Radio Transmitter and Receiver with Software-Defined Radio to Model Location and Intensity of Forest Fires

ECE/BME 499

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Executive Summary

Wildfires are increasingly severe threats to natural ecosystems and human settlements. Traditional detection methods, such as satellite imaging, suffer from delays and resolution limitations. This project proposes an alternative technique that leverages Software Defined Radio (SDR) to monitor ionospheric disturbances triggered by forest fires. Using Ettus USRP devices, we successfully transmitted and received a 5 MHz signal embedded with Barker's code, and verified its behaviour through direct line transmission. We were able to get phase arrival times and those can be used to detect the exact location of forest fires. Future work would include over the air transmission, ionospheric reflection and triangulation. Our prototype offers a good initial setup for the project to be continued.

I Introduction

Forest fires are a growing environmental threat. Early detection is crucial for minimizing damage and enabling a timely response. This project addresses this need by proposing the Earth's ionosphere as a medium to detect electromagnetic disturbances caused by forest fires. Using Software Defined Radio (SDR), our system detects phase shifts in radio waves. The social impact is that this project contributes to environmental safety and disaster prevention, aligning with EGBC's Code of Ethics, acting in the public interest, promoting sustainability, and enhancing quality of life. The main use base of this technique would be forest management agencies, emergency responders, and environmental organizations.

II Objectives

- Design and build a system to detect forest fires by measuring ionospheric disturbances using Software Defined Radio (SDR).
- Use SDR to record the phase and timing of reflected radio waves from the ionosphere.
- Triangulate data from multiple receiver stations to estimate the position and intensity of the disturbances.
- Goal to achieve:
    - Prototype setup at a single receiver location
    - Successful detection of a 5 MHz wave.
    - Preliminary analysis of ionospheric wave patterns.

III Design Specifications

1. **RF System Configuration**

   Carrier Frequency: 5.3 MHz

   Justification: This frequency is within the range required for ionospheric reflection while minimizing absorption losses.

   Hardware Configuration:

   USRP N210 SDRs (x2) - one with an LFRX daughterboard and another with an LFTX daughterboard.

   Justification: The LFRX/TX boards provide necessary performance at (1-30MHz)

2. **Antenna System**

   Type: Dipole antennas (14.1m total length)

   Electrical Characteristics:

   - ¼ wavelength at 5.3 MHz
   - 50Ω impedance matching

   Justification: This antenna provides the best directionality and is the correct size for our carrier signal.

3. **Signal Design**

   Modulation: Continuous wave propagation with BPSK-encoded 7-bit Barker's sequence.

   Justification: The 7-bit Barker's code matches the USRP's maximum sustainable correlation rate.

4. **Power Budget**

   Transmit chain:

   - USRP Output: +20dBm
   - Amplifier: 50W RF power amplifier

   Justification: The 50W amplifier ensures a reliable ionospheric link margin, assuming a reasonable fade margin. It also makes our signal strong enough to reach the ionosphere.

5. **Safety Compliance:**

   RF exposure controls per Health Canada SC-6

IV Literature Survey

As mentioned in our executive summary, wildfires present a growing global threat, creating an urgent need for improved detection methods. Recent advances in Software-defined radio technology offer a promising alternative to traditional methods currently being employed. This project builds upon prior work in ionospheric monitoring and RF signal processing to develop a new system for wildfire detection that addresses critical gaps in current monitoring infrastructure.

The theoretical basis stems from established research demonstrating that ecological disturbances such as earthquakes and wildfires can induce measurable ionospheric disturbances through electromagnetic effects. Bruce Nicholas' Master's Thesis on phased-array ionospheric imaging provides particularly relevant insights, demonstrating how high-frequency signals can detect ionospheric disturbances with high precision. His work successfully captured phase-coherent reflections using a custom beam former and antenna array, validating the core principles we adapt for wildfire detection.

Forest fires heat the surrounding air, generating vertical thermal plumes that disturb atmospheric stability and create turbulence; by detecting changes in buoyancy frequency, these fire-induced anomalies in the atmosphere can be identified.

Alternate methods currently being employed for forest fire detection include:

Satellite Imaging

Satellite systems are used to detect thermal anomalies using infrared imaging (IR). Weather conditions can interfere with sensing. Nasa Worldview [6]. Satellites are used to detect and record electromagnetic radiation reflected from Earth's surface. Data is processed to create data images depicting Earth's land, atmosphere, and oceans.

