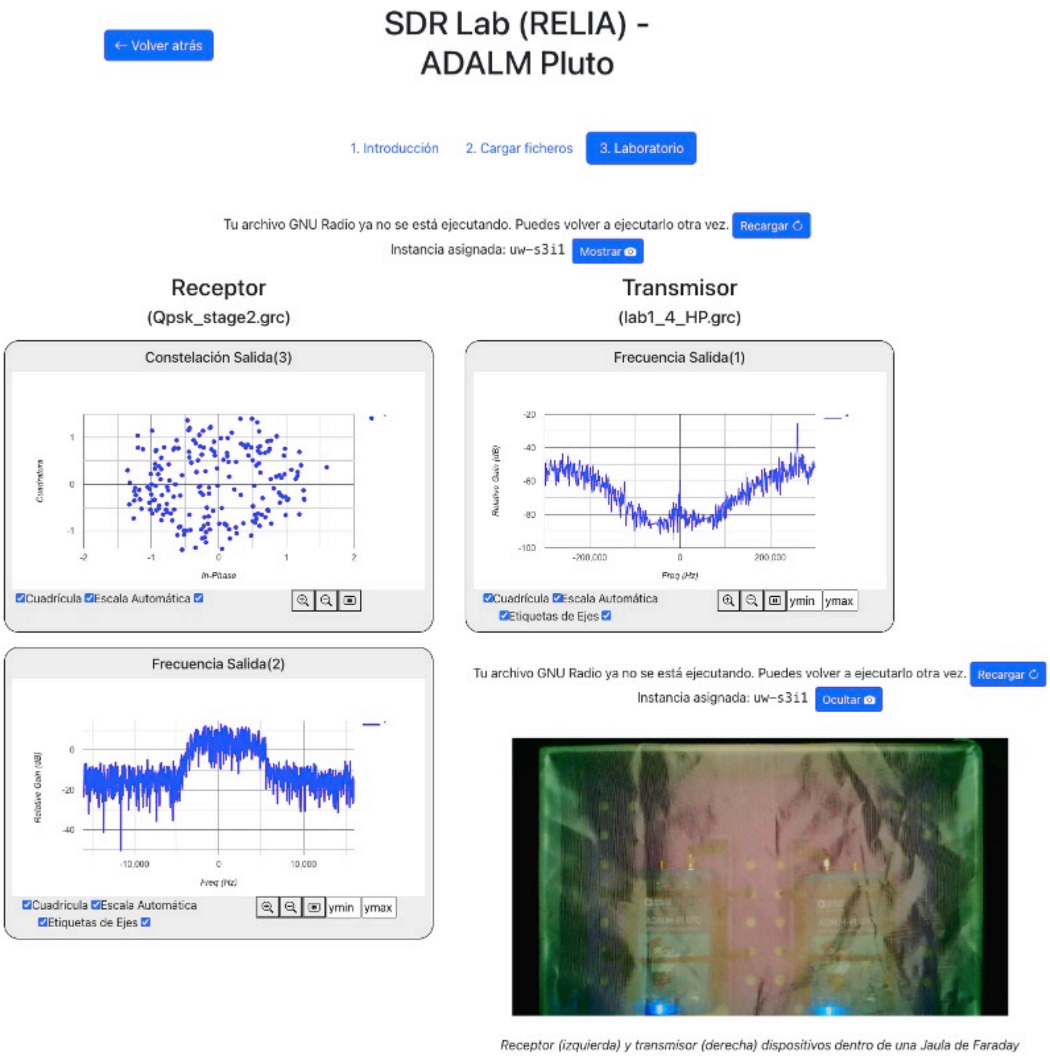
Given the diverse circumstances across various Latin American countries, creating a standardized design and approach for a remote lab that accommodates all these variations presents a challenge. To facilitate research on the impact of digital inequalities, it has been decided to expand the development of RHL-RELIA by offering versions of the remote lab in Spanish and Portuguese. This initiative aims to broaden accessibility in regions where university students may not have a strong technical command of the English language, thus enabling broader participation and engagement.

This expansion is particularly pertinent considering the landscape depicted by the Language School of the University of the Americas in Ecuador. The institution highlights the scarcity of competitive English courses in Ecuadorian schools, leading to gaps that impede an optimal learning trajectory. Consequently, students face significant challenges related to linguistic competence upon accessing higher education institutions, which are essential for graduation [136].

