

RHLab Interoperable Software-Defined Radio (SDR) Remote Laboratory

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Abstract. Educational remote laboratories, dedicated to radio frequency (RF) communications, represent an innovative effort aimed at bridging the gap between theory and practice. This advancement is even more empowered by the advent of Software-Defined Radio (SDR) technology, which allows students to create a wide array of prototypes for RF communication systems. The SDR community provides highly adaptable hardware that can be easily customized with just a few lines of code. Additionally, the availability of SDR hardware is extensive, offering various features tailored to users' specific needs. One of the key advantages of the flexibility inherent in SDR technology is the shared libraries among its devices. This feature fosters interoperability which is the ability of different SDR devices or components to work together effectively. In this context, the Remote Hub Lab (RHL/RHLab) has been working to incorporate this functionality into the RHL-RELIA remote lab project. RHL-RELIA stands as a remote wireless communication lab, with its initial iteration based on the ADALM-PLUTO SDR. However, as it evolves, RHL-RELIA is incorporating other SDR devices, such as the Red Pitaya, which introduces unique features not found in the ADALM-PLUTO. This degree of diversification empowers students with a broad spectrum of choices, allowing them to select the SDR device that aligns most closely with their individual interests and educational requirements.

Keywords: GNU Radio, Interoperability, Software-Defined Radio, Remote Laboratory, Embedded Systems

1 Introduction

In the curriculum of electrical and computer engineering courses, laboratories are integrated to offer students hands-on experience across a diverse range of subjects [1]. Traditionally, students receive physical lab kits and are granted access to lab facilities to execute their assignments [2]. However, in recent years, the introduction of remote labs has emerged as a viable alternative, offering students convenient access to equipment at any time, eliminating geographical restrictions, fostering collaboration among peers, and improving accessibility

for students with disabilities [3]. This transition also contributes to promoting equitable access in education [4].

Remote laboratories have attracted considerable interest in educational research since the 1990s, as indicated by the numerous definitions found in the academic literature [5–7]. It is crucial to distinguish between “remote labs” and “virtual labs”. Virtual labs are computer-based applications simulating non-physical environments, whereas remote labs enable users to access and control physical equipment from a remote location through computer and communication infrastructure [8]. The educational efficacy of remote and virtual laboratories has been validated [9–13] with their development closely tied to the role of internet technology.

In Electrical and Telecommunication Engineering, courses in wireless communication that employ RF techniques are integral to the curriculum. Traditional communication laboratories equip students with a kit of components for their lab assignments [10] including RF devices for signal transmission and reception, along with essential components like antennas and cables. SDR technology simplifies this process, reducing setup time and offering flexible hardware that can be modified with code. SDR enhances versatility, applicable in various educational settings for different types of communication [14]. This approach positively impacts education, enriching learning experiences and fostering research and collaboration among developers and instructors aligning with high standards of educational quality [15, 16].

In the context of SDR remote laboratories for educational purposes, numerous initiatives provide educational solutions, often focusing on a single type of SDR device. Nevertheless, the SDR technology encompasses a diverse range of devices available in the market, each differing in several aspects. Additionally, SDR devices share a substantial portion of libraries and software tools, ensuring compatibility with a common set of resources. This particular feature fosters the inclusion of the concept of interoperability that permits the interaction with two or more devices from the same SDR family. In this direction, we³ [17] and LabsLand⁴ involved in the development of the RHL-RELIA project [18, 19] are now incorporating the Red Pitaya SDR⁵ as a second SDR device alongside the ADALM-Pluto⁶ to provide an interoperability option, offering users a wide range of SDR selections.

The paper’s structure is as follows: Section 2 offers an overview of interoperability concepts in communication remote labs, along with insights into projects featuring remote labs equipped with this characteristic. Section 3 details the design of the RHL-RELIA system, integrating new SDR devices. Section 4 explains the current progress of the project. Finally, Section 5 summarizes the article, draws conclusions, and explores avenues for future work.

