Open-Source Antenna Pattern Measurement System SDR-based Student Research and Development

Abstract

Weber State University (WSU) has developed an 'open-source' antenna-pattern measurement system physically comprised of software-defined radios (SDRs) and 3-D printed hardware. The present WSU 'open-source' prototype integrates Python, GNU Radio Companion, and Linux on a single laptop PC. Multiple student projects have investigated methods to improve measurement fidelity in non-optimal environments. For example, excellent agreement between measured and simulated radiation patterns has been obtained using coherent AM detection. The following paper summarizes the development of the current system and presents results from student research.

1. Introduction

1.1. Background

Electrical Engineering faculty at Weber State University (WSU) have pursued software-defined-radio (SDR) applications to expand RF measurement capabilities for education and applied research. Examples of open-source SDR instrumentation developed for RF measurements include periodic and random Jitter (G. Anthonys & Streeter, 2019), RFID system performance (D. DeDonno, January 2013), and array localization algorithms (V. Goverdosvsky, July 2016). Sections 2 describe the development of an SDR-based antenna radiation pattern measurement system presented at the AMTA 2020 conference (C.W. Hearn, 2020). Section 2.6 summarizes the analysis of two modulation methods in a non-anechoic environment (Hansen, 2020). The antenna pattern measurement system developed at WSU was inspired by the published work of Picco and Martin (V. Picco, Dec 2011). Their practical system utilized commercially-available 2.4 GHz wireless routers. Open-source (DD-WRT) software replaced the original firmware. An estimate of the received field strength was obtained from the (DD-WRT accessible) received signal strength indicator (RSSI) measured between routers. Antenna position control and RF signal measurement were realized using National Instruments LabVIEW (https://www.ni.com/en us/shop/labview.html). The Picco and Martin (P&M) prototype was developed and results were published in 2011. Since the publication of their results, software-defined-radios (SDRs) have become economically viable for student projects. In addition, the tremendous growth of three-dimensional printer technology has made available hardware well-suited for integration to a pattern measurement system. The GNU Radio software library (https://wiki.gnuradio.org/index.php/Main$_{Page}$) was chosen for the WSU project to maintain the flexibility of LabVIEW with commercial software fees. GNU Radio Companion is a Linux-based open-source software platform for communication and signal processing that is well-suited for student-initiated code development. Position control is achieved using an Arduino microcontroller with open-source software developed for 3-D printer systems (https://grbl controller.software.informer.com/3.6/.). Low-cost, commercially-available three-dimensional printer hardware (e.g. gears, synchronous belts) and software are utilized for position-control. The following sections describe the development and current research of an open-source antenna pattern measurement system. A summary of current research describes the assessment of a coherent modulation method utilized to reduce measurement noise interference in non-anechoic environments.

1.2. Feedback from Paper Submission

Complete developments of pattern, directivity, and gain discussed in the following sections are available in numerous texts. Two popular examples include (W. L. Stutzman, 1998) and (Balanis, 1997). An antenna pattern is a graphical representation of the normalized (electric) field magnitude at a fixed distance from the antenna as a function of direction. (1)

$$F(\Theta,\Phi) = \frac{E(\Theta,\Phi)}{E_{MAX}}$$

Normalized directivity is the radiated power density relative to the measured maximum power density. Normalized Directivity and Gain are related to the square of the antenna pattern. (2)

$$|F(\Theta,\Phi)|^2 = \frac{D(\Theta,\Phi)}{D_{MAX}} = \frac{G(\Theta,\Phi)}{G_{MAX}}$$

Preliminary work. Under review by the GNU Radio Conference (GRCON). Do not distribute.

An approximation of the gain from the measured pattern of a lossless antenna may be determined by scaling the measured data to a calculated gain. (3)

$$G(\Theta, \Phi) \approx G_{Total} \cdot |F(\Theta, \Phi)|^2$$

A Method of Moments commercial software (e.g. FEKO) may be used to model the prototype and calculate maximum Gain values. Comparisons of measured patterns to simulation are straightforward once the measured pattern data is normalized and scaled to the calculated maximum gain. The method described is limited to a qualitative check, but it would be a relevant demonstration of validation in an educational setting.