Figure 7.2 illustrates RHL-RELIA interfaces in Spanish, while Figure 7.3 depicts them in Portuguese. These new variants will not only be more accessible for students but will also benefit instructors by enabling broader and more precise feedback to assess and compare their perceptions.

7.5 Conclusions of the Chapter

Digital inequalities represent a complex social challenge that extends beyond simple access to technology, impacting multiple facets of society. While similarities exist between the United States and Latin America, the manifestation of these inequalities varies across regions. In Latin America, there's been a notable increase in the pursuit of higher education, especially among youth from


SDR Lab (RELIA) - ADALM Pluto

Tu archivo GNU Radio ya no se está ejecutando. Puedes volver a ejecutarlo otra vez.

Instancia asignada: uw-s3i1

Receptor (Qpsk_stage2.grc)

Transmisor (lab1_4_HP.grc)

Tu archivo GNU Radio ya no se está ejecutando. Puedes volver a ejecutarlo otra vez.

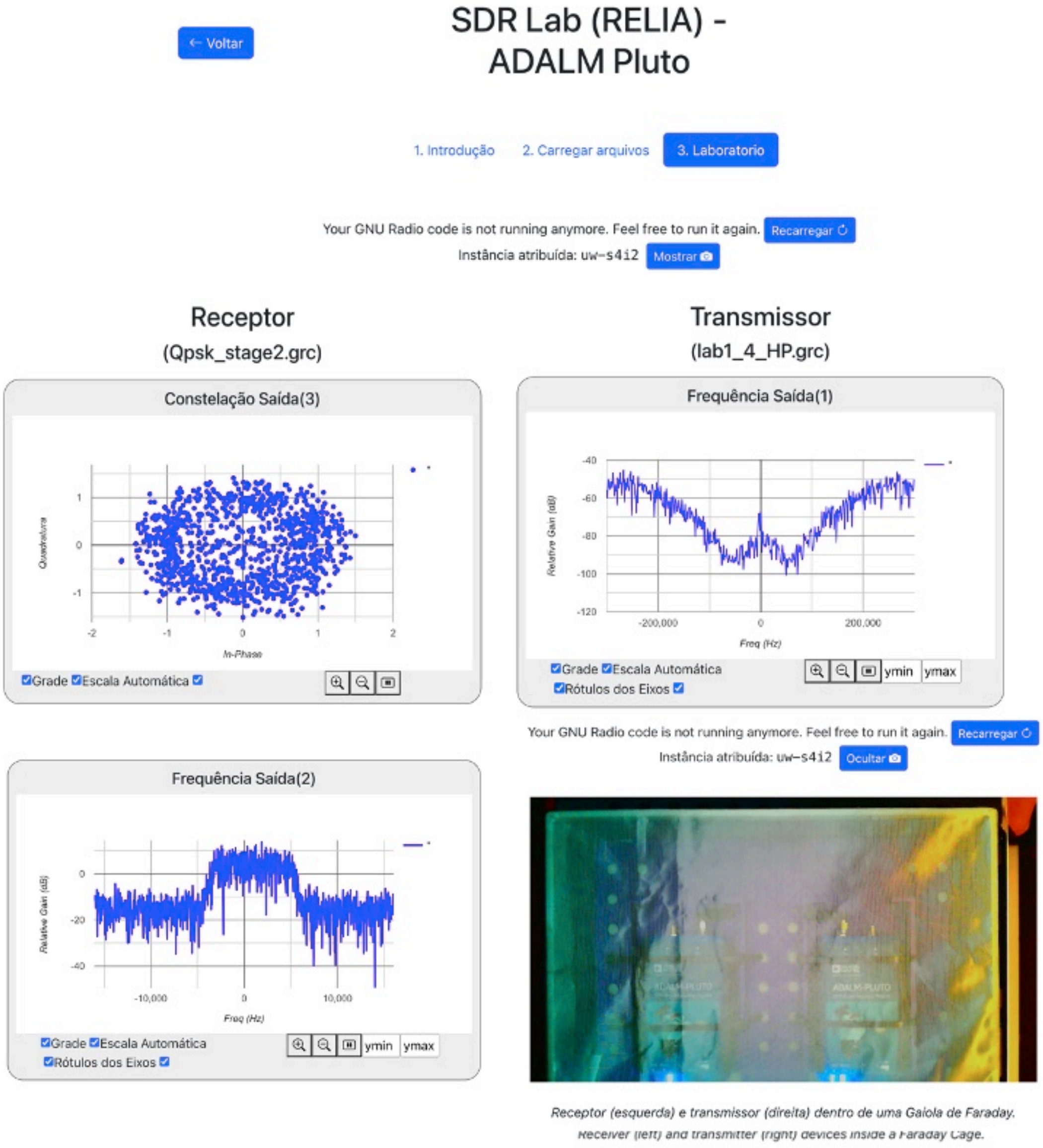
Instancia asignada: uw-s3i1

Receptor (izquierda) y transmisor (derecha) dispositivos dentro de una Jaula de Faraday