³ <https://rhlab.ece.uw.edu>

⁴ <https://labsland.com>

⁵ <https://redpitaya.com/>

⁶ <https://wiki.analog.com/university/tools/pluto>

2 Background

The concept of interoperability within SDR remote labs pertains to the capability of incorporating diverse devices that collaborate on the same platform, allowing users to enhance the versatility of the lab environment [20]. This feature’s advantages in a remote lab empower students to select the appropriate SDR hardware based on their specific needs. In the realm of RF devices, several key parameters include:

- Frequency Range: It covers the range of frequencies relevant to transmit or receive. Different SDRs are designed for specific frequency bands of operation.
- Sampling Rate: It determines how quickly the SDR can digitize analog signals. Higher sampling rates are beneficial for capturing high-frequency signals.
- Bit Resolution: It defines the number of bits in each sample. Higher resolution provides a more accurate representation of the analog signal.
- Dynamic Range: It indicates the SDR’s ability to handle signals of varying amplitudes. A large dynamic range permits to detection of both weak and strong signals.

A prominent SDR project that offers interoperability is REDHAWK⁷, a software package facilitating the design, development, deployment, management, and upgrading of network-enabled SDRs in real time. Initially starting as the OSSIE project [21], REDHAWK aims to provide portability in the development of software radio applications, given the necessity of running the same software on different hardware for SDR applications.

REDHAWK’s primary contribution lies in providing a platform that renders the hardware transparent to the programmer, thereby reducing the time and cost of code development [22]. However, its utilization necessitates specialized software and dedicated hardware, precluding its remote use and limiting its potential as an educational tool with equitable access [23].

Adopting a similar approach, we incorporated interoperability into the RHL-RELIA project. RHL-RELIA, an implementation of the MELODY model, serves as an agnostic technological model providing design considerations for educational remote labs controlling SDR devices [24].

In its initial version, RHL-RELIA utilized the ADALM-Pluto SDR, known for its affordability, versatility, and community support, offering students practical experiences aligning well with modern educational approaches emphasizing real-world applications in the field of software-defined radio and communications. To enhance interoperability, RHL-RELIA introduced the Red Pitaya SDR device as a second component.

The Red Pitaya, a high-performance tool with commendable hardware and an open-source software project, supports exploration, learning, and the development of various applications [25]. Red Pitaya has gained widespread popularity

⁷ <https://redhawksdr.org/>

as a versatile learning platform since its launch. It has been embraced by amateurs, educators, and professionals alike for diverse project creations [26–30]. This device has found application in several educational remote labs, such as the Gheorghe Asachi Technical University of Iași, which developed a linear electronic circuit based on Red Pitaya for electrical engineering courses. This project leverages Red Pitaya’s features, including flexible hardware and peripherals like Ethernet, to remotely manipulate and visualize a signal wave originating from a breadboard [31].

Other projects also utilize Red Pitaya as a core component in educational remote labs. For instance, the National Institute of Technology, Malang, Indonesia, developed an electronics telecommunication remote lab involving Red Pitaya, functioning as an oscilloscope, signal generator, spectrum analyzer, and multi-tester device [32].

Compared to the ADALM-PLUTO, the Red Pitaya SDRlab 122-16 offers several additional features, as Table 1 demonstrates. Firstly, it boasts a more powerful programmable System-on-Chip SoC: the Zynq Z-7020. This upgrade from the Z-7010 within the PlutoSDR results in a significant enhancement, with the Z-7020 offering 164% more FPGA logic cells, 133% more BRAMs, and 175% more DSP slices. These enhancements ensure that the SDRlab 122-16 is considerably more future-proof in terms of computational power. Secondly, the SDRlab 122-16 provides a greater number of input and output channels, enabling the execution of more intricate programs. Thirdly, Red Pitaya offers a broader range of connectivity options. Although it shares the USB 2.0 port with the PlutoSDR, it extends its capabilities by including an Ethernet port. This additional feature proves highly beneficial, particularly for wireless connections to a host computer. Moreover, the Red Pitaya SDRlab 122-16 fills the frequency range gap left by the PlutoSDR, reaching frequencies as low as 200 kHz. Lastly, the SDRlab 122-16 boasts higher input and output resolutions compared to the PlutoSDR.

