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Abstract

Software Defined Radio (SDR) is an emerging technology, which has gained interest from commercial, military and medical sectors in regard to wireless communication. A SDR may be defined as a radio communication system, which emulates the functionality of hardware typically utilized in radio communication devices through the use of software. The benefits of such a device are that the radio may be easily reconfigured at a low cost due to the fact that its main functionality is software based. The objective of this project was to design, manufacture, and test a low cost portable spectrum analyzer, capable of detecting and measuring Radio Frequency (RF) signals particularly generated by Remote Sensors in real time as well as doing the same for human generated noise, such as vehicles, engines and machinery, computers, broadcasting radio stations and transmitters, etc., through the use of a SDR. This objective was accomplished using inexpensive off-the-shelf SDRs and frequency up-converters and a MATLAB code written. Testing of the system yielded a Signal-to-Noise Ratio between 65-100 dB corresponding to modulating signals with a peak to peak voltage in the range of 10 mVpp – 1 Vpp, higher than this led to distortion. The bandwidth of the system was measured for multiple configurations and it was determined that the overall system was capable of detecting any sinusoidal waves whose frequency was within half of the sampling rate, and that square waves had a limited bandwidth of 13 KHz due to the loss of higher order harmonics at frequencies above this range.

Index Terms— SDR, Software Defined Radio, Remote Sensing, FM Modulation

1. Introduction

SDR is defined as a radio communications system where the components that were traditionally implemented in hardware, are instead implemented by software, through a computer or another embedded system where the signal processing occurs. The most common version is the
RTL-SDR, for its price and versatility. The front end of an RTL-SDR receives the live RF signal through the front end, then down converts the signals to baseband and digitizes them. Figure 1 shows a typical block diagram of the components of an SDR. The device then outputs samples of the baseband signal across the USB interface. The common frequency ranges for these devices are 25MHz to 1.75GHz [9].

For this project, the SDR chosen and used was a “NooElec NESDR Smart SDR” along with a “NooElec Ham It Up Upconverter”, whose purpose is to shift any received signals up by 125 MHz. Both are shown in Figure 2. There are many different software programs to operate the SDR, for this project MATLAB was selected and code was written to receive the RF signals, spectrally analyze them, and gather the data needed.

This system was utilized to detect and receive modulated signals. Modulation may be defined as the process of varying one or more properties of a high frequency carrier wave with a low frequency modulating signal that contains some information to be transmitted. There are many different types of modulation schemes, however this application is concerned with amplitude modulation (AM) and frequency modulation (FM), which vary the amplitude and frequency of the
carrier wave, respectively. The modulating signal and carrier wave are represented by the functions $S_m(t)$ and $S_c(t)$, as shown below.

$$S_m(t) = A_m \cos(2\pi f_m t + \phi) \quad S_c(t) = A_c \cos(2\pi f_c t)$$

Amplitude Modulation is the process of multiplying the modulating signals and carrier wave and is represented by the following equation,

$$S_{AM}(t) = \frac{A_mA_c}{2} \left[\cos(2\pi (f_c + f_m)t + \phi) + \cos(2\pi (f_c - f_m)t - \phi)\right]$$

resulting in two frequency sidebands in the modulated signal. An image of an AM signal in the time domain is shown in Figure 3.

![Figure 3: Time domain representation of an AM signal](image)

Frequency Modulation is the process of embedding the integral of the modulating signal within the carrier wave and is represented by the following equation,

$$S_{FM}(t) = A_c \cos(2\pi f_c t + 2\pi K \int_0^t S_m(\tau) d\tau)$$

An image of an FM signal in Figure 4.

![Figure 4: Time domain representation of an FM signal](image)

Demodulation is the process of extracting the modulating signal from the modulated carrier wave, and like modulation there are many different schemes in which it can be implemented. The demodulation techniques implemented are referred to as the envelope detector for the AM demodulation and the discriminator for the FM demodulation. The envelope detector is simply implemented by taking the absolute value of the AM signal and then lowpass filtering in the digital domain. This is shown the following equations and in Figure 5.
\[ S_{AM}(t) = \frac{A_m A_c}{2} \left[ \cos(2\pi(f_c + f_m)t + \phi) + \cos(2\pi(f_c - f_m)t - \phi) \right] \]

\[ S_{|AM|}(t) = \text{Abs}(S_{AM}(t)) \]

\[ S_M(t) = \text{LPF}(S_{|AM|}(t)) \]

