

Implementation of a Software-Defined Radio based Global Positioning System Repeater

[†]William ‘Gray’ Blass, [‡]Andrew Hennigar, and [†]Shiwen Mao

[†]*Department of Electrical and Computer Engineering, Auburn University, Auburn, AL 36849-5201*

[‡]*Department of Mechanical Engineering, Auburn University, Auburn, AL 36849-5341*

Abstract

Software-Defined Radios (SDR) are a step forward in the evolution of wireless communications. Through well-established programming tools including, but not limited to, VHDL, C++, MATLAB, and Python, an engineer can accomplish many challenging and interesting tasks that were not possible before, such as interrogate and analyze Radio-frequency identification (RFID) tags, create a GSM mobile station, or even track aircrafts through Mode S transmissions. The SDR sets itself above traditional technologies through flexible applications and ease of use, and has great potential for wireless communications and networking research, as well as for enhancing the undergraduate wireless engineering curriculum. This paper details the design and implementation of an indoor GPS repeater that records GPS signals to playback into a building, where no GPS coverage is available. The playback GPS signals will be transmitted on the original GPS spectrum band, i.e., L1 at 1575.42 MHz, so that an ordinary GPS device can receive them. The Universal Software Radio Peripheral (USRP) N210 is used alongside RF daughterboard WBX (50 MHz - 2.2 GHz) and configured through the GNU Radio open source software. The experiments performed demonstrate the USRP’s ability to record and playback GPS signals that can be received and processed by an off-the-shelf GPS device in the indoor environment. In addition to the technical goals, we also intend to fully develop this project and integrate it with an SDR lab course that is under development at Auburn University, to exploit the high potential of SDR as an effective teaching and learning tool for undergraduate wireless engineering education.

Keywords

Global Positioning System (GPS); GNU Radio; Software Defined Radio (SDR); Universal Software Radio Peripheral (USRP).

Introduction

The Software Defined Radio (SDR), as its name implies, performs signal processing of wireless radio waveforms using a piece of software executed on a computing platform. With SDR, a radio can be reconfigured on-the-fly. Software-Defined Radios (SDR) are a step forward in the evolution of wireless communications. Through well-established programming tools including, but not limited to, VHDL, C++, MATLAB, and Python, an engineer can accomplish many challenging and interesting tasks that were not possible before, such as interrogate and analyze Radio-frequency identification (RFID) tags, create a GSM mobile station, or even track aircrafts through Mode S transmissions. The flexibility offered by SDR also allows implementation of radio communication systems that are

interoperable among different standards, protocols, frequency bands, user requirements and functionalities¹.

The SDR sets itself above current technology through flexible applications and ease of use, and has great potential for wireless communications and networking research², as well as for enhancing the undergraduate wireless engineering curriculum^{3,4,5}. With a pre-existing background in signal processing, a student can easily be taught how to apply their signal processing knowledge to build a working radio, which makes classroom teaching of abstract communications and signal processing theory tangible.

Recognizing the high potential of SDR for teaching and student learning, many universities are beginning to offer SDR projects or courses^{3,4,5}. Students usually have access to many undergraduate courses focused on mathematics and theory, but relatively less on hands-on work. By introducing labs that offer an approachable, hands-on experience, students can exercise their lessons in ways more applicable to the real world. To this end, SDR has a great potential to serve as a highly effective instruction tool for wireless engineering.

This paper details the design and implementation of an indoor GPS repeater that records GPS signals to playback into a building, where no GPS coverage is available. The playback GPS signals will be transmitted on the original GPS spectrum bands, i.e., L1 at 1575.42 MHz, so that an ordinary GPS device can receive them. The Universal Software Radio Peripheral (USRP) N210 is used alongside RF daughterboard WBX, which can operate in the wide frequency band between 50 MHz - 2.2 GHz, and configured through the GNU Radio open source software⁶. The experiments performed demonstrate the USRP's ability to record and playback GPS signals that can be received and processed by a standard GPS device in the indoor environment. In addition to the technical goals, we also intend to fully develop this project and integrate it with an SDR lab course that is under development at Auburn University, to exploit the high potential of SDR as an effective teaching and learning tool for enhancing undergraduate wireless engineering education.