1.3. Linksys Prototype

Two WSU undergraduates reconstructed the P&M system as part of a senior capstone project. The reconstructed system utilized readily-available Linksys routers connected to the reference antenna (SOURCE) and the antenna-under-test (AUT). Open-source firmware (DD-WRT) was loaded on the routers to access the RSSI level versus position. National Instruments LabVIEW software controlled two stepper motors for elevation and azimuth orientation of the AUT. The senior project obtained coarse pattern measurements of a test antenna, however difficulties mentioned in the original article reappeared with the WSU recreation of the P&M prototype.

2. Open-Source SDR Prototype

2.1. First SDR Prototype

A second antenna pattern measurement system prototype was developed with modifications focused primarily on addressing mechanical challenges (e.g. slippage, position control) and single frequency operation. A photograph of the current prototype is shown in Figure 1. The mechanical system was redesigned with a focus on the use of PVC components and synchronous-belt hardware. Design and fabrication of the rapid-prototype-material (RPM) parts are discussed in Section 2.3. The second system consisted of two SDRs, two stepper motors, and one Arduino Uno to control the stepper motor drive board. A block diagram of the complete system is shown in Figure 2. One computer was dedicated to operate the control software with a user interface. A summary of the 2nd prototype modifications include:

- Open source motor control
- GRBL on Arduino, easy to modify/configure
- Synchronous (toothed) belts/pulleys
- Hack RF software-defined radios
- 30 MHz-6 GHz potential frequency range
- GNU Radio Software control of SDRs

Modifications chosen for the second prototype increase cost and system complexity. Potential increases in capability and measurement accuracy were justification for the design modifications.

2.2. Position and Data Acquisition Control

An Arduino microcontroller with a commercially-available motor-driver shield establishes position control for the AUT. An external power supply provides 12 Volts DC and up to a maximum 30 Amps pulses to drive the stepper motors. Control of the motors is established through a series of GRBL ‘G-code’ commands over the virtual serial port provided by Arduino. G-code commands are sent to the GRBL motor control firmware to control position, speed, and direction of the stepper motors during measurements. GRBL is an open-source firmware for CNC machines and 3D printers. G-code is used by hobbyists for 3-D printing as a standard for directing spindle/nozzle movement.

Figure 1. Antenna Pattern measurement system. Emphasis was placed on use of commercial PVC material with 3-D printer hardware including synchronous belts and gears

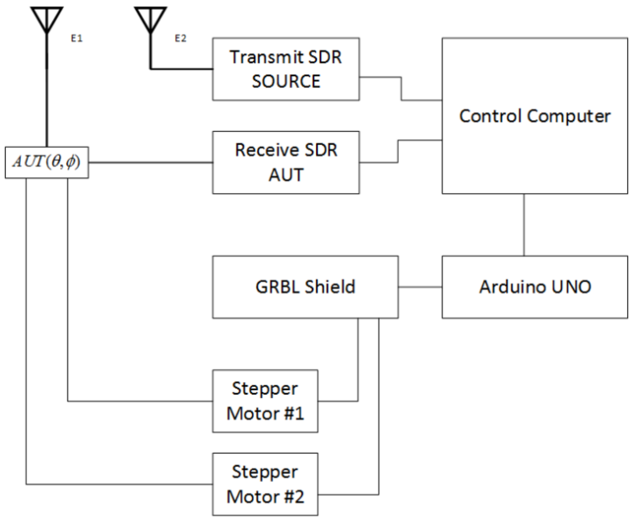

Figure 2. Block diagram of Antenna Pattern Measurement system.

