Implementation of Software-Defined Antenna and Radio Test System for Congested Spectral Environments

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Abstract

Research in Software Defined Radio (SDR) is often focused on the software aspects related to digital signal processing for agile radios. However, the front-end hardware plays a significant role in the overall performance of SDR networks. In dynamic and adaptive radio systems, static antenna design can greatly limit the system's performance potential. Reconfigurable narrowband antennas offer an opportunity to enable full-system software control with the ability to jointly configure the software-based signal processing chain along with the configuration of the front-end antenna. In this article, we present initial work towards the development of a GNURadio-based test system for SDR and reconfigurable antennas. Furthermore, we introduce our open-source GitHub repository, gr-recon, which provides example scenarios for use of the New Scale Pathways software tool to remotely configure distributed GNURadio flowgraphs and front-end reconfigurable antenna hardware.

1. Introduction

Reconfigurable narrowband antennas with operating frequency agility can provide several performance benefits like size compactness, improved noise performance, and suppression of out-of-band interferences. However, much of the research effort has focused on observing the hardware capabilities, and antenna reconfiguration is rarely implemented with a software-defined radio (SDR). The hardware/software modularity of an SDR testbed provides an opportunity to adapt the signal processing parameters along with the antenna configuration, enabling a test system capable of demonstrating and analyzing the performance impact of reconfigurable antennas on modulated data streams. Accordingly, we are developing an SDR-based platform to test the performance of tunable antennas in a modern communication environment.

From a hardware perspective, the antenna's operating frequency is continuously tuned using piezoelectric linear actuator motors that vary the overall capacitive loading of the passive antenna. The linear actuators are controlled using external software, which converts the electrical signal to a mechanical movement of the actuator. As a preliminary step of testing the system, we are using the GNURadio software to automate the antenna's tunability alongside a modulated data stream. In this paper, we will describe our efforts towards the co-configuration of a GNURadio signal processing flowgraph and the front-end antenna's operating frequency, which also impacts the operating bandwidth. We will describe our test configuration and analysis of a 3-node system with Tx and Rx nodes using the reconfigurable antenna design and a third interfering node. The interfering node is set to generate various out-of-band signals that would negatively impact the primary link's performance without proper anti-aliasing. This test setup will highlight the value of this narrowband filtering within the antenna structure in order to mitigate aliasing issues from the out-of-band interference without the need for additional hardware associated with anti-aliasing filters.

Our key contribution is the development of an SDR-based test bed to characterize the performance of tunable narrowband antennas in a modern communication system. Specifically, the hardware/software modularity of the SDR platform is used to jointly configure the antenna's frequency along with parameters in active GNURadio flowgraphs.

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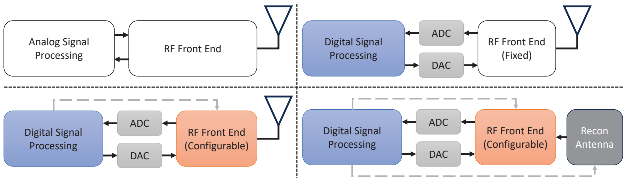


Figure 1. Evolution of SDR towards radios with software control capabilities throughout the signal chain (including characteristics of the front-end antenna).

2. Background and Motivation

The evolution of SDRs and SDR hardware has created extensive opportunities for dynamic and adaptive radios and radio environments. This evolution began with the adoption of high-speed ADCs/DACS and the ability to apply digital signal processing for much of the signal chain. The advancement of SDR hardware took this further with the ability to configure parameters of the analog RF front end, however, the antenna has historically been viewed as a static component. Fig. 1 highlights the next step in fully reconfigurable radios, where the conventionally static antenna is replaced with a reconfigurable antenna that can be controlled and configured as part of the dynamic and adaptive signal chain.

