STEVENS INSTITUTE OF TECHNOLOGY

SDR Amateur Repeater

EE322: Engineering Design 6

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This document provides basic background information and engineering foundations knowledge for the design and eventual implementation of a Software Defined Amateur Radio Repeater. It was developed during the Spring 2011 semester as a part of the Engineering Design program at Stevens Institute of Technology, and provides practical information about SDR system architecture, modulation techniques, repeater architecture, amateur radio considerations, and duplexing design methods, with an eye toward practical implementation.

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Team Member Responsibilities

Erik Thompson:
- Team Leader
- Duplexing
- Sampling Theory and Techniques
- Introduction to Software Defined Radio

Matt Schurmann:
- Software Radio System Architecture

Scott Curtis:
- Modulation Techniques

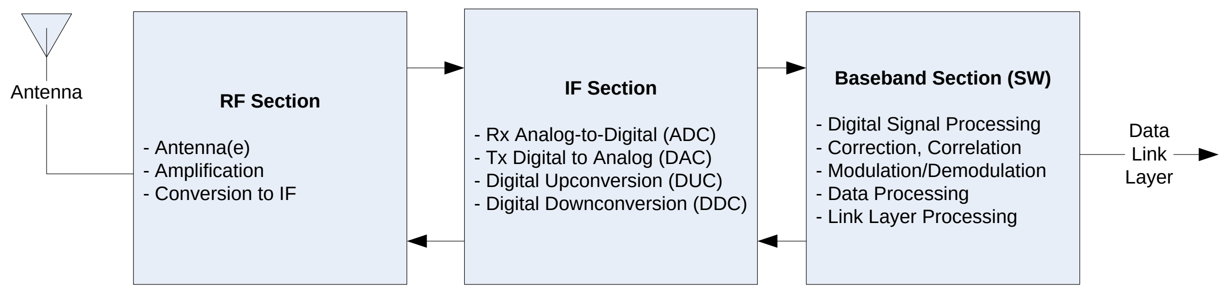
Jon Pirog:
- Radio Repeater Background
- Amateur Radio Background/Requirements

Introduction to Software Defined Radio (SDR)

Software defined radio is a radio system where some or all of the radio signal processing is implemented in software. The term first emerged in 1991, and initial research was motivated by military needs [1]. Initial research looked at using a so called "pure" architecture, analog to digital conversion is performed at the antenna, and all processing is performed on a digital basis. The problems with this approach involve the Nyquist Sampling Theorem; namely that in order to fully recover the sampled signal, you need to sample the signal at a rate at least twice as high as the largest frequency present in the signal. At high frequencies, this becomes impossible to do without introducing intolerable error into the system. Research thus shifted to more "pragmatic" architectures. The idea behind "pragmatic" architectures is to due as much of the protocol stack as possible in software, and do everything else in hardware. As technology progresses, lower level layers of the stack can be implemented in hardware [2]. A typical "pragmatic" architecture is described below.

SDR System Architecture Overview

The block diagram architecture of a generic software defined radio transceiver is broken up into three parts: radio frequency (RF), intermediate frequency (IF), and baseband [3]. See the diagram on the next page:



Since the objective of this project, and greatest strength of SDR is re-configurability through software, it will be a major goal of the project to implement as much of the architecture as possible using software methods, and reconfigurable, programmable hardware modules.

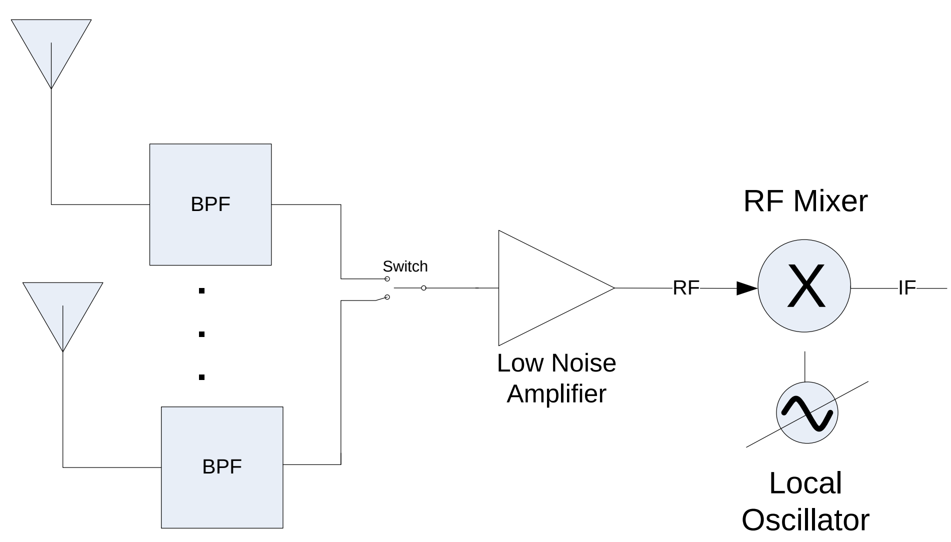
RF Section

Typically the most hardware-intensive portion of an SDR, the RF section is the only section of the SDR that must use mostly passive (non-software controllable) components.