2.3. Mechanical Design

Mechanical modifications to the P&M design proceeded with the design goal to utilize commercial off-the-shelf (COTS) components when possible. Custom parts were prototyped on-site. Design challenges related to the Antenna Pattern Measurement System included the multi-axis movement requirements, control of mast motion, and low conductivity of the structure and motors to minimize scattering/interference with the antenna signal reception. The azimuth and elevation control stepper motors were chosen to minimize EMI with the measured signal. Synchronous drive belts used in commercial 3-D printers were incorporated to rotate the AUT mast about two axes of motion. Future measurement prototypes will include bearings constructed of non-conductive polymer material were also procured and included in the drive system. The primary structure was constructed of commercially available plastics, including PVC pipe to minimize the costs. Custom parts were designed and fabricated at Weber State University. Examples include the synchronous belt sprockets, and mounting brackets. Images of the custom designed parts used in the Antenna Pattern Measurement System assembly are presented in Figure 3. SolidWorks 3D CAD software was utilized in the design process to verify functionality, clearances, as well as range of motion. The mechanical design also included the mounting and packaging of the associated electronics, stepper motors, and power supply.

Figure 3. Antenna Pattern Measurement System Prototype Part CAD Models.

2.4. Measured Results

Prototypes of three antennas were constructed to evaluate an antenna design and development process for undergraduate students. It is anticipated future student-built prototypes will be designed for Wi-Fi band $(f \approx 2.4GHz)$ with a free-space wavelength of approximately $\lambda \approx 12.5cm$. Models were constructed using commercial Method-of-Moments software (FEKO) for comparison. Measured Radiation pattern data was scaled to the simulated Gain values (GTOT) for a quarter-wave monopole over a finite ground plane, a Yagi-Uda directional antenna, and an air-backed circular micro-strip patch antenna. Discussion of the validation step and presentation of results are available.(Hearn, 2020)

2.5. Noise-Subtraction versus Coherent AM

A Noise-subtraction method of measuring received signal strength was implemented with the first WSU prototype. Statistical characterization of noise power may be investigated in the future, but a straightforward noise-subtraction algorithm Intro-define noise-subtraction method as state it is the original data acquisition algorithm for the WSU prototype. The 'noise subtraction' method of measuring signal strength transmits and measures a received uniform noise signal. At each position, an ambient-noise and signal+ambient-noise are recorded. The ambient-noise measurement is subtracted from the signal+noise measurement. An example of a principal plane pattern (in linear format) of the 2.4 GHz Yagi prototype is shown in Figure 4. Coherent Amplitude Modulation (Double-Sideband-Suppressed Carrier – DSB-SC-AM) is the linear-modulation method integrated to the WSU antenna pattern measurement system. The close proximity of the source and AUT allowed for synchronization of the receive and transmit SDRs.

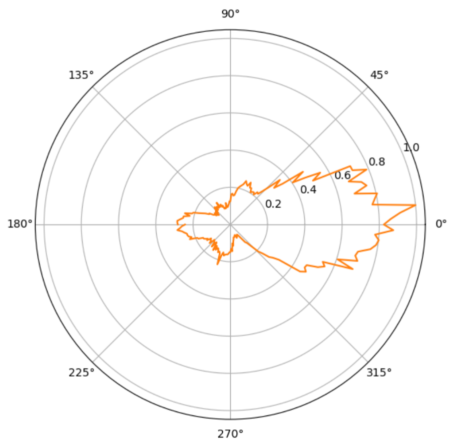

Figure 4. Example of 2.4 GHz Yagi prototype measured pattern using noise reduction method.

The coherent DSB-SC AM system was developed based on the work of Saraswati, Asuti, and Mishra [14]. A DSB-SC AM transmitter and receiver, shown in Figures 5 and 6 respectively, were developed using GNU radio software and the same Hack RF One SDRs described in Section III. The osmocom source block receives the signal measured by the SDR receiver. The signal is then multiplied by the carrier signal. The carrier signal is the same 2.4 GHz sinusoid used in transmitter. The multiplication shifts the frequency to baseband. For long-range communication receivers using coherent detection, a Costas loop is used to lock the phase of the DSB-SC AM signal with the phase of a local oscillator set to the carrier frequency (S. B. Saraswati & Mishra, 2016). The carrier signal at the SDR transmitter