Figure 7.2: RHL-RELIA Spanish version interface

disadvantaged backgrounds. This trend is driven by the recognition that obtaining higher education is crucial for improving job opportunities in the formal economy, thus leading to higher individual incomes.

Within the realm of remote labs, the survey of United States students revealed specific digital disparities, which can be categorized within the three levels of digital inequalities. In the first-level inequalities were identified in some students from low-income families who seek alternative



Your GNU Radio code is not running anymore. Feel free to run it again.

Instância atribuída: uw-s4i2

Your GNU Radio code is not running anymore. Feel free to run it again.

Instância atribuída: uw-s4i2

Receptor (esquerda) e transmissor (direita) dentro de uma Gaiola de Faraday.

Receiver (left) and transmitter (right) devices inside a Faraday Cage.

Figure 7.3: RHL-RELIA Portuguese version interface

remote lab resources that do not rely on an Internet connection. This is significant given that in 2020, the Internet connectivity rate in the United States was 90.9%, compared to 73.9% in Latin America during the same period [137]. Hence, a similar conclusion could be drawn for Latin America. However, it's anticipated that the digital gap in the region will decrease in the future, thanks to dynamic global processes associated with the development of the expanding information society [138]. Nonetheless, it's essential to emphasize that mere Internet access in Latin America does not guarantee a reduction in the digital gap, necessitating government support programs, as seen in Uruguay. Therefore, a more comprehensive analysis is required to comprehend the root causes of digital disparities in the region.

Furthermore, within the first level of digital disparities, certain students indicated a preference for accessing remote labs through a web browser. This preference stems from the ability to utilize older or inexpensive computers without concerns about complex software requirements. This underscores the importance of advancing the development of remote labs accessible via web browsing. Such labs can tap into graphical libraries, enabling comprehensive interaction with the remote device.

The findings also suggest that the remote laboratory serves as an effective tool for fostering creativity and collaboration among peers, which can help alleviate digital inequalities at the second level. For instance, students have emphasized how the remote lab facilitated collaborative coding projects, real-time issue troubleshooting, and idea exchange through online forums and platforms. Moreover, remote labs promote innovation by providing a controlled environment where individuals can explore alternative problem-solving approaches and experiment with various engineering concepts.

When addressing digital inequalities in Latin America, a region where this issue is presumed to be more complex, it becomes necessary to delve deeper into this problem by utilizing a remote lab with Latin American students. This is why RHL-RELIA is being expanded to offer versions in Spanish and Portuguese. This adaptation will enable researchers in the region to conduct pedagogical studies and analyze equity in access through academic reports, educational material, surveys, and interviews with users. By doing so, remote tools will be provided to help reduce digital disparities, paving the way for more inclusive and equitable access and laying the foundation for a promising future in the educational field of the Latin American region.

Chapter 8

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This dissertation has detailed the development and application of the MELODY model for designing remote laboratories equipped with Software-Defined Radio (SDR) devices. The model features a layered design that incorporates both hardware and software components, supported by a classification framework. To explore the primary research questions posed in this dissertation, three case studies were conducted. These case studies illustrated the implementation of the MELODY model and suggested its potential to enhance the effectiveness and accessibility of remote laboratory environments. This exploration contributes to our understanding of how remote labs can be effectively tailored to meet educational needs.

Chapter 2 provides a comprehensive background on the technical features of SDR technology as applied in remote laboratory settings, distinguishing between common features found in educational remote labs—such as network type and computer access—and specialized features unique to SDR applications including user requirements, equipment costs, isolation, and interoperability. This analysis across five SDR educational labs highlighted the absence of a standardized development approach, despite the presence of shared hardware elements. The chapter also reviewed state-of-the-art educational remote labs, identifying innovative approaches that aim to enhance user engagement, minimize costs, and promote cooperation. Notably, it discussed federated remote labs, which allow secure, multi-location access to remote hardware, and ultra-concurrent remote labs, which leverage pre-recorded data to increase the scalability and accessibility of learning experiences. These insights underscored the need for a model and a standardized classification framework, setting the stage for this dissertation's contribution to the field.