Reconfigurable, or software-defined, radios and radars, have long been hailed as the solution to congested and contested spectrum. While extensive work on reconfigurable front-ends and antennas show promise for spectrum sharing (Bernhard, 2007; Hall et al., 2012; Tawk et al., 2012; 2011; Dietrich et al., 2001; Gou et al., 2011; Eslami et al., 2010; Boerman & Bernhard, 2008; Bass & Ruyle, 2019; Jung et al., 2010), and extensive research and development has been pursued through the use of SDR-related technologies (Restuccia & Melodia, 2020; Restuccia et al., 2019; Uvaydov et al., 2021; Sankhe et al., 2019), very little has been accomplished demonstrating a reconfigurable front-end attached to an SDR (Boerman & Bernhard, 2008; Eslami et al., 2010; Gou et al., 2011; Tawk et al., 2012; 2014; Bahceci et al., 2017; Kumar et al., 2014). Accordingly, research advances in reconfigurable front-ends remain distinct from SDR-related research. Although reconfigurable front-ends add complexity, they can act as both a frequency and spatial filter, reducing noise and interference in a system, which is critical for SDR and software-defined radars to enable spectrum sharing.

3. Reconfigurable Antenna Hardware

The reconfigurable antenna hardware used in this work consists of a Printed-Circuit Board (PCB) integrated slot antenna, which was first proposed in (Agasti et al., 2023b). Radiation takes place through the semicircular annular slot

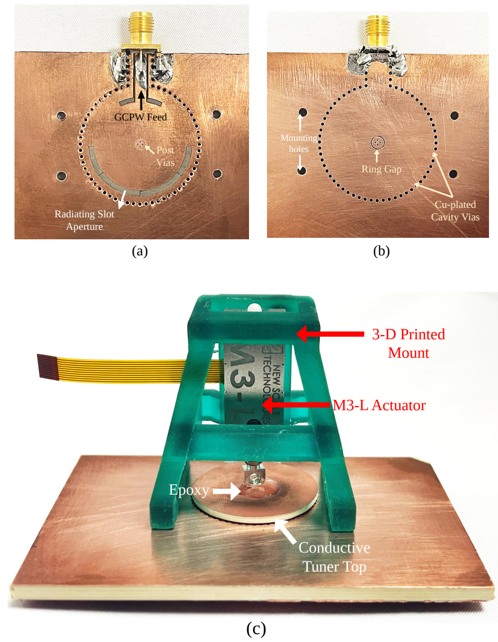


Figure 2. Fabricated Prototype of the tunable antenna (a) Bottom-view with the feed and radiating slot aperture (b) Top-View (c) Full assembly with the M3-L linear actuator and the 3-D printed mount.

placed on the ground plane of the cavity, as seen in Fig. 2. The center frequency of the antenna is tuned by using a contactless capacitive tuning scheme utilizing long-range linear actuators from New Scale Technologies. The M3-L actuator motor has a step size of 0.5 μm and a total displacement range of 6 mm (New Scale Technologies).

A conductive circular disk, suspended above the cavity, is attached to one end of the linear actuator. By changing the vertical distance between the cavity ceiling and the conductive disk, the center frequency of the antenna can be varied across a wide range. The total frequency range over which the antenna can operate is from 1.7 GHz to 2.6 GHz when the vertical gap is varied from 24 μm to 531 μm using the long-range actuators, as seen in Fig. 3. Note that the antenna can be tuned continuously across the tuning range.

A reconfigurable frequency-agile filtering antenna, or a filtenna, belongs to a highly-integrated class of antennas where the filtering and radiation functionalities are seamlessly combined into a single unit. Due to the integrated filtering capability, the filtenna unit can achieve a higher out-of-band noise suppression and increase the overall system performance while maintaining a compact front-end module. In (Agasti et al., 2023a), a filtenna unit was proposed using the reconfigurable slot antenna shown in Fig. 2. The filtenna consists of a tunable resonator, in addition to the tunable antenna, to further enhance the filtering capabil-

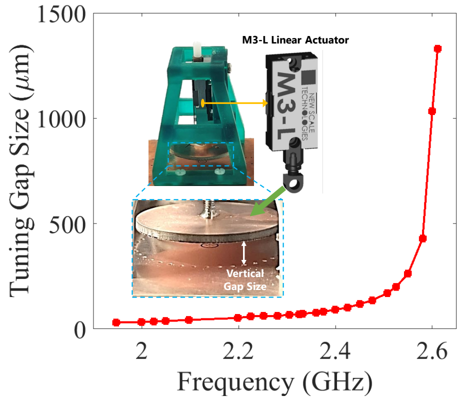


Figure 3. Measured tuning curve for the reconfigurable antenna. The center frequency of the antenna is tuned by vertically displacing the conductive disk across a large range of gap sizes.

ity of the system. In the reconfigurable filtenna hardware, there are two linear actuators to simultaneously change the frequency of the resonator and the antenna using the contactless capacitive tuning scheme described in (Agasti et al., 2023a).