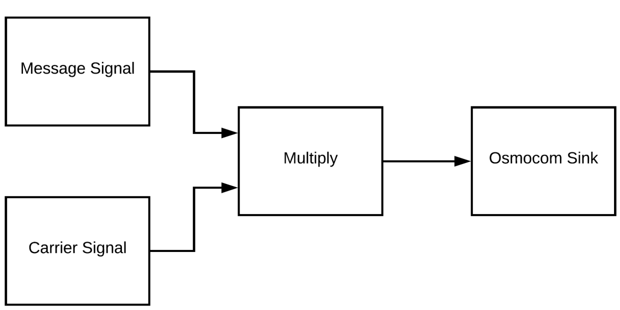

Figure 5. DSB-SC AM Transmitter Flow Chart.

and the SDR receiver were synchronized by connecting the clock signal of the SDR transmitter to the clock signal of

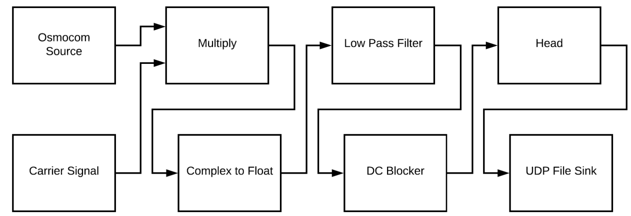

Figure 6. DSB-SC AM Receiver Flow Chart.

the SDR receiver. Figure 7 is a comparison plot (linear format) of a principal plane plots of normalized patterns of the 2.4 GHz Yagi prototype using the two methods. The noise-subtraction method shown in Figure 4 is compared to the coherent-AM method described.

2.6. Comparison of Modulation Methods

Antenna measurements in an ‘ideal’ (anechoic) environment using measurement-grade RF hardware would be the first choice for an accurate quantitative comparison of the two modulation methods. Research-grade patterns could be used as a basis for quantitative comparison. Limited resources required an alternative approach (J.McCormick & Parini, Dec 2011). A repeatability campaign with multiple pattern measurements for the three prototypes under similar conditions was completed for the analysis. Twelve antenna pattern measurements were taken of each of the three antennas using the noise subtraction method. Twelve additional measurements of each antenna were completed using the noise coherent DSB-SC AM method. A small sample size of 12 was chosen because of the long length of time required in obtaining each antenna pattern measurements. Following an approach described by (Stark & Woods, 1994), a margin of error, at each angular position was calculated using equation for both the noise subtraction method and the coherent DSB-SC AM method.

$$\epsilon = t\frac{\sigma}{\sqrt{n}}$$

In the equation above σ is the standard deviation of the n=12 data points at one specific angular position. A t-distribution table was used to select values of t for the above equation to give a margin of error with a 95% confidence.

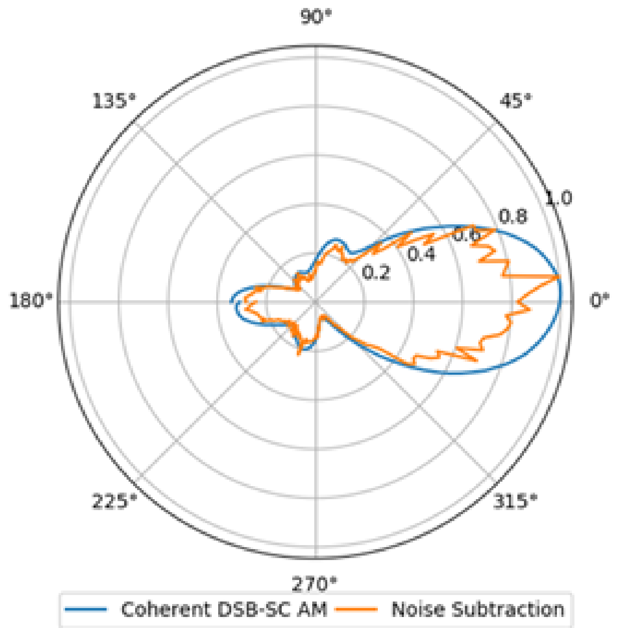

Figure 7. Measured principal plane pattern boresight ($\Theta = 90°, 180° < \Phi < 180°$) of the Yagi antenna prototype. Both the Coherent DSB-SC AM and Noise Subtraction methods are shown for comparison.