Basic responsibilities of the RF section are as follows:

- Receiving and amplifying the input signal
- Noise Rejection
- Conversion to and from IF frequency to RF
- Amplifying DAC output, and transmitting signal over a channel

Consider a generic RF receiver front-end architecture for an SDR shown below [4]. The transmit side will be quite similar, just with reversed direction.



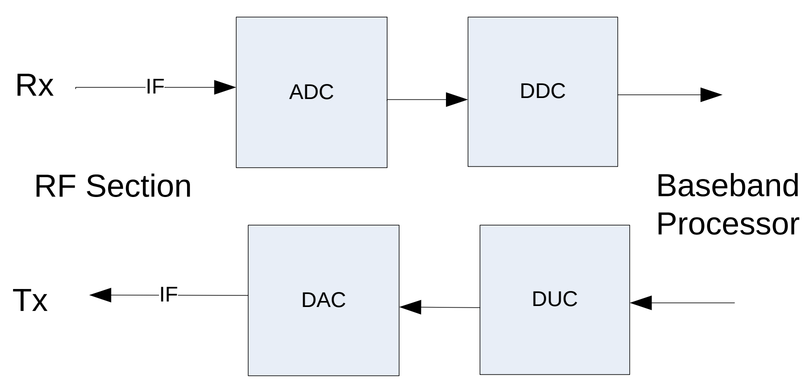
First notice that in general, for the highest degree of interoperability, and re-configurability, the system may need to use multiple antennae, and a controllable RF switch to control them. It poses a serious design complexity issue to design a single wideband antenna capable of receiving and transmitting reliably on a wide range of RF frequencies, so in general, multiple antennae will be required. Some literature even suggests the use of a "smart antenna" – an array of antennae employing special signal processing techniques to determine the direction of received signals, their frequencies, and select/tune an antenna, as well as orient it properly to receive the signal most efficiently [5]. This will probably be outside the scope of the project, however.

Very important to the system performance, is the addition of a low noise amplifier (LNA). On both the receiver and transmit sides, power amplification will be required – as received signals are generally low-power due to path losses, and for power concerns, is impractical/unnecessary to operate the entire system at enough power to transmit over a wireless channel. Most importantly, the LNA selected will need to be very linear, and have a considerably low noise figure. Amplification may generally be completed in multiple stages, especially at the transmit side, where linearity, and gain are equally important to system performance.

As discussed previously, it will also be necessary to mix the analog amplified signal down to a lower frequency before it can be sampled practically. Very high speed ADC modules will be prohibitively expensive in the RF regime, so a variable mixer is used to convert the signal to a more manageable frequency for ADC/DAC. The local oscillator (LO) used for mixing, can be controlled with software.

IF Section

There are two basic functions of the intermediate frequency section of the SDR system: analog/digital conversion, and up/down conversion. Usually the RF section mixer will tune the signal to a range of MHz – a range which is reasonable to sample in, using the right ADC/DAC architecture:



In general, ADC architecture will be critical to receiver performance. Although a mixer was used in the RF section to loosen some of the ADC speed requirements, MHz range is still a considerably high frequency to quickly convert an analog signal to a baseband signal with many bits of precision. Traditionally, a flash ADC architecture would be used for speed, but since they generally provide few bits of precision, it is also advised to use a pipeline ADC [6], which basically uses a series of low-resolution flash ADC components to implement a type of binary search on the signal. Similarly, a modified pipeline architecture can be employed for the DAC stage on the transmit side as well [7].

A baseband processor unit and an IF signal are not fully compatible, however. It is therefore necessary to do a digital form of mixing, conversion – upconversion before the DAC for transmission, and downconversion before the baseband processor at the receiver. This digital conversion step will convert the signal from an IF signal to a baseband signal on the receiver side, and prepare it for DAC, and RF mixing on the transmit side.