Table 1: Red Pitaya SDRlab 122-16 & ADALM-PLUTO Specifications

	SDRlab 122-16	ADALM-PLUTO
SoC	Zynq Z-7020	Zynq Z-7010
Transceiver	AD9767 & LTC2185	AD9363
Transmitter Channels	2	1
Receiver Channels	2	1
Transmitter RF Range (Hz)	300k - 60M	2*325M - 3.8G
Receiver RF Range (Hz)	300k - 550M	
Output Resolution (bits)	14	2*12
Input Resolution (bits)	16	
Connectivity	USB 2.0 & 1Gb Ethernet	USB 2.0
SD Card Port	Yes	No
Digital I/Os	16	No

3 System Design

The architecture of RHL-RELIA in interoperability mode is designed to accommodate a variety of SDR devices. In a general scenario, the SDR device must feature either a USB 2.0, USB 3.0, or Gigabit Ethernet interface connector to enable connection with a cost-effective Raspberry Pi. A comprehensive block diagram is presented in Figure 1, illustrating the user's remote access to the RHL-RELIA system through a server. Within this interface, students can select their preferred SDR station.

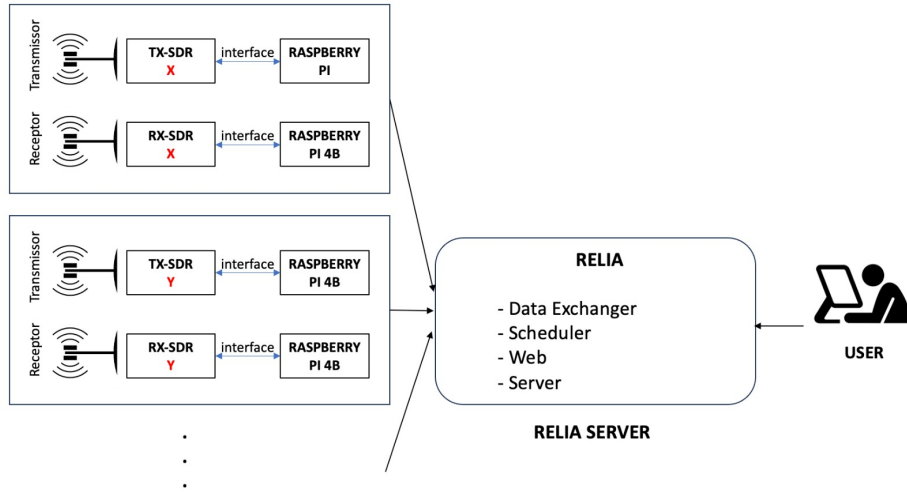


Fig. 1: RHL-RELIA general interoperability architecture.

In the specific hardware setup with Red Pitaya, the configuration encompasses two Raspberry Pis and two Red Pitayas. Each Red Pitaya is linked to an individual Raspberry Pi through an Ethernet interface (utilizing a USB connection in the case of ADALM-Pluto), and both devices are equipped with dedicated Ethernet ports. Following this, the two Raspberry Pis are interconnected with the RHL-RELIA server. A block diagram illustrating these interconnections is presented in Figure 2.

In difference from other previous remote lab projects with Red Pitaya elaborated in Section 3, RHL-RELIA utilizes the GNU Radio Companion (GRC)⁸ environment in order to configure Red Pitaya. This installation requires a modification in the Red Pitaya's firmware.