3. Upgrades

3.1. Hardware

The latest antenna pattern measurement system was developed replacing the older PVC components with 3-D printed parts modeled in Solid-works. The new design was created in order to make a more mobile system. The more mobile system allows students to test antennas in multiple noisy environments. As well as, the system is better suited for outreach and collaboration events.

3.2. Software

The software of the system was upgraded through student efforts and research. The list of upgraded software include:

- Python 3.6.5 – Python 3.9
- GNU Radio 3.7.13.4 – 3.9.2.0
- Linux 4.19 – Debian Bullseye

One major point of research was the transmitter gain on the newest systems distorted directional antennas. In previous systems the RF and IF gain were set to the max of 14 and 47 respectively. When ran on the newer laptops the main lobe of directional antennas were clipped off, exaggerating side lobes. The gain was modified in the python code down to 0 and the expected patterns were once again recorded.

Figure 8. Mast head created from 3-D printed materials

3.3. Platform

Raspberry Pi's run on an offshoot of Linux Debian called Raspbian or Raspberry PI OS. An SD card is programmed with the latest Raspbian software. The dependencies and python version is updated to match former PC tests. The first antenna tests are run on a Raspberry Pi 3. The antennas used are a quarter wave mono-pole and a patch antenna with no ground plane. A second set of measurements are recorded on a Raspberry Pi 4. The raspberry Pi 3 had significant noise in the measured data. Figure 9 shows a mono-pole antenna pattern measured with both the Raspberry Pi 3 and Raspberry Pi 4. Figure 10 is a similar measurement with a patch antenna. The controllable variables were kept constant in every measurement. The same antenna, SDR, and distance between antennas were used in each test. The same SD card was swapped back and forth between the PI 3 and PI 4 to create an exact match of the recorded software. "DRI2 Failed to authenticate" errors plagued the PI 3 test as well. The only working solution was to reboot the PI 3 pointing to a memory issue. However, more research would be needed to narrow down the exact cause. The PI 3 was concluded to be insufficient in data measurement and analysis compared to the PI 4.

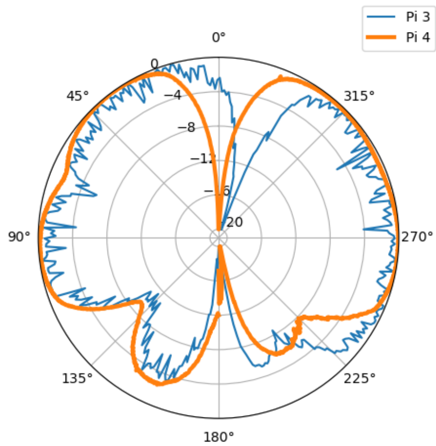

Figure 9. Raspberry Pi 3 vs 4 Mono-pole Antenna.

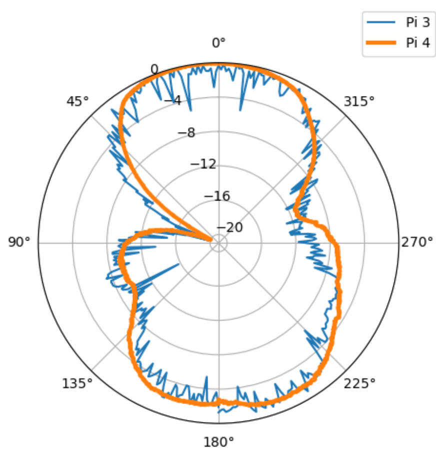

Figure 10. Raspberry Pi 3 vs 4 Patch Antenna.

4. Conclusions and Future Work

A low-cost antenna pattern measurement system based upon the Picco and Martin concept was modified to incorporate software-defined radios and commercial hardware. Additional parts were constructed using 3-D printer technology. Comparisons of simulated and measured gain patterns for three lossless antennas are presented. A qualitative comparison of the two modulation methods indicates the coherent modulation technique results in smoother antenna pattern measurements. The system has undergone several upgrades from software to hardware through student efforts. The automated antenna measurement system will continue to be an educational resource suitable for introductory antenna characterization. Applied research areas will focus on the optimization of antenna pattern measurements in non-anechoic environments. The open-source antenna pattern measurement system has also created collaboration opportunities with other universities.

5. Acknowledgement

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