Generally, digital up/downconversion is implemented using a field programmable gate array (FPGA), which although user configurable, is not entirely ideal, as it will generally not allow the system to be configured by software in real-time. Similarly, some SDR designers also choose to use an application-specific integrated circuit (ASIC) to perform digital conversion. For real-time configurability, it is recommended that a digital signal processor (DSP) be used to perform conversion in the IF stage of the SDR architecture, because generally, baseband software will be able to manipulate DSP operation based on the requirements it sees, which could change in real-time.

Baseband Section

While it is very important that significant performance be achieved in the previous two stages, it is the baseband section of the system that will require the most attention from a designer – primarily, because it is the baseband processor that will be responsible for the main functions of the system:

- Encoding/Decoding
- Interleaving
- Modulation/Demodulation
- Baseband DSP, filtering etc…
- Error correction
- Signal Correlation
- Data Link layer interfacing [8]
- On-the-fly configuration of RF/IF hardware when needed

Typically, implementations of a baseband section will use either an FPGA, DSP, or a dedicated microcontroller and related digital circuitry (memory, power, etc…). Probably the most versatile option for baseband processing is the microcontroller – as it will generally be the most powerful, easy to program/interface with, and compile code for. However, there is a tradeoff involved with using a microcontroller-based architecture, as this type of system will generally require a good deal of power.

Programming for the system will need to be done in a low-level language: C/Assembly for a microcontroller, or a hardware description language (HDL) for an FPGA. Limited power consumption, monetary cost, and practicality will usually drive an SDR design toward a less powerful baseband interface, so the speed increase from a low-level language (an order of magnitude in some cases) will generally be needed to provide the intensive digital signal processing required by the SDR architecture.

Finally, it will also be the job of the baseband processor to interface with a sink for the communications data it is responsible for processing. In the case of this project, an SDR repeater, the baseband processor will be responsible for transmitting the information it has received, possibly using a different protocol stack etc… as well as communicate over a serial interface to a personal computer running a graphical user interface (GUI) front-end for a user to configure the system. Current plans include using Python for GUI development.

Sampling Theory and Techniques

We can model the sampling of a signal as the multiplication of the signal with an impulse train, where the rate of the impulses is equal to the sampling rate. In the frequency domain, this corresponds to convolving the signal with an impulse train. This creates a number of identical images that are centered around frequencies that are the sampling rate apart. Thus, it turns out that in order to recover the signal using a low pass signal, the sampling rate must be at least twice the largest desired frequency in the signal [9].

As mentioned above, this poses a problem for the acquisition of high frequency signals, as acquisition rates are limited by the ADC used. There is another option, however. This is to use undersampling. If you choose a sampling rate that is at least twice the bandwidth you desire, you create multiple images of the signal at lower frequencies such that there is no overlap. A bandpass filter could easily be used to recover the signal [9].

Modulation Techniques

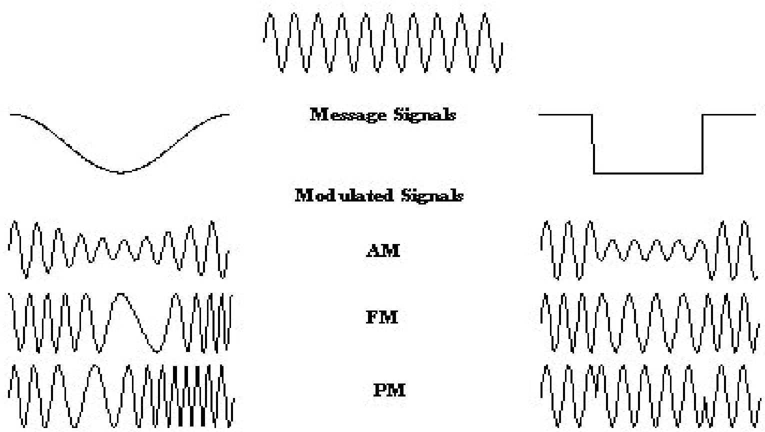
Modulation is a method where a signal is integrated with a signal carrier. It is the process of varying some properties of a periodic wave with an external signal. Generally a high frequency sinusoidal signal is used as the carrier signal. In terms of telecommunications, such as radio, modulation is a way to convey a message signal so that it can be transmitted through physical means, such as air propagation. The high frequency signals are able to travel over long distances. A band limited signal is imposed onto a carrier signal of higher frequency so the modulated signal has an overall higher range of frequencies, while the band limited signal is preserved.

Demodulating a signal is the inverse of modulating a signal. It restores the original band limited signal from the modulated signal. Like modulation, demodulation, also known as detection, uses different techniques in order to restore the original signal.