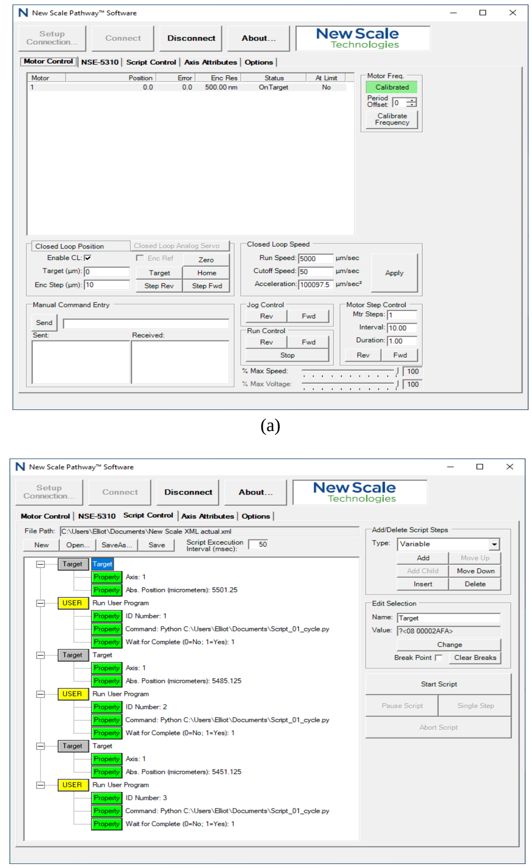
3.1. New Scale Pathway Software

The frequency reconfiguration scheme for tuning the antenna and filtenna hardware is achieved using the external linear actuators. The linear motion of the M3-L actuators is operated through the New Scale Pathway software that allows for individual operation of the motors using manual motor control, as well as script control, as seen in Fig. 4. To account for measurement errors, the actuators include an embedded closed-loop control system to automatically calibrate the motor.

In order to automate the measurements, the motors were moved using the script control option (Fig. 4(b)). A Python script was created to determine the position of the motor corresponding to different center frequencies of the reconfigurable antenna. The script uses a curve-fit equation to determine the exact vertical gap needed for tuning an antenna using pre-measured datasets of gap sizes for different frequencies. The Python script interfaces with the New Scale Pathway software by creating an XML file that commands the actuator motor to move to a target position, thereby tuning the antenna's center frequency.

4. SDR Software and Hardware

The GNURadio signal processing toolkit provides an extensive set of signal processing blocks. In addition, the core GNURadio library includes software tools that simplify the implementation of remote control of parameters (i.e., XMLRPC) and remote access of measurements (i.e., ZMQ) in active GNURadio flowgraphs. Furthermore,



(a)

(b)

Figure 4. New Scale Pathway Software Interface (a) Manual Control mode with real-time measurement of the actuator displacement (b) Script Control Mode for defining the displacements corresponding to different center frequencies.

GNURadio offers simplified access to SDR hardware, including the universal software radio peripheral (USRP) equipment from National Instruments and Ettus Research.

In this work, we have integrated the New Scale Pathways software, described above, with GNURadio's XMLRPC and ZMQ tools such that scripts running within the Pathways software are able to remotely configure parameters in active GNURadio flowgraphs. These parameters include characteristics of the baseband waveform and the SDR hardware configuration - including the carrier frequencies set on USRP hardware. When combined with the Antenna configuration parameters described in Section 3, we can jointly configure the antenna setting(s) with the waveform settings (e.g., signal bandwidth, Tx/Rx carrier frequency, etc.). Furthermore, as demonstrated in the examples to follow, we can remotely pull power measurements from active flowgraphs and create an automated data collection procedure that cycles through a set of desired configurations and measures performance after each update.