In the remainder of this paper, we will first present the preliminaries on SDR, GPS signals, and other required equipment for the project. We then describe the SDR design of the GPS signal repeater and our preliminary test results. We conclude the paper with a discussion of future work.

Software-Defined Radio

As discussed, an SDR is a radio whose entire protocol stack, including the physical layer, is entirely software defined¹. This allows the radio to be configurable to multiple purposes over different frequency bands or protocols, making the SDR invaluable in operations that require multiple protocols or frequency bands. This is a breakthrough over the majority of standard radio equipment, which are essentially hardware radios.

To achieve these goals, specific hardware designs are required to be flexibly reconfigurable for different waveforms, protocols, and frequency bands. This issue becomes irrelevant for the SDR thanks to its software base. If for any reason at all, a different modulation technique or protocol needs to be used, the solution is as simple as loading the appropriate code to the SDR platform.

This is drastically different from the traditional approach of adopting multiple chipsets. The result is a diverse, adaptable device that is able to adjust itself to support different waveforms and protocols all by uploading the proper code to it, thus enabling a great degree of reconfigurability and interoperability of the radios.

The hardware design of the SDR can be best illustrated with the ideal SDR, as shown in Figure 1. For RF reception, the signal received by the antenna is amplified by a low-noise amplifier (LNA), and is then converted into a digital signal by its analog-to-digital converter (ADC). On the transmission side, the digital signals are converted to analog through a digital-to-analog converter (DAC) and amplified through a power amplifier (PA), which then gets transmitted. The baseband processor in the daughterboard takes care of all the physical layer filtering, modulation, and conversions. Therefore, various applications/protocols/waveforms can be implemented in software and run on the SDR hardware platform, which consists of a field-programmable gate array (FPGA) and a general purpose processor (GPP).

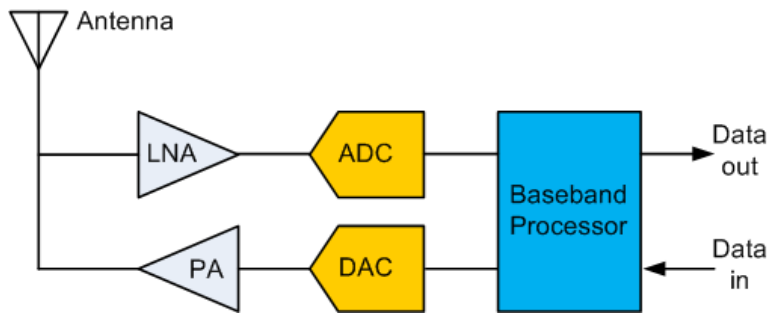


Figure 1 Block diagram of an ideal SDR^{1,2}.

Global Position System (GPS) Signal

GPS signals consist of a few sets of frequencies specified for different purposes. As shown in Figure 2, civilian usage is governed by the L1 frequency (1575.42 MHz) that transmits the Course/Acquisition code (C/A code)⁷. All satellites transmit this C/A code with a pseudo-random (PRN) code at 1.023 Mbps unique to each satellite and orthogonal to each other. This allows receivers to be able to distinguish these codes to reconstruct the actual message data using the corresponding C/A code. This is a form of Code Division Multiple Access (CDMA) in that the different satellites are distinguishable even though they transmit at the same frequency.

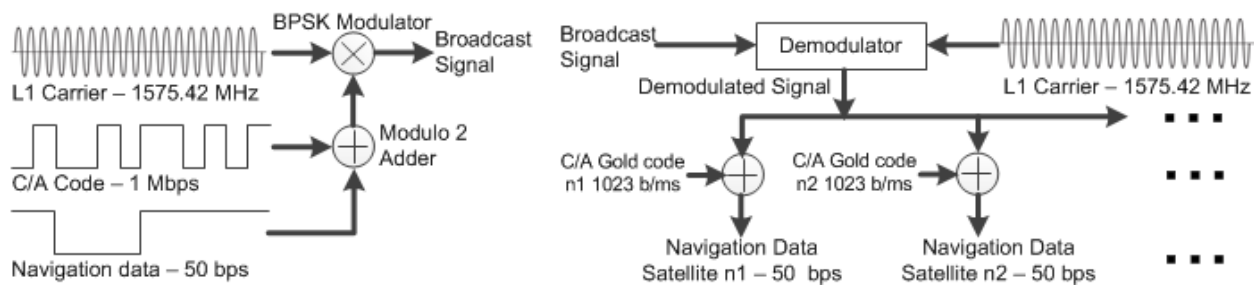


Figure 2 Illustration of the modulation and demodulation of GPS signals.