⁸ https://wiki.gnuradio.org/index.php/Guided_Tutorial_GRC

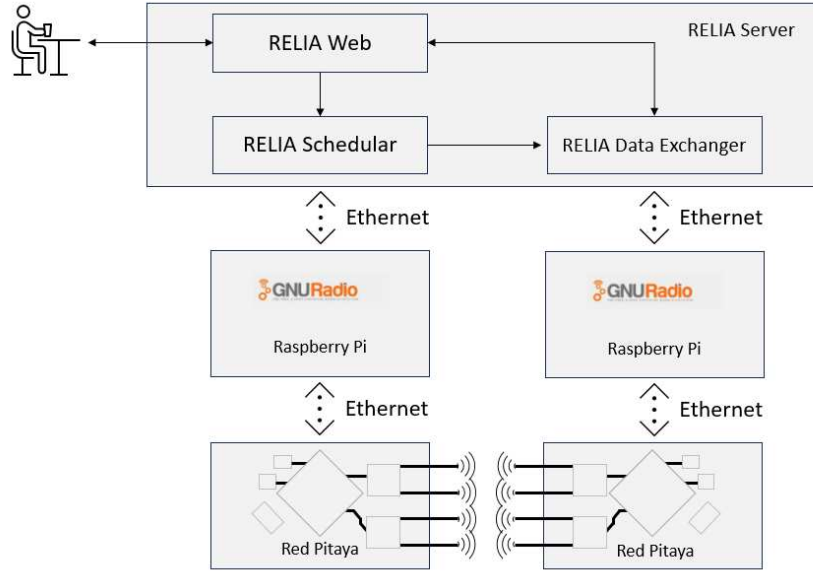


Fig. 2: Interoperability framework of two Red Pitayas in RHL-RELIA.

4 Results

4.1 Functionality Test of Four Channels with Custom Image

Prior to initiating interoperability between two Red Pitayas, we conducted initial testing of the device by installing a custom image with GRC libraries on it. A loop antenna is connected between a transmitter and receiver ports on the Red Pitaya, depicted in Figure 3. Subsequently, the Red Pitaya was controlled by a Raspberry Pi, and programs were executed to assess functionality. The Red Pitaya successfully transmitted signals specified by GRC programs and effectively received them through its receiver.

4.2 Interoperability between Two Red Pitayas

We then moved on to perform interoperability between two distinct Red Pitayas. The connection is shown in Figure 4. First, a single tone transmission was performed in order to test the accuracy of the frequency transmitted. Given that each Red Pitaya incorporates an internal oscillator, even when configured with the same frequency value, slight frequency shifts are expected. While these shifts may be insignificant in certain applications, estimating their values remains crucial for more complex experiments.

The results of this basic experiment are illustrated in Figure 5. Figure 5a shows the experiment of transmitting a signal frequency of 50 kHz modulated

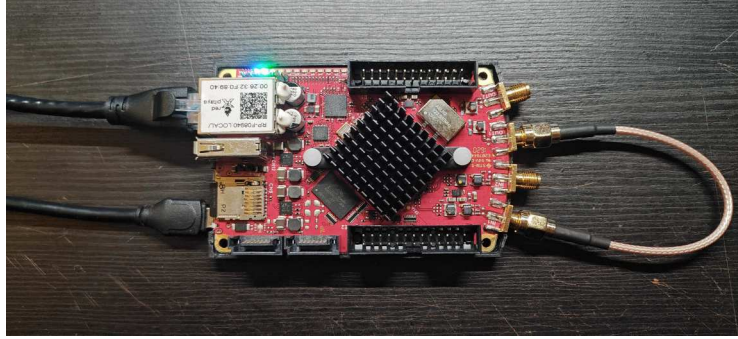


Fig. 3: Loop test using a single Red Pitaya.