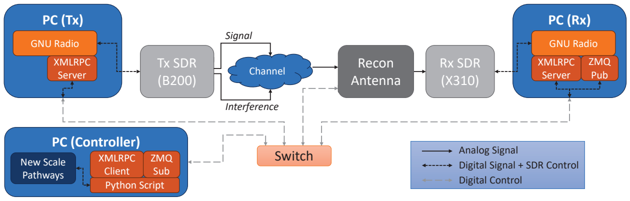


Figure 5. Testbed architecture and software configuration

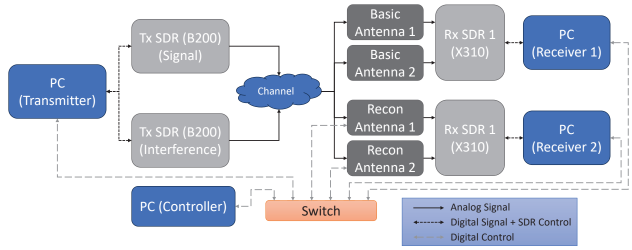


Figure 6. Extended Testbed Architecture (*future*)

4.1. GNURadio

GNURadio's XML-RPC and ZeroMQ (ZMQ) tools serve distinct yet complementary roles for facilitating networked communication. XML-RPC is commonly utilized for control plane activities, allowing dynamic modification of parameters in a running GNU Radio flowgraph. This enables adaptive tuning of an active flow graph. On the other hand, ZeroMQ specializes in data plane activities, offering low-latency, high-performance messaging capabilities for the exchange of data samples or packets between different GNURadio flowgraphs or networked systems. In the context of this research, ZMQ provides data feedback for analysis outside GNURadio. Together, these technologies offer a versatile framework for flowgraph monitoring and control and flowgraph data feedback.

4.2. USRPs

The USRP product line offers a range of hardware at various price points and capabilities. In our baseline testing for this work, we utilize the USRP B200 and the USRP X310 with UBX160 daughtercard. The broad coverage of these USRPs allows for testing across the full range of capabilities for the reconfigurable antenna hardware introduced in Section 3. USRP hardware implements digital-to-analog- and analog-to-digital-conversion, along with carrier frequency modulation and additional functionality for the RF front-end; however, the radio conversion is conventionally implemented with static RF antennas. In prior work, we have demonstrated methods for integrating USRPs with non-conventional front-end hardware, including work in SDRs for optical wireless communications (Little et al., 2018; Ahmed et al., 2022). In this work, we integrate USRPs with the hardware introduced in Section 3.

5. Testbed Architecture

As a primary contribution of this work, we have developed a testbed architecture and corresponding software for joint configuration of the reconfigurable antennas (Sec 3) and the conventional SDR signal chain (Sec. 4). The hardware/software integration for our initial design is depicted in Fig. 5. In this design, the RF link consists of a transmitter (Tx) node and receiver (Rx) node, each running GNURadio and connected to a USRP. The Input to the Rx node's USRP is the tunable antenna (depicted in Fig. 2) which can be directly configured by the third computer (i.e., the controller) via New Scale Pathways. Notably, the New Scale Pathways software is only available for Windows OS.

In the GNURadio Flowgraphs at the Tx and Rx nodes, an XMLRPC server is initiated such that flowgraph parameters can be remotely configured by an XMLRPC client over the control network. Furthermore, the Rx node uses a ZMQ PUB Sink to publish measurements which can be subscribed to by a remote node over the control network. Finally, and most importantly, the control node's XMLRPC client and ZMQ subscriber is managed within a Python script (or scripts) at the control node. This script (or scripts) can be executed from within the New Scale Pathways software as an external user program, allowing the architecture to be fully controlled from scripts running within Pathways.

As an extension to this architecture, we also introduce the design depicted in Fig. 6. Given the remote configuration capabilities of the Tx and Rx nodes in the baseline implementation, the architecture is scalable to include additional Tx and Rx nodes. The implementation of this extended architecture is pending access to additional SDR hardware, but the design follows the structure of our baseline implementation where parameter control at each Tx/Rx node is based on the control network's IP address conventions and unique XMLRPC servers running at each Tx/Rx node. Similarly, measurement parameter(s) at each Rx node can be accessed via ZMQ PUB Sinks associated with unique ports/addresses. With this design, a variety of user-specified python scripts can be developed for control and/or measurement, and these scripts can be executed from within New Scale Pathways scripts that also implement the desired antenna configurations.