In addition to distinguishing satellites from each other, a receiver must be able to obtain their positions. This information is modulated on top of the C/A code at 50 bps and is called the Navigation Message. This Navigation Message is split up into 3 parts. The first part is the GPS date and time along with the satellite status. The second part is the ephemeris data that allows the receiver to determine the satellite's position. The ephemeris data is good for up to 4 hours. The third part is the almanac information, which contains information about all satellites including their positions and PRN codes. The almanac information is considered good for 180 days. The main purpose of the almanac information is to assist the receiver in determining which satellite it needs to look for, and identifying its unique PRN code. Then, the receiver downloads the ephemeris data from that satellite.

For civilian use, the L1 frequency is used with BPSK modulation for transmitting the C/A code. After demodulation, the signals are separated using their unique binary codes referred to as "Gold Codes." There are up to 32 different Gold Codes of 1023 bits that are used. They appear to be random, but are actually deterministic with an extremely long period. The signals are decoded using modulo 2 addition of the Gold Codes from satellites n_1 to n_k , which are the PRN identifiers of the satellites.

If the receiver has acquired the satellite it requires from the almanac information, it looks to identify the corresponding satellite. Otherwise, it enters a search mode to obtain the almanac information. After decoding, the resulting data is the Navigation Message at a data rate of 50 bps. In order for all of these to work, however, an unobstructed line of sight (LOS) path is required between the satellite and the GPS receiver. This will be discussed a little bit later into the paper.

Experiment Setup

The goal of this project is to design an SDR based GPS repeater that can be programmed to record and replay GPS signals. That is, if the GPS signals are suitably recorded, it could be played back to a standard GPS receiver that initially does not have LOS paths to the satellites.

The specific SDR used is the USRP N210 model made by National Instruments (NI). This particular SDR communicates with a computer through a Gigabit Ethernet connection with a data rate of 1000 Mbps. The daughterboard used is the WBX daughterboard that can transmit/receive signals in the range from 50 MHz to 2200 MHz, which includes the L1 frequency band. Since the daughterboard lacks internal attenuators, we also adopt a 30 dB attenuator for the playback GPS signal at the output of the SDR, so that the GPS receiver won't be overloaded. This attenuator also ensures that other GPS receivers that may present in the neighborhood won't be interfered.

Because the lab station is indoors, a GPS specific antenna is connected to the roof that is drawn down to the receiver of the SDR⁸. The off-the-shelf GPS receiver used in the experiment is a Garmin Nuvi 760. This one is chosen because it has an antenna port on the back. The transmitter of the SDR is directly connected to this antenna port. For the software configuration, Ubuntu 12.04 is the operating system for a desktop computer and GNU Radio Companion (GRC) for the design of the GPS repeater. Another important piece of equipment is the GPSD-O (GPS Dedicated Oscillator) as the clock source for the USRP. Without this, a recorded signal will not

be able to be properly decoded by a standard GPS receiver. The setup with the USRP and receiver is illustrated in Figure 3 and a photo of the testbed setup is shown in Figure 4.

The GPS antenna receives GPS signal that is wired into the lab room. The signal is amplified by 50 dB. The USRP N210 SDR platform converts the analog GPS signal into digital signals for storage in the computer. The computer runs the GRC, which saves the digital GPS signal during the receiving phase. Then the stored signal is transmitted to the USRP N210 for playback. The USRP N210 converts the digital signal into an analog signal and transmits it in the indoor environment. The GPS receiver then receives the playback analog GPS signal and computes its current location.