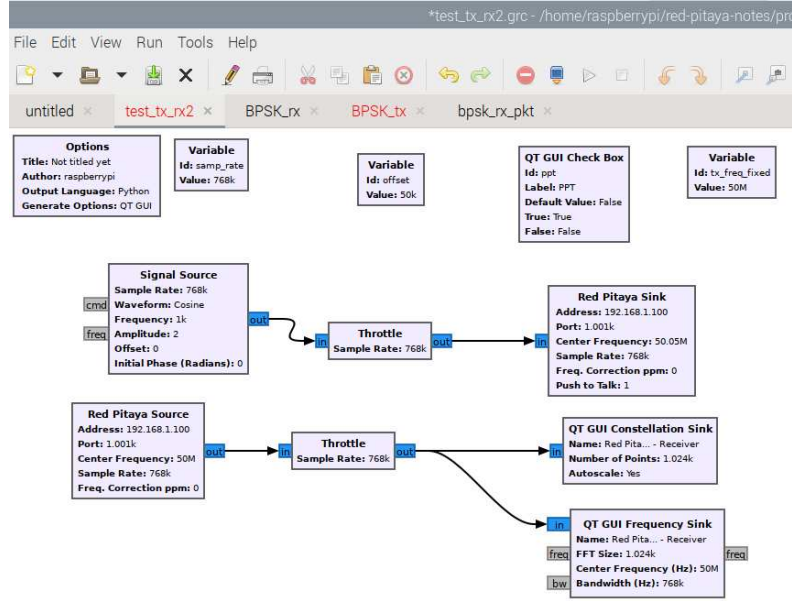


Fig. 4: Hardware setup for performing interoperability between two Red Pitayas.

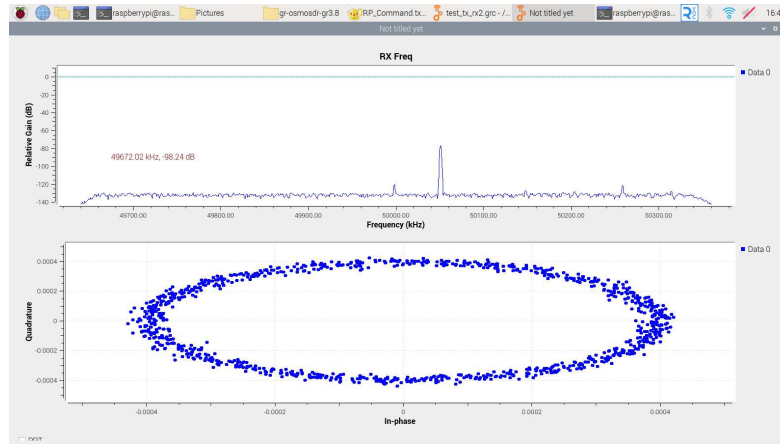
on a carrier frequency of 50 MHz. Given the communication type is In-phase (I) and Quadrature (Q), it becomes imperative to examine each signal component. This constellation representation serves as a potent tool for both the analysis and visualization of digital signal characteristics in communication systems. The results are illustrated in Figure 5b.

The second experiment focuses on Binary Phase Shift Keying (BPSK), a digital modulation scheme employed in telecommunications for transmitting binary data ('0's and '1's) by manipulating the phase of the signal [33]. This experiment holds significance as it constitutes one of the fundamental components in telecommunication courses, providing students with insights into more advanced transmission techniques.

Figure 6 displays the results of the experiment involving the random transmission of a sequence of 1's and 0's. The design of the experiment in GRC can be observed in Figure 6a, with the corresponding results presented in Figure 6b.