6. Results and Analysis

In this work, we have developed a preliminary codebase to demonstrate the potential impact of reconfigurable antenna design along with the functional test capabilities associated with fully controlling the antenna configuration(s) and SDR signal chain parameter(s) from within the New Scale

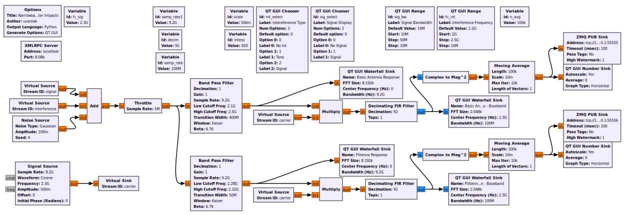


Figure 7. Multi-rate flowgraph to simulate basic and tunable antenna responses and demonstrate out-of-band interference that is introduced without proper filtering prior to down-conversion.

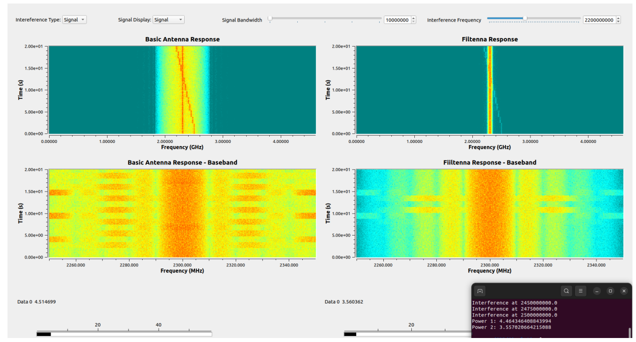


Figure 8. Simulation results showing automated configuration of signal and interference parameters via XMLRPC and power measurements via ZMQ (configured from Python script on the GNURadio computer via localhost connections).

Pathways software. The developed code is openly available from our gr-recon GitHub repository (Onwuchekwa et al., 2023). The repository contains GNURadio flowgraphs and associated Python scripts for simulating the impact of a reconfigurable narrowband implementation. It also contains flowgraphs, Python scripts, and New Scale Pathways scripts for automated data collection within the baseline architecture (Fig.5).

6.1. Simulation

To demonstrate the value of a narrowband reconfigurable antenna, we have developed a simulated model of a basic RF front-end implementation within GNURadio. This simulation-based flowgraph also allows for testing the network architecture's functionality before incorporating the physical hardware.

Since the front-end hardware and associated frequency response will impact the signal prior to sampling and down conversion, we implement a multi-rate flowgraph that defines a hypothetical sample rate large enough to view this theoretical spectrum from DC to 4.6GHz. Since the sample rate is obviously impractical, we incorporate a throttle block with a much lower sample rate (i.e., 5MHz) and use the hypothetical 9.2GHz sample rate for modeling and visualization purposes only. This is a nice benefit of simulation within GNURadio (or in offline digital signal processing), as the characteristics of individual blocks and processing modules are based on a user-specified value for sample rate. From here, we can apply a digital filter with characteristics that are representative of a conventional antenna and/or tunable antenna. Finally, we simulate a simplified carrier demodulation process and then down sample this digital model of our analog signal to 100MHz. This signal is representative of the typical complex baseband equivalent of our passband signal, including any out-of-band interference that now appears within the band due to aliasing and non-ideal filtering prior to downsampling.

The core of this simulation flowgraph is shown in Fig. 7, where the implementation of the primary and interference signals (introduced within the virtual source blocks) is implemented elsewhere in the flowgraph. The generation of these signals includes selection blocks that allow for enabling or disabling the signals and for selecting between a tone and signal as the primary interference. In addition, the flowgraph in Fig. 7 also includes the necessary XMLRPC server block and ZMQ PUB Sink blocks, all of which are configured for the use of the localhost.