Ground Sensor / Camera Surveillance

Camera towers and smoke sensor systems. Require many infrastructures and have a limited range. Defence Research and Development Canada ground sensors [7]. These sensors work by detecting ash and carbon monoxide that are in the air. These sensors are real-time and used to detect early fire to limit the spread of wildfire.

Technique	**Coverage**	**Delay**	**Weather Dependent**	**Cost**	**Sensitivity to Fire**
Satellite IR Imaging	Very High (global)	Medium	Yes	High	High (thermal)
Ground Sensor Network	Low (local)	Low	Yes	Medium - High	High

Ionospheric Sensing	**High (regional)**	**Very Low**	**No**	**Low**	**Medium**

V Team Duties & Project Planning

Name	Duties
Ayman Al Rubaey	**Lead Research:** Completed reading Nicholas Bruce's master thesis [1] and ECE 350 Lab 2 [2] to understand USRPS. Started doing research to find the best way to use analog for the receiver. Completed reading "LimeSDR USB Channel Alignment" [4] on github to find out a different digital method than USRPS. Did research on Buoyancy frequencies to figure out how to calculate frequency changes of forest fires. Setup the two USRP hardware and was able to send and receive a 5MHz signal through a function generator. Designed a website and poster with a summary of the project.
Ian Sefton	**Team Lead:** Coordinate with supervisors and student team on time and place to meet, send weekly report to TA, deal with other administrative duties, and editing midterm and final reports. **Research:** Spent time looking at Nicholas Bruce's Master's Thesis [1] and understanding ECE 350 Lab 2 (which is strong component of this project) [2]. Setup the two USRP hardware and was able to send and receive a 5MHz signal through a function generator. **Part sourcing:** Involved with finding military grade tubing that will support our two radial receiver antenna, assisted with gathering two USRP's on loan from UVic Engineering Labs, and involved with trying to find a MIMO cable which is yet to be obtained
Alexander Gowans	**Research:** Reviewed Bruce's thesis [1], for information on the use of dual USRPs, as well Lab 2 from ECE 350 [2]. **Part sourcing:** Searching for dipole antennas and the elusive MIMO cable. Reviewed pricing and lead times of various components [5] for the event some needed to be acquired.

	GNU Radio: Creating and testing GNU radio block diagrams for creating, transmitting, and handling the bpsk waveform.
Oluwateniola Fasanmi	**Research:** Searched for ways to use two LFRX daughterboards in one USRP. Looked into ways of synchronizing two USRPs without a MIMO cable and/or having two LFRX daughterboards in one USRP. [8][9] **Part sourcing:** Looked into various types of USRP boards, specifically their MIMO compatibility/ dual LFRX daughterboard compatibility.
Eric Le	**Research:** Basic radio wave theory. [1] Master student thesis on transmitting radio carrier waves and receiving data from that wave from the ionosphere and antenna setup. [1] Overview of ECE 350 labs for GNU software. [2] Modulation techniques for tagging signals to receive and correlate. Attended meetings with master students to further understand RF and DSP (Levonte Buzas and Ben Kellman). **GNU Radio**: testing receiving and transmitting radio wave with demodulation techniques (Barkers Code and LFM). **Part sourcing:** Searching for antennas and MIMO cable.

VI Design Methodology & Analysis

The core design method took an iterative approach. Several options and paths were laid out, such as 2x2 MIMO, single, and analog. The choice between these and some of the individual parts, such as the antenna, was restricted based on availability, and as a result, some concessions in performance were made. Once the core hardware was decided on, work began on ensuring basic functionality by transmitting a simple unmodulated carrier wave, first on the software, then through the RX/TX devices via direct wiring, and finally through air transmission. Once the hardware was confirmed to be working with a simple waveform, we could now begin modulating the waveform and repeating the process of software, hardware wired, and hardware air to ensure correct behaviour before increasing complexity. Analysis was performed via both software scopes and physical oscilloscopes to confirm that the waveforms being sent and received were as expected.