Overview of Modulation/Demodulation Techniques

The three basic modulation techniques are AM (amplitude modulation), FM (frequency modulation), and PM (phase modulation). The techniques all use a carrier signal. Each technique is named after which characteristic each modifies. For instance, amplitude modulation modifies the property of amplitude of the carrier signal, and frequency modulation modifies the property of frequency of the carrier signal. Each technique has its own advantage and disadvantage.

See the following diagram for a visual representation of the different types of modulation:



Time Domain Effects of Different Modulation Techniques [20]

Amplitude modulation is simple to design but has a couple disadvantages. AM is prone to interference due to noise spikes from the transmission medium. If there is a loss of connection then the digital data that is received are zeros. Frequency modulation has immunity to noise on the transmission medium and there is always a signal present so any loss of signal can be noticed easily. The disadvantage to FM is that it requires 2 frequencies, which makes it more complex, and the detection device needs to be able to recognize both frequencies when the signal is lost. Phase modulation only requires the use of one frequency and it is easy to detect the loss of carrier. The primary disadvantage is that it is complex to generate and detect phase changes [10].

Techniques for both analog and digital modulation currently exist. Each method has a different aim or goal. For instance, digital modulation is used to transfer a digital bit stream over a band pass channel. Analog modulation is used to transfer an analog low pass signal over an analog band pass channel. Some analog modulation methods that fall under the amplitude modulation category include: double-sideband modulation, single-sideband modulation, and vestigial sideband modulation. Another type of analog modulation is angle modulation, which supersedes frequency modulation and phase modulation [11].

Different techniques are used for digital modulation. The fundamental digital modulation methods are based on keying. There is PSK (phase-shift keying), FSK (frequency-shift keying), ASK (amplitude-shift keying), and QAM (quadrature amplitude modulation). There are many ways that keying is implemented. For example, for PSK, there is differential PSK. A sub-Category of SFK is multi-frequency shift keying. Keying is a method of representing digital data as variations of amplitude, frequency, or phase.

Modulation in an Amateur Radio Context

Angular modulation is used for narrow band voice applications in amateur radio. VHF/UHF applications tend to use FM [12].

Different repeaters use different types of modulation depending on the application that the repeater is being used for. For instance, an amateur television repeater uses Frequency DVB-S modulation and an amateur transponder uses USB modulation and LSB modulation [13].

Repeaters and Amateur Requirements

Amateur radio repeaters are electronic devices that receive weak or low level amateur radio signals and retransmit them at higher levels or power so that the signal can cover longer distances without degradation. Because of this, many repeaters are located on hilltops or tall buildings as this increases their coverage area or “radio horizon” or “footprint”. The most basic repeaters consist of an FM receiver on one frequency and an FM transmitter on another frequency usually in the same radio band, connected together, so that when the receiver picks up a signal the transmitter is keyed and rebroadcasts whatever is heard [14].

Amateur Radio frequencies

Amateur radio repeaters are found mainly in the VHF (very high frequency) allocated in the 6-meter band (50-54 MHz), 2-meter band (144-148MHz), 1.25-meter band (222-225MHz) and the UHF (ultra high frequency) 70-centimeter band (420-450 MHz). Even so, amateur radio repeaters can be used on almost any frequency pair above 28 MHz. Repeater frequency sets are known as “repeater pairs” and in the amateur radio community most follow ad hoc standards for the difference between two frequencies, commonly called the “offset”. In the USA 2-meter band the standard offset is 600Khz (0.6 MHz) but non-conforming “oddball-split” repeaters can be found, usually for technical reasons. Actual frequency pairs used are assigned by local frequency coordinating councils [12]. In the context of this project all VHF and UHF bands should be covered by the customizable SDR.

Types of amateur radio repeaters

Simplex repeater

A type of system known as a simplex repeater uses a single transceiver and a short-duration voice recorder, which records whatever the receiver picks up for a set length of time (usually 30 seconds or less), then plays back the recording over the transmitter on the same frequency. A common name for them is a "parrot" repeater.