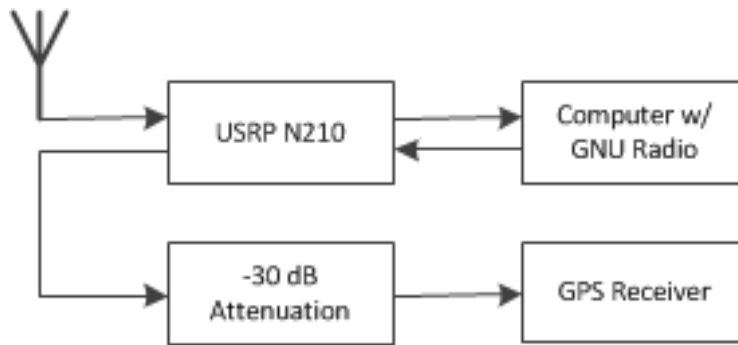


Figure 3 Block diagram of the GPS repeater testbed.



Figure 4 Testbed setup with the GPS receiver and the USRP.

SDR GPS Repeater Design and Test Procedure

The GPS Repeater is implemented with GNU Radio and executed in the USRP N210. Figure 5 presents the GRC design. The blocks on the left side are constants used throughout the program. System parameters such as the sampling rate, bandwidth, name of the program, and gains are defined here to be used throughout the process. We have two different setups for recording and playback, respectively. The top two blocks were not used for this test. The USRP blocks can be adjusted to be centered at a specific frequency (in this case the L1 GPS frequency), and to have a gain value set to them along with a bandwidth, and other various functions. Another important



Figure 6 The receiver does not acquire the satellites while indoors.