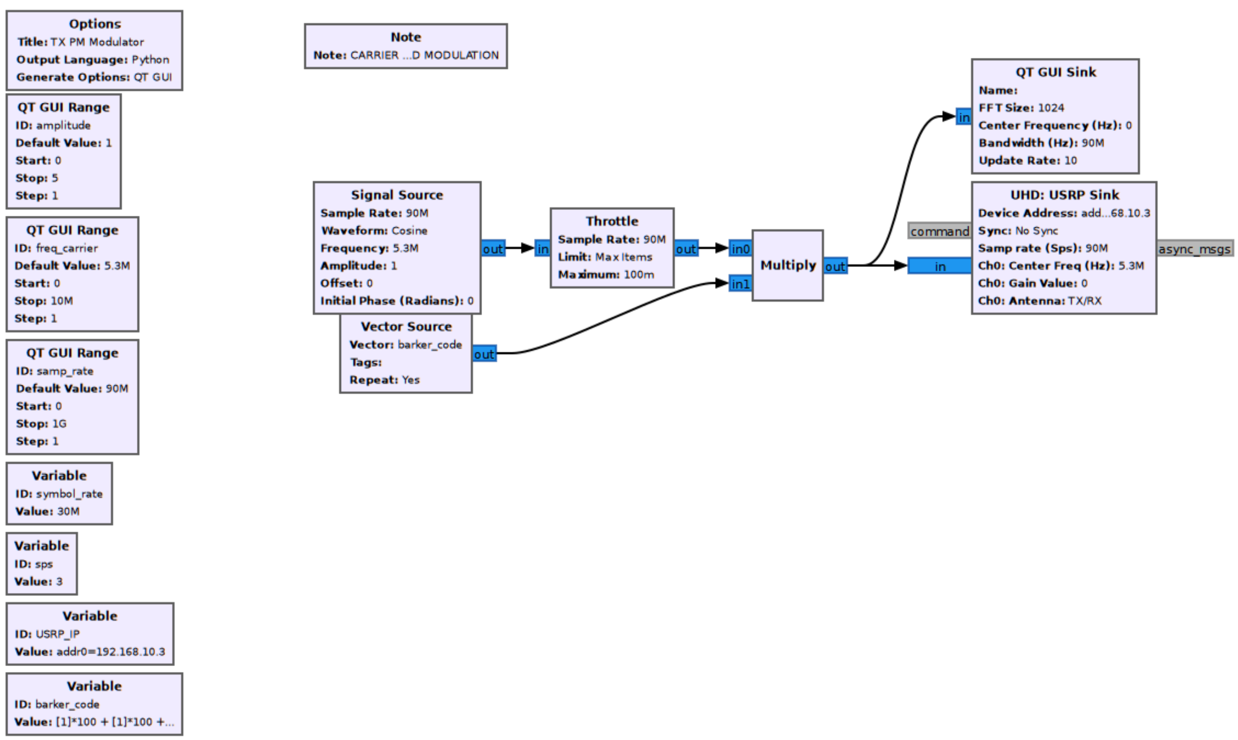


Figure 1. GNU Radio TX Block.