In Fig. 8, we demonstrate the resulting GUI from running this flowgraph, along with the outcome observed when running the associated Python script that sweeps an interference signal across the range of the broadband antenna's response. It also reads and prints the power measurements within the terminal running the associated python script. While this model is a simplification of the overall RF front-end, it demonstrates the importance of appropriate narrowband filtering prior to down conversion and sampling. We also highlight that this simulation flowgraph can vary the tunable antenna's center frequency and associated response, which will enable further demonstration of the reconfigurable antenna system's performance.

6.2. Antenna/Radio Co-Configuration

To demonstrate the software integration capability of the antenna configuration and GNURadio, an experimental setup following the architecture in Fig. 5 was assembled (Fig.9). The primary goal was to test the software integration for automated data collection using direct configuration through the New Scale Pathways software.

For the test scenario, the center frequency of the antenna was programmed to cycle through different center frequencies, with the first test configured at a center frequency of 2.3 GHz. The interference tone was swept across a range of 2.1 GHz to 2.5 GHz in steps using the main Python script, which was executed through the New Scale Pathways software, as seen in Fig.10. A pseudo-code for the control script coordinating between GNURadio and Pathways is

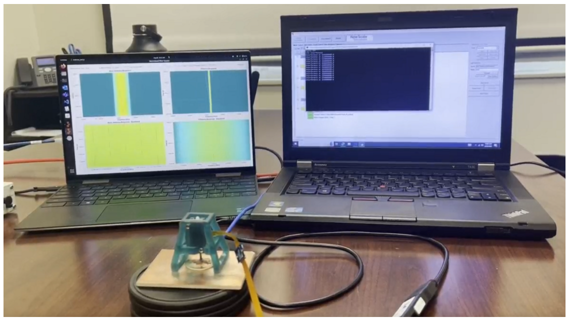


Figure 9. Physical deployment demonstrating control node (Windows PC, right) with New Scale Pathway software, the tunable antenna, and receive node (Linux PC, left) running GNURadio.

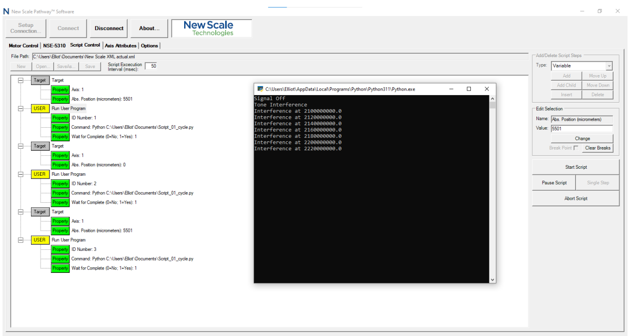


Figure 10. New Scale Pathway program configured using a control Python script to tune the reconfigurable antenna to a specified user-defined frequency.

included in Algorithm 1. The GNURadio flowgraph for the Tx and Rx nodes are remotely configured in the Pathways script via the external user program (i.e., Python script), and power measurements at the Rx node are recorded at the control node in order to observe the impact of the interference tone as it sweeps across different frequencies.

The result of this experiment demonstrates that the hardware/software modularity of the SDR platform can successfully configure the antenna's frequency parameters while allowing control over the active GNURadio parameters. This integration capability will allow for automated system data collection operating under different interference scenarios.

7. Summary and Conclusion

In conclusion, this paper documents a method to connect and automate frequency reconfigurable antennas with GNU Radio. Reconfigurable antennas can provide filtering at the antenna aperture - providing increased robustness to spectral interference in congested and contested frequency bands. Future work will use the experimental setup to document the impact of tunable filtering front-ends on system-level performance metrics like packet error rate.

Algorithm 1 Software Integration of New Scale software and GNURadio

```
Set center-frequency (f_c) configuration
Run User Program (python script)
    Enable Tx and Disable Interference
    Set Tx and Rx Center Frequency (f_c)
    Wait 5s
    Record Measurement
    Disable Tx and Enable Interference
    for all Interference Frequencies (f_int)
        Set Interference Center Frequency (f_int)
        for all Bandwidth Settings (B)
            Set Interference bandwidth (B)
            Wait 5s
            Record Measurement
Wait for Completion
Initiate next frequency configuration
```

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