Chapter 3 delineates the foundational principles of the MELODY model, organizing its structure around four pivotal elements: Architecture and Shared Terminology, Creation Guidelines, Datasets for Standardized Testing, and a Classification Framework. The initial elements focus on the architectural design and general technical considerations necessary for SDR development, enhancing the model's adaptability and relevance for varied remote lab applications. For instance, the Infrastructure layer, which is part of the Architecture and Shared Terminology, includes specialized units such as noncooperative components specifically designed for radar applications, showcasing the model's versatility. The latter elements, Datasets and the Classification Framework, are dedicated to establishing rigorous testing and evaluation metrics based on engineering standards. These help in setting definitive technical parameters that not only facilitate comprehensive assessments of the labs but also enable effective comparisons with other remote laboratories. Notable metrics developed under this framework include isolation, receiver characterization, scalability, interoperability, accessibility, and usage efficiency, each quantified on a scale from one to five stars. This structured approach allows for a nuanced evaluation of the labs, ensuring that they meet both educational and technical benchmarks effectively.

Chapter 4 delves into the detailed rubric of the classification framework used within the MELODY model, focusing on assessing various forms of interference that impact SDR operations in a multi-radio system. This assessment categorizes interference into four types—receiver-blocking, transmitter noise, intermodulation interference, and self-receiver interference—each contributing to the calculation of the Signal-to-Interference-plus-Noise Ratio (SINR). SINR is crucial as it defines the operational signal strength relative to the most significant interference encountered. The chapter outlines standardized methods for measuring this interference, adhering to engineering standards commonly applied in scenarios like Wi-Fi and Bluetooth coexistence. Additionally, it establishes a critical relationship between SINR and the Bit Error Rate (BER) for BPSK communication at 2.4GHz, setting a baseline SINR necessary for effective communication. Further, the chapter details the development of six tests for comprehensive receiver characterization—Linearity, Receiver Constant, Input and Output Noise Power, Minimum Detectable Signal, and Frequency Stability. These tests are integral to MELODY's evaluation rubric, with the model's ratings influenced by the thoroughness of receiver testing. The scalability rubric evaluates the economic feasibility of expanding the lab infrastructure, considering the cost per SDR/computer unit. Interoperability is assessed by the diversity of SDR devices within the lab, and accessibility focuses on the ease of user interaction, particularly through web browser manipulation, which is highly rated for facilitating user engagement. Finally, lab usage sessions are critically evaluated, with higher ratings awarded to labs that maximize operational efficiency and user engagement during available hours. This comprehensive approach to classification and evaluation underscores the MELODY model's robust framework in enhancing the technical and educational efficacy of remote laboratories.

Chapter 5 explores the first case study of the MELODY model, which entails the development and implementation of the RHL-RELIA lab for wireless communication. The RHL-RELIA lab is structured around a central University server block that manages multiple lab instances, each consisting of a pair of ADALM-Pluto devices—one for transmission and the other for reception—controlled by a Raspberry Pi 4B. This setup facilitates a sophisticated management system through components including a WebServer Scheduler, a Database, and a Data Exchanger. The webserver is notably enhanced with widgets that enable real-time plotting of streaming data, utilizing modern web widget libraries to replace traditional QT libraries used in SDR interfaces, thereby improving the user interface and interaction. In addition to these technological advancements, RHL-RELIA incorporates the Red Pitaya 122-16 SDR to extend its capabilities and frequency range beyond what the ADALM-Pluto devices offer, significantly enhancing the lab's interoperability and technical scope. Upon evaluation within the MELODY's classification framework, RHL-RELIA demonstrated excellent performance, meeting high standards across most evaluation criteria as detailed in Table 3.9. The pedagogical impact of RHL-RELIA was also assessed, with evaluations conducted by the Office of Educational Assessment (OEA). These assessments revealed high levels of user satisfaction, particularly noting the lab's flexibility, ease of use, and cost-effectiveness. These outcomes highlight MELODY's focus on enhancing equitable access to advanced educational technologies, underscoring the significant educational benefits of integrating such sophisticated systems in remote laboratory settings. The success of RHL-RELIA not only validates the MELODY model but also sets a precedent for future developments in remote laboratory education.