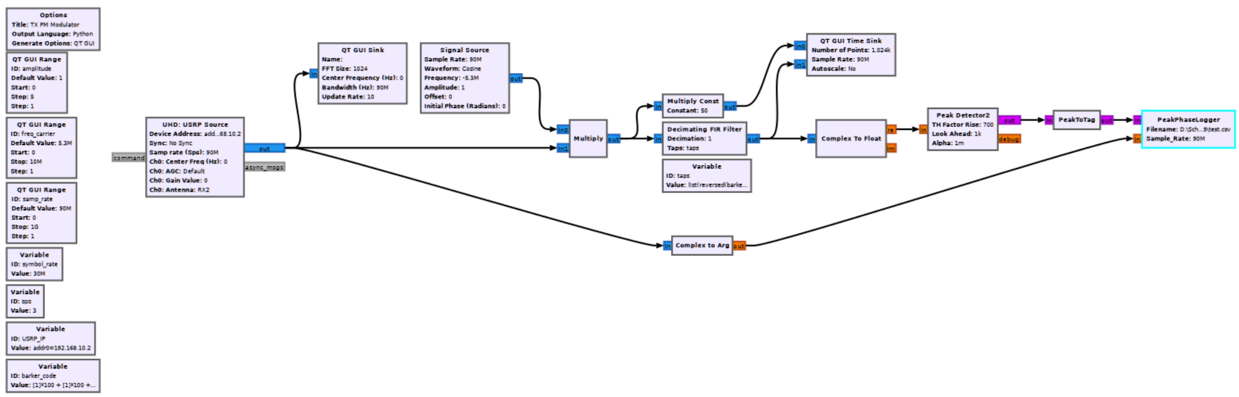


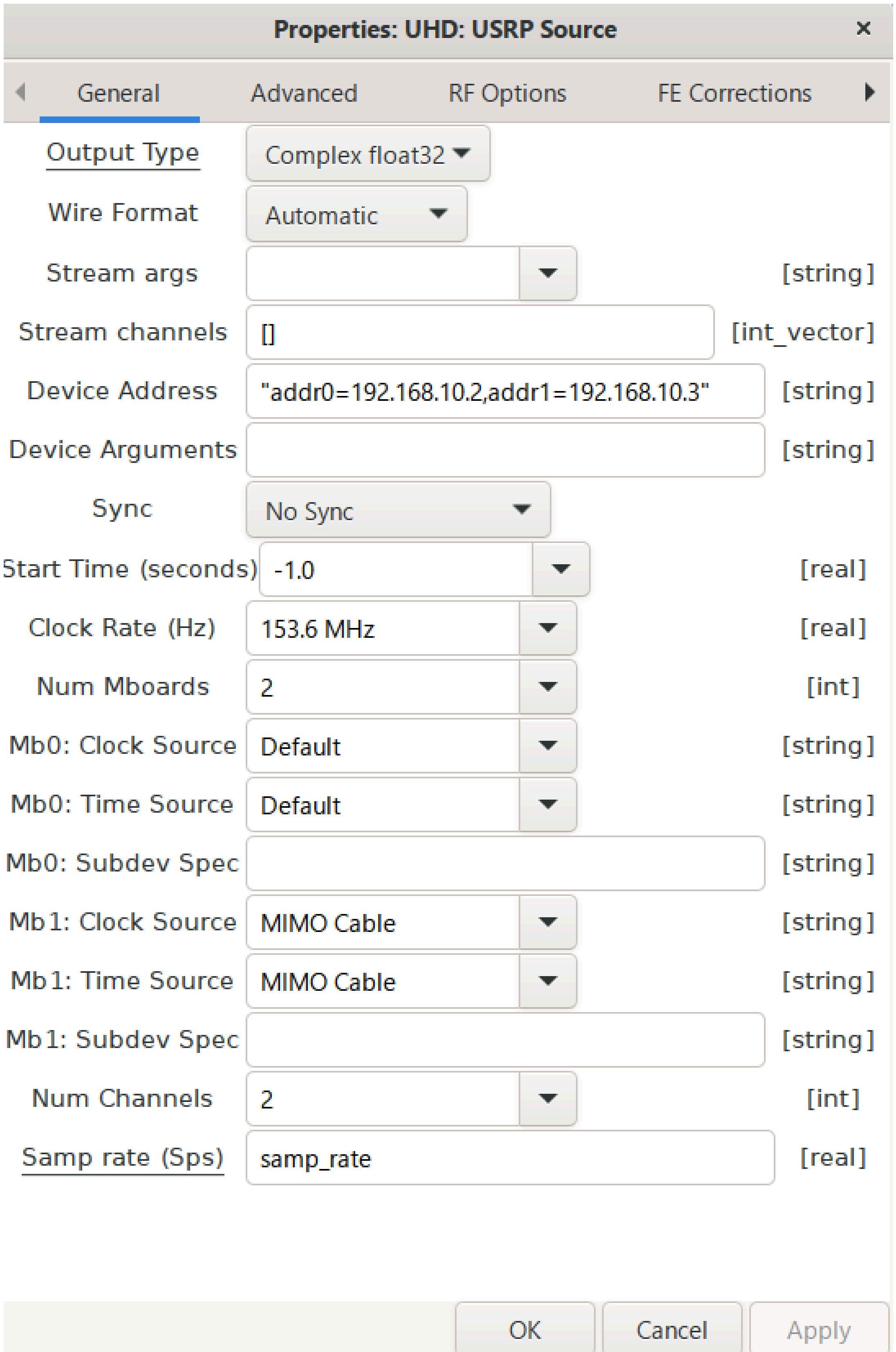
Figure 2. GNU Radio RX Block.