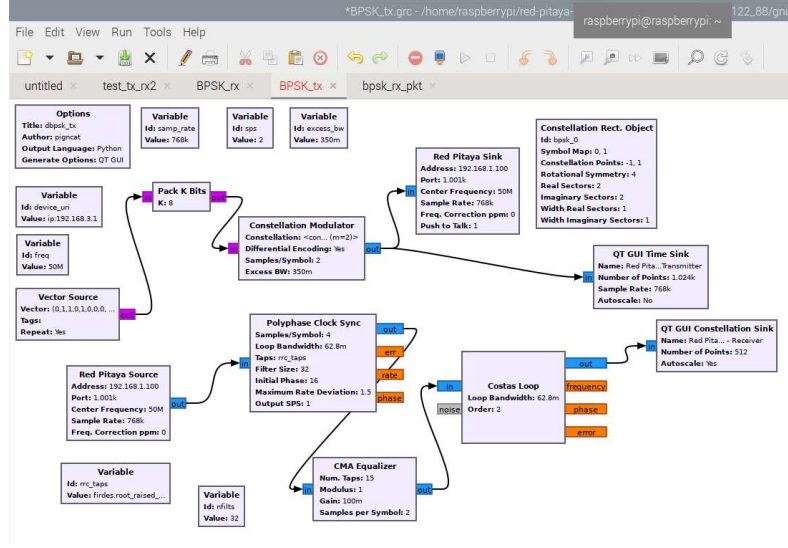


(a) RHL-RELIA single frequency tone transmission reception test - GRC.

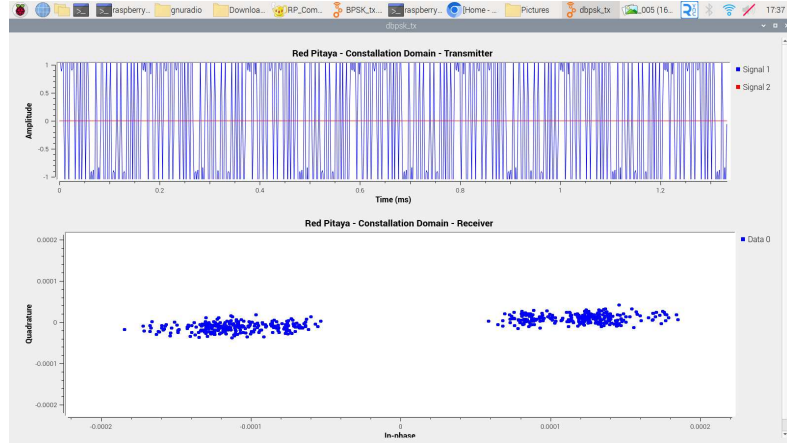


(b) RHL-RELIA single frequency tone transmission reception test - plot.

Fig. 5: Single tone test results.



(a) RHL-RELIA BPSK transmission reception test - GRC.



(b) RHL-RELIA BPSK transmission reception test - plot.

Fig. 6: BPSK test results

5 Conclusion and Future Work

This paper demonstrates the integration of the Red Pitaya SDR into the RHL-RELIA remote lab, introducing an interoperability feature. This functionality will allow students to select the most suitable SDR device based on the specific requirements of a communication project. Each device possesses strengths in different application domains. Furthermore, this interoperability presents a cost-effective advantage, as educational institutions can acquire RHL-RELIA and customize the lab by selecting the number and types of SDR devices that align with their specific requirements.

Red Pitaya enhances the lab's versatility by offering additional features. Notably, it incorporates a micro SD card slot, expanded onboard memory, a substantial number of GPIO pins, and onboard Ethernet ports. These features extend the application scope of RHL-RELIA to various RF domains, including radar applications, and facilitate the implementation of advanced functions such as partial reconfiguration.

In future developments, the project aims to introduce a specialized web interface that allows users to exploit the distinct features of each SDR device fully. Moreover, the initiative plans to integrate more SDR devices, transforming the remote lab into a resource suitable not only for educational purposes but also for professional-level applications. This expansion is in line with the MELODY model, emphasizing both versatility and scalability. However, as the project integrates a diverse range of SDR devices on a larger scale, additional interference tests are essential. This testing is crucial to establish mechanisms for isolation, mitigating interference between different SDR stations. Isolation is predominantly achieved by placing them in RHL-RELIA 3D-printed Faraday Cages, mounted on PhaseDock plates in the LabsLand Prism4 structure. As the lab's infrastructure grows to accommodate a large number of SDR technologies, ensuring reduced interference between SDR stations becomes a priority.

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