Chapter 6 presents the second case study of the MELODY model, the RHL-RADAR, which is tailored for radar courses. This specialized tool provides students with the opportunity to engage with real data processing directly relevant to radar technology, simplifying complex system setups. Unlike the RHL-RELIA lab, the RHL-RADAR employs a single ADALM-Pluto SDR operating in full duplex mode, optimizing the system for stable synchronization necessary for accurate data analysis. The RHL-RADAR is designed to measure the rotational velocity of objects, such as a fan, by analyzing micro-Doppler signatures that correlate with the fan's rotational speed. The precision of this system is remarkably high, achieving measurements within a 3% error margin compared to standard tachometer readings. Such precision underscores the RHL-RADAR's capability in providing hands-on learning experiences with a level of accuracy that closely mimics real-world engineering tasks. To assess the performance and educational value of the RHL-RADAR, it was evaluated against the criteria set by the MELODY model's classification framework. The results of this evaluation, detailed in Table 3.9, highlight the lab's efficacy and alignment with the pedagogical goals of the MELODY model. This evaluation also offers comparative insights by juxtaposing the RHL-RADAR's performance with other remote laboratories discussed in Chapter 2, emphasizing its unique contributions to the field of radar education. This case study not only validates the utility of the MELODY model in a specialized educational setting but also demonstrates its adaptability and effectiveness in enhancing student learning through advanced technological applications.

Chapter 7 explores the third case study of the MELODY model, which focuses on addressing digital inequalities within the context of remote lab development. This case integrates a comprehensive literature review of digital inequalities with practical insights from surveys and focus groups involving U.S. students using an FPGA remote lab. The study identifies and discusses the tangible challenges faced by students from low-income families, particularly their limited internet access and the availability of suitable devices. The findings reveal a clear connection between these digital barriers and the students' preferences for remote labs that are accessible without constant internet connectivity, using simpler, more affordable technology. These preferences highlight the need for remote labs to be adaptable and accessible to ensure no student is disadvantaged. In response to these findings, adjustments have been made to the MELODY model's classification framework, particularly enhancing the Lab Accessibility category. This modification not only reflects the model's responsiveness to user needs but also underscores its commitment to fostering equitable access to remote lab resources.

Based on the findings of this dissertation, responses to the posed research questions have been clearly articulated. In addressing the first question, the MELODY model has proven to be an effective, technology-agnostic framework specifically tailored for the development of educational remote labs focusing on SDR technology. This model integrates engineering standards, user-centered design, and pedagogical considerations, which collectively enhance its utility. Its successful application in projects such as RHL-RELIA underscores its capability and adaptability in crafting remote laboratories tailored for SDR applications. The positive outcomes and robust performance of RHL-RELIA reinforce the model's practical viability and effectiveness. Regarding the second research question, this thesis highlights the critical connection between digital inequalities and remote laboratory accessibility. The research utilized a combination of theoretical analysis and direct feedback from users to enrich the MELODY model, making it a dynamic tool for addressing these inequalities. By integrating specific technical modifications and user-focused enhancements, the MELODY model effectively bridges the gap between technological advancements and societal needs, promoting greater inclusivity within educational environments.

8.2 Future Work

The research conducted in this dissertation has established the MELODY model as a robust framework for developing and evaluating remote laboratories equipped with SDR technology. To further enhance its capabilities and applicability, future research should explore its expansion across various scientific and engineering disciplines. Integrating the MELODY model with emerging technologies such as artificial intelligence, machine learning, and the Internet of Things (IoT) could offer innovative enhancements in user interaction, data analysis, and laboratory automation. Additionally, considering the significant role of digital inequalities as highlighted in this study, it is crucial to adapt and test the model in diverse global contexts. This includes localizing the framework to different languages and cultural norms and tailoring it to various technological infrastructures to ensure wide accessibility.

Moreover, conducting longitudinal studies could provide valuable insights into the long-term educational impacts of remote laboratories on students' learning outcomes and career advancements. These studies would help in understanding the sustained benefits and possible improvements needed in remote laboratory education. Efforts should also be made to continuously enhance the accessibility features of the MELODY model, ensuring that it is inclusive for all students, including those with disabilities. This might involve developing adaptive user interfaces and creating more intuitive interaction designs. Lastly, the potential establishment of collaborative and federated networks of remote labs among institutions could facilitate shared resources, larger-scale experiments, and inter-university projects, significantly extending the educational reach and collaborative potential of remote laboratories.

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