VII Design & Prototype

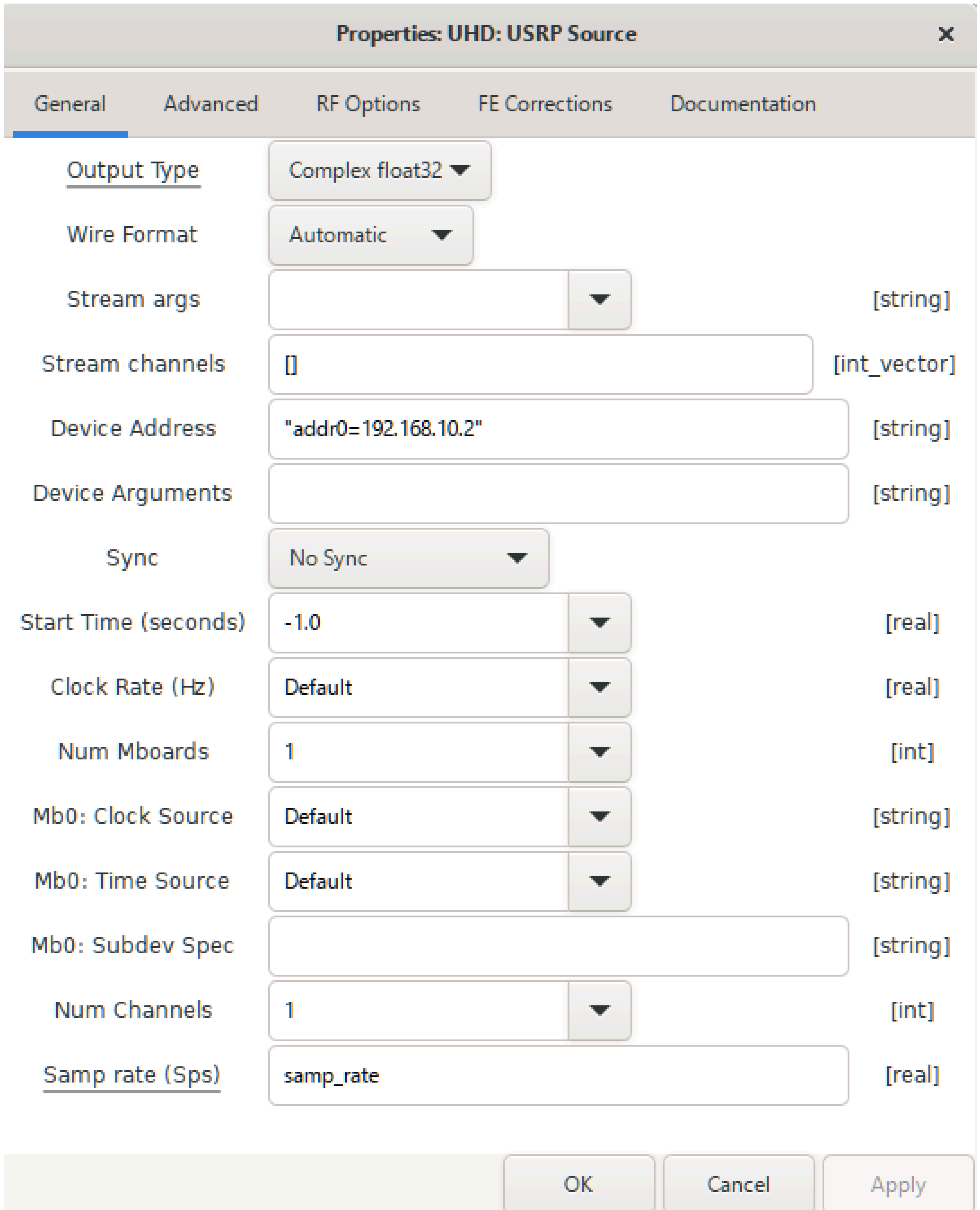
The final prototype consists of two USRP devices, one using the LFRX board variant and the other using the LFTX board. These devices are then connected to individual PCs via Ethernet cable to receive instructions via GNU Radio. The device works by creating a 5.3MHz carrier signal via software, modulating the phase with a Barker's code and then transmitting the signal via the USRP. This signal is then sent via direct connection to the receiving USRP. The received signal is then demodulated to get the Barker Code signal passed through a decimating FIR filter in order to receive peaks from the correlation of the code. These peaks are then used to tag a given sample, which is then compared to the same sample on the originally received wave. The time of arrival and phase are then saved and used to determine the distance and intensity of wildfires. Future considerations include transmitting this signal over the air as well as operating on the saved data. The time difference between each received peak will be treated as an amplitude and plotted vs time to give the 'captured' wave from the ionosphere. The major limitations going forward are related to the method of phase modulating the carrier, which will require some form of syncing the two USRPs. One way to do this would be by using the MIMO cable to phase lock the two devices; however, this requires them to be in the same location, which makes capturing only the airwave and not the ground wave trickier. Alternatively, a manual adjustment of the demodulating carrier frequency on the receiver side could be used in lieu of more advanced syncing methods.