Same-band repeater

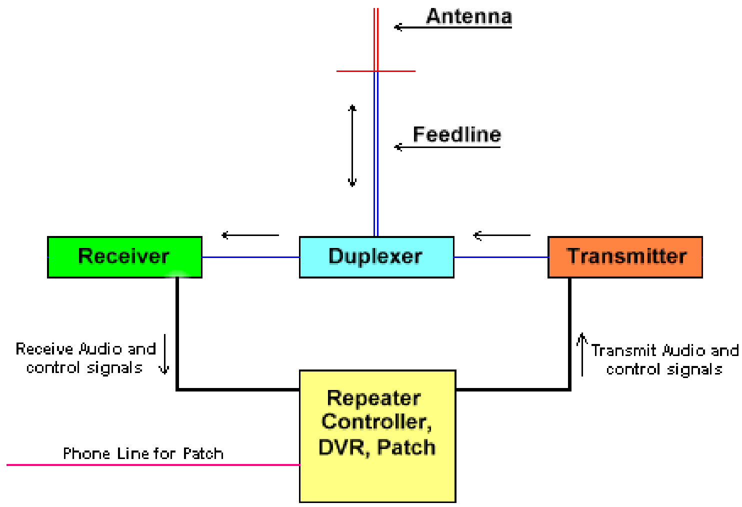
Standard repeaters require either the use of two antennas (one each for transmitter and receiver) or a **duplexer** (described later) to isolate and then transmit and receive signals over a single antenna. Similarly, a diplexer allows two transmitters on different frequencies to use one antenna, and is common in installations where one repeater on 2m and a second on 440 MHz share one feed line up the tower and one antenna. Most repeaters are remotely controlled through the use of audio tones on a control channel. Repeaters can be setup as a "Link System" where transmitting on one repeater simultaneously transmits on all repeaters in the system. These systems are used for area or regional communications, for example in *Skywarn*.

Cross-band repeater

A cross-band repeater (also sometimes called a replexer), is a repeater that retransmits a specific mode on a frequency in one band to a specific mode on a frequency in a different band. This technique allows for smaller size and less complexity of the repeater system. Repeating signals across widely separated bands allows for simple filters to be used to allow one antenna to be used for both transmit and receive at the same time, avoiding the use of complex duplexers to achieve the required rejection for same band repeating. Most dual-band amateur transceivers are capable of cross-band repeat.

Digipeater

Another repeater used in amateur packet radio is a form of digital computer-to-computer communications dubbed "digipeaters" (for digital repeaters). These repeaters are used for activities and modes such as packet radio, Automatic Position Reporting System, and D-STAR's digital data mode. They operate in a store-and-forward manner, by receiving and then retransmitting on the same frequency after a short delay [12].



Sample Architecture of a Full Duplex Repeater [19]

Since the 'repeater' listens and talks at the same time in relaying your message, it operates in full duplex mode. (Custer n.d.) For the purpose of this project the SDR should be capable of full duplex with the potential to simulate other repeater configurations.

Duplexing

There are two types of duplex modes: half and full. In half duplex mode, the transmission and reception functions do not occur at the same time. In full duplex mode, the transmitter and receiver operate simultaneously. Since repeaters use separate frequencies for transmission and reception, duplexing is typically carried out using bandpass filters [15]. The filters are usually implemented using LC circuits, resonators, and cavities. Duplexers have also been made using specific routings of microstriplines in order to allow for easy integration. Finally, duplexers have been implemented using surface acoustic wave devices [16]. Problems with these duplexers include that they cannot be put into an integrated circuit. Additionally, these filters have high losses and must be tuned to the repeater frequencies.

Alternatives to duplexing filters include using circulators and cancellation techniques [17,18]. A circulator is a 3 or 4 port device that only allows energy to be transmitted to the next port in a predefined rotation [18]. This feature can be used to route transmitted and received signals. In cancellation techniques, a priori knowledge of the transmitted signal is used to filter it from the received signal, thus providing isolation from the two signals [17].

S.W.O.T. Analysis

Strengths –

- The SDR technology is well-developed, and robust. No new significant theoretical research should be required to complete the project
- There are many professors at Stevens working on software defined radio, so it should not be very difficult to find help where needed
- Amateur operators are usually early adopters of new technology, so there should be a quick transition to software implementations
- SDR implementations will be much easier to tweak and maintain than their current more rigid counterparts
- The SDR approach will lead to a more economical development process: in general, the SDR architecture will be cheaper to develop, and easier to rapid-prototype
- An SDR repeater will also be much more interoperable, and portable than another type of repeater

Weaknesses –

- There is probably a very small market for amateur radio repeaters to begin with: cursory estimates place 18,000 repeaters in the USA, which is not a very sizable amount considering the population of approximately 300 million
- Repeaters are large investments, and people may not be willing to make investment to replace something that already works
- Strict regulatory requirements need to be adhered to, possible licensing issues exist
- The software approach, while it may be cheaper to develop, will almost surely take more time to develop than a comparable repeater

Opportunities –

- Being implemented in software, the SDR repeater will be very easy to maintain, and very reconfigurable. It could be able to support multiple bands, frequencies, and modulation schemes

Threats –

- Implementing software duplexing does pose a serious concern. The group does not know of a well-established method of duplexing via software, so it may require quite a bit of time to develop and test.
- Development cost will almost surely exceed the $250 given budget for design projects

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