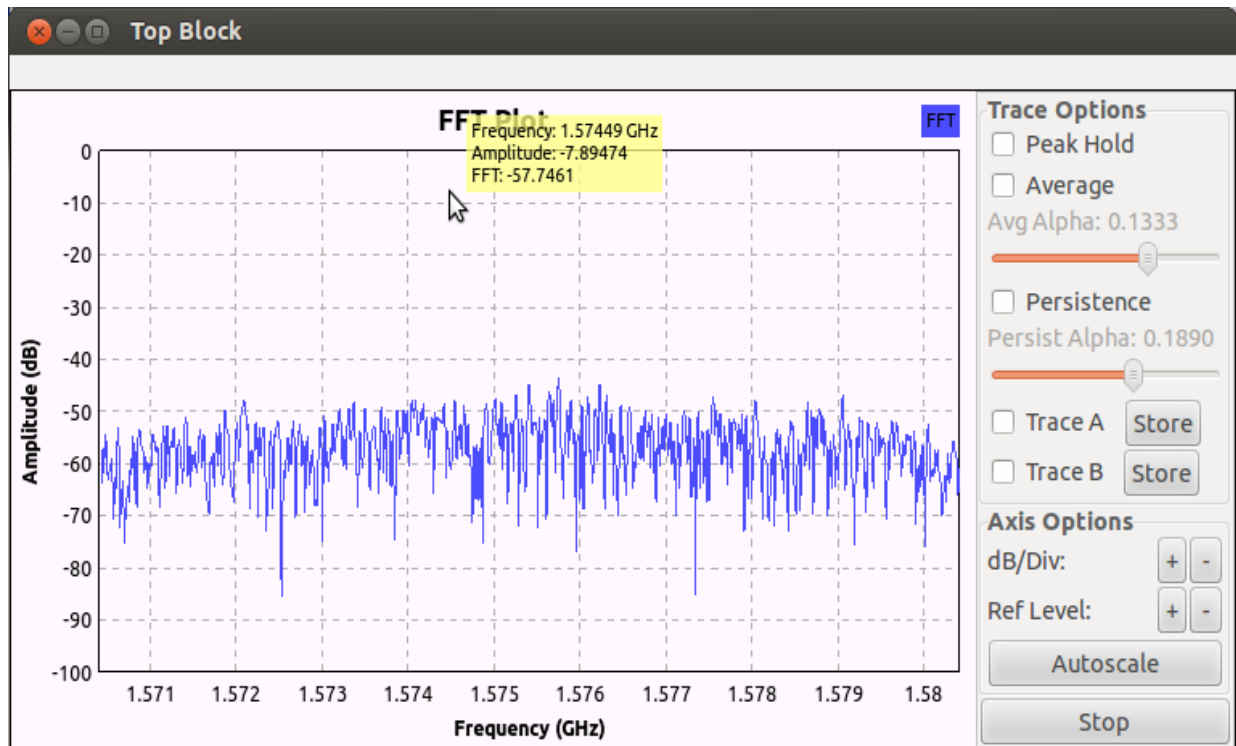


Figure 7 FFT of the recorded GPS data.

After recording is done, it is time to switch over to the playback. The GRC design is switched to playback the captured signal to the GPS receiver. This setup includes the bottom two blocks “File Source” and “USRP Sink” in Figure 5. At this time, the process is effectively reversed. The file becomes a source and the data is sent to the USRP as an output. From this point the signal is sent out to the GPS receiver.

Preliminary Results

We conduct some preliminary experiments with the SDR-based GPS repeater system. Figure 8 shows that the receiver did properly obtain the position of the building, while Figure 9 shows that the GPS receiver even had a good reception. The experiments performed demonstrate the USRP's ability to record and playback GPS signals that can be received and processed by a standard GPS device in the indoor environment.

We also find that even a student who lacks extensive knowledge on GPS signals and signal processing can perform this experiment after completing the several basic SDR labs we developed earlier. All that it comes down to is connecting a few things in the physical realm and then changing some settings in the GRC blocks. Then record the signal and play it back. With the SDR hardware/software platform, all of these become not very difficult to program. This project can serve as a simple introduction tool on how to work with an SDR. This project can also be used to enhance classroom teaching and learning with respect to many important topics in wireless engineering, such as modulation/demodulation, direct-sequence spread spectrum (DSSS), code division multiple access (CDMA), satellite communications, and GPS, among others.

Conclusions and Future Work

Thanks to its versatility and smooth learning curve, SDR's are not only the future of wireless communications and networking, but also a useful instructional tool for wireless engineering. In this paper, we presented a project on building an SDR-based GPS repeater. The focus was on demonstrating how an SDR records and plays back modulated signals. This project could be useful to offer undergraduate students a hands-on and simple programmable experience to test out the abstract communications theory.

For future work, we plan to tackle the more challenging problem of decoding the captured GPS signal through an SDR implementation. We also plan to fully develop this project and integrate it with an SDR lab course that is under development at Auburn University, to exploit the high potential of SDR as an effective teaching and learning tool for enhancing undergraduate wireless engineering education.

References

- 1 Reed, Jeffrey H., *Software Radio: A Modern Approach to Radio Engineering*, Prentice Hall PTR, Upper Saddle River, NJ, 2002.
- 2 Huang, Yingsong, Philip Walsh, Yihan Li, and Shiwen Mao, "A distributed polling service-based MAC protocol testbed," *Wiley International Journal of Communication Systems*, vol.27, no.12, pp.3901—3921, Dec. 2015. DOI: 10.1002/dac.2584.
- 3 Jiang, Fan and Shiwen Mao, "Integration of software-defined radios into undergraduate communications system courses for minority students," in *Proc. The 2014 ASEE Southeastern Section Annual Conference*, pp.1—10, Macon, GA, Mar./Apr. 2014.
- 4 Mao, Shiwen, Yingsong Huang, Yihan Li, Prathima Agrawal, and Jitendra Tugnait, "Introducing software defined radio into undergraduate wireless engineering curriculum through a hands-on approach," in *Proc. The 2013 ASEE Annual Conference*, pp.1—10, Atlanta, GA, June 2013.

- 5 Heath, Robert W., Jr., *Digital Wireless Communication: Physical Layer Exploration Lab Using the NI USRP*, National Technology and Science Press: Allendale, NJ, 2012.
- 6 GNU Radio, "GNURadio: The free & open software radio ecosystem," [online] Available: <http://gnuradio.org>
- 7 Wikipedia, "GPS signals," [online] Available: http://en.wikipedia.org/wiki/GPS_signals.
- 8 Hennigar, Andrew, *Analysis of Record and Playback Errors of GPS Signals Caused by the USRP*, MS Thesis, Department of Mechanical Engineering, Auburn University, Aug. 2014.