The steps for initializing the USRP setup are as follows.

- Install GNUradio, radioconda, and the UHD packages.
- In Windows' network settings, change the Ethernet IPV4 to 192.168.10.1
- With the USRP connected to the PC via Ethernet and turned on, run the `uhd_find_devices` command in radioconda. By default, the USRP has an IP of 192.168.10.2.
- If using a MIMO 2x2 setup, the two USRPs may have an IP conflict.
- Connect a single USRP without the MIMO connected.
- In Radioconda, navigate to the folder where your UHD packages are installed. (`cd <install-path>/lib/uhd/utils`)
- Change the IP of the device and then power cycle it. `./usrp_burn_mb_eeprom --args=<optional device args> --values="ip-addr=192.168.10.3"`
- Reconnect as 2x2 and rerun `uhd_find_devices`
- Both devices should now be recognized, and the 2x2 MIMO setup documentation will work correctly.
- Within GNU Radio, the following settings will apply to a 2x2 MIMO setup.



- For a single USRP as used in the final prototype, use the following.



- Ensure the correct channel is selected in the RF options tab. Listed as RX/TX A/B on the daughterboard and corresponding to RX/TX 1/2 in the options.
- Test by sending/receiving a simple single-frequency signal and check on an oscilloscope.

VIII Testing & Validation

Initial testing was performed using direct wired connections between transmitter and receiver USRPs. The modulated Barker-coded signal was successfully transmitted, received, and demodulated. Scope plots verified peak detection and correct sample tagging. Validation of functionality under controlled conditions provides a solid baseline for extending to air-based transmission. Additional validation will be required for ionospheric reflection scenarios.

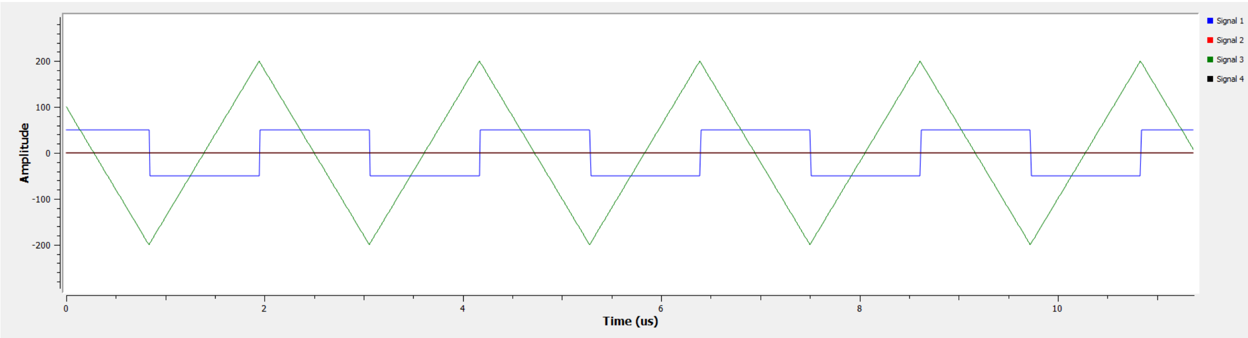


Figure 3. 2 Bit Barker's Code.