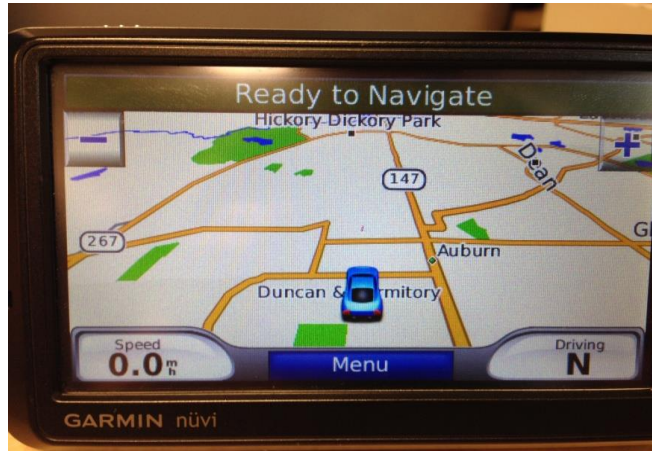


Figure 8 The standard GPS receiver correctly found the position from the replayed GPS signal.

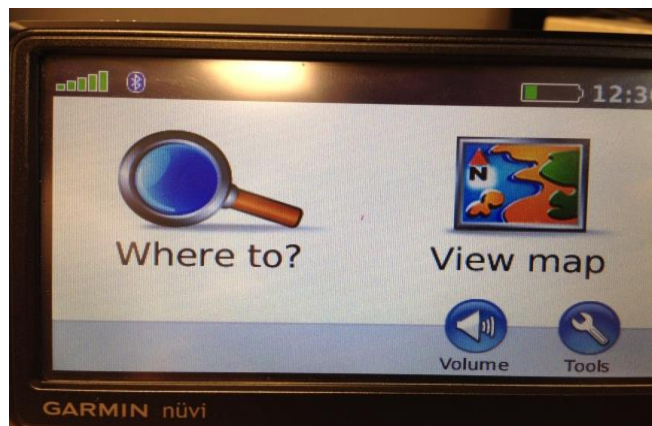


Figure 9 The standard GPS receiver had high signal strength while connected to the USRP-based GPS repeater.

William 'Gray' Blass

William 'Gray' Blass is a junior student in the Department of Electrical & Computer Engineering, Auburn University, Auburn, AL 36849-5201. He is a Member of Phi Eta Sigma (College National Honor Society). He earned SOA University, AU Board of Trustees, and Bonnia H. Arnall Scholarships. He is currently enrolled in a Coop program with Technology

Service Corporation's Huntsville branch in Huntsville, AL to further enhance his engineering skills and experiences. His research interest includes GPS systems and Software Defined Radios.

Andrew Hennigar

Andrew Hennigar finished his bachelors in Mechanical engineering in 2010 and came back to school in 2012 working under Dr. Bevly with GPS signals. He has been published at the PLANS conference in Monterey CA for his work with the USRP recording and playing back GPS signals. He has been attempting to use the USRP for a comparison study of multiple receivers, aiming to prove that USRP can be used as an accurate GPS source.

Shiwen Mao

Shiwen Mao is the McWane Professor in the Department of Electrical & Computer Engineering, Auburn University, Auburn, AL. His research interests are wireless networks and multimedia communications. He is on the Editorial Board of IEEE Trans. Wireless Commun., IEEE Internet of Things J., IEEE Commun. Surveys & Tutorials, among others. He is a Distinguished Lecturer of IEEE VTS Society. He received the 2013 IEEE ComSoc MMTC Outstanding Leadership Award and the NSF CAREER Award in 2010. He is a co-recipient of The IEEE WCNC 2015 Best Paper Award, The IEEE ICC 2013 Best Paper Award and The 2004 IEEE Communications Society Leonard G. Abraham Prize in the Field of Communications Systems.