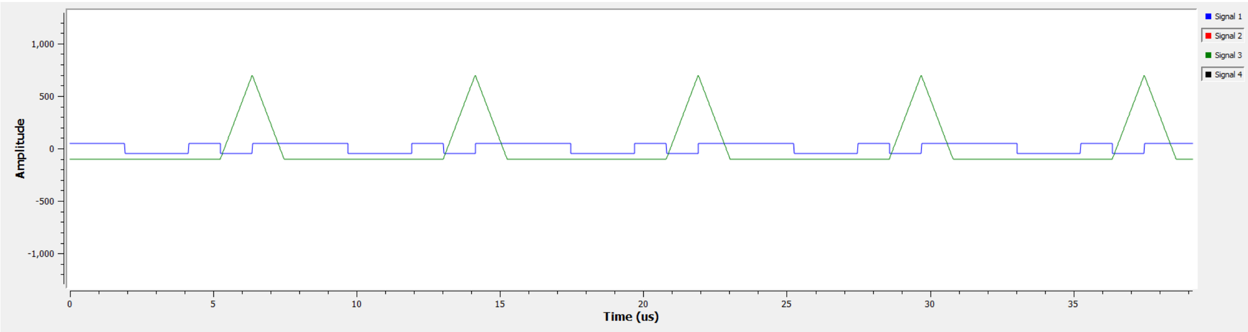


Figure 4. 7 Bit Barker's Code.

	Standard	Standard
1	Timestamp	Phase
2	7.766666666666666e-06	-2.1153335571289062
3	2.3322222222222223e-05	0.6772003173828125
4	3.11e-05	2.073467254638672
5	4.665555555555556e-05	-1.4171826839447021
6	6.221111111111111e-05	1.3753539323806763
7	7.776666666666667e-05	-2.115295648574829
8	9.332222222222222e-05	0.6772382259368896
9	0.00011665555555555555	-1.4171446561813354
10	0.00013221111111111111	1.375391960144043
11	0.00014776666666666666	-2.115257740020752
12	0.0001633222222222222	0.6772762537002563
13	0.0001711	2.0735433101654053
14	0.00018665555555555556	-1.4171066284179688
15	0.0002022111111111111	1.3754299879074097
16	0.00021776666666666666	-2.1152195930480957
17	0.00023332222222222223	0.677314162254335
18	0.00025665555555555555	-1.417068600654602
19	0.0002722111111111111	1.3754680156707764
20	0.00028776666666666665	-2.1151816844940186
21	0.0002955444444444444	-0.7189145684242249
22	0.0003111	2.0736193656921387
23	0.00032665555555555556	-1.4170305728912354

Figure 5. Phase Arrival Time of 7 Bit Barker's Code Wave.

XI Cost Analysis

Component	Description	Cost
Ettus USRP N210	SDR platform by Ettus Research (legacy model)	\$3000 - \$6000 (used) [10]
Dipole Antenna	Basic dipole antenna for transmission	\$100-\$200 [10]
Ettus LFRX/TX USRP Daughterboard	Daughterboard for USRP's to enable transmission and receiving	\$150 - \$250 (used) [10]
SMA-to-SMA and SMA-to-BNC cables	Connectors for antennas to USRPs. Rated 50Ω to match USRP.	\$25 [10]

Note: All equipment was provided by the Uvic laboratory thus the reason for using legacy USRP's. Our project used legacy models of USRP's which increased the cost. Other cheaper alternatives such as LimeSDR (~\$100) can be used in place of the N210.

X Conclusion & Recommendation

In conclusion, we developed a working prototype capable of transmitting and receiving a 5 MHz wave embedded with a Barker's code through a wired connection. The next major step involves transitioning to wireless antenna-based communication and validating against ionospheric signals. Incorporating buoyancy frequency analysis will allow mapping the intensity and timing of forest fire-related disturbances. With further development, this system has the potential to be scaled into a real-time forest fire detection and alerting tool.

A recommendation would be to use a different modulation technique called LFM (linear frequency modulation). Using Barker's code will give frequency timing problems and requires the use of a MIMO cable to avoid them. This is an issue because in a real case scenario, the USRPs will be in two different locations and connecting a MIMO cable would be difficult. While LFM can solve this issue by modulating frequency, thus both USRPs don't need to be synced with a MIMO cable.

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