**Figure 5: Envelope detection in the digital domain**

The discriminator is a little more complicated, but its fundamental purpose is to differentiate the FM signal to remove the modulating signal. This functionality is implemented by first shifting the signal to baseband and then lowpass filtering out the carrier frequency terms. Once the carrier frequency is removed the signal is differentiated by removing the modulating signal from the integral in the FM signal. The equations to implement this functionality are shown below.

\[ S_{\alpha}(t) = A_c \cos(2\pi f_c t + 2\pi K \int S_m(\tau) \, d\tau) \]

\[ S_{\text{baseband}}(t) = S_{\alpha}(t)e^{2\pi f_c t} \]

\[ S_{\alpha}(t) = \frac{A_c}{2} \left[ \cos(2\pi K \int S_m(\tau) \, d\tau) + \cos(2\pi K \int S_m(\tau) \, d\tau) \right] - \frac{1}{2} \sin(2\pi K \int S_m(\tau) \, d\tau) - \sin(2\pi K \int S_m(\tau) \, d\tau) \]

\[ S_{\theta}(t) = \text{LPF}(S_{\text{baseband}}) \]

\[ S_{\theta}(t) = \frac{A_c}{2} \left[ e^{2\pi f_c t} \right] \]

\[ S_{\text{after differentiation}}(t) = S_{\theta}(t) \cdot S_{\text{after LPF}}(t) = A_c / 2 \left[ e^{2\pi f_c t} \right] \]

\[ S_{\text{envelope}}(t) = \frac{\partial}{\partial t} S_{\text{after differentiation}}(t) = -2\pi K \int S_m(\tau) \, d\tau - 2\pi K \int S_m(\tau) \, d\tau \]

\[ S_{\theta}(t) = \frac{A_c}{2} \left[ e^{2\pi f_c t} \right] \]

\[ S_{\text{envelope}}(t) = 2\pi K S_m(t) \]

\[ S_{\theta}(t) = \frac{A_c}{2} \left[ e^{2\pi f_c t} \right] \]
Now that the functionality and terminology of the applications implemented in this design project have been covered. The code written and utilized, testing performed, and results obtained will be described.

The code written in MATLAB has three basic sections. The first section of code prompts the user for input to configure the simulation with the desired parameters. The input requested of the user is as follows; the operating mode which can be either AM or FM, the desired center frequency of the signal of interest, the tuner gain parameter (which can range from 0-50 and serves to amplify the received signal), whether to enable or disable the data logging feature (which produces a .txt file in a desired directory), and lastly the simulation time which is entered in seconds or the value “inf” which corresponds to a continuous mode. The second section of code sets up parameters necessary to configure the SDR, and the third section defines the system objects utilized in the MATLAB script. The objects include the SDR itself, all filters utilized for both the AM and FM modes, the audio output object, all spectrum analyzers and all the time scopes. MATLAB is an object-oriented scripting language and essentially these objects act as individual functions. The final section of code is the actual processing section, which implements the AM and FM demodulation loops.

In the FM demodulation loop, the first step is to check whether data logging feature is enabled, if it is a .txt file is generated. Then the code enters a loop for the duration of the simulation time specified by the user. The first step in the loop is to fetch a frame of data from the SDR. Next the delay and conjugate of this frame of data are taken. The delay and conjugate are then multiplied, and the angle of the result is extracted which approximates differentiation of the signal effectively demodulating the signal. After the demodulated signal is obtained it is decimated from a sampling rate of 240 KHz to 48 KHz and low-pass filtered at 20 KHz. The decimated signal is then passed through a de-emphasis filter to remove the emphasis placed on the modulated signal. This signal is then sent to the audio output and all the scopes specified in the system objects. In addition, the frequency, Vpp, and time logged of the demodulated signal are written to the .txt file generated.

The AM demodulation loop starts in the same fashion as the FM, by first checking whether the data logging functionality is enabled. Next a frame of data is taken from the SDR and the signal is bandpass filtered to shift the signal to baseband. Next the absolute value of the signal is taken and then the signal is decimated to reduce the sampling rate from 240KHz to 48KHz and lowpass filtered at 20KHz producing the demodulated signal. The demodulated signal is then sent to the scopes and the audio output. In addition, the frequency, Vpp, and time recorded of the demodulated signal are written to the generated .txt file.

2. Methodology

The test setup consisted of two Tektronix AFG3021C signal generators. One generating the modulating signal and running in continuous mode, and the other generating the carrier signal while running in FM modulation mode. The modulation mode parameters utilized were a 1 MHz Sine wave with amplitude of 100 mVpp, a deviation of 100 KHz, and an external FM Source. The
modulating signal generator output was input to the external input on the back of the carrier signal generator. The output of the carrier signal generator was then output to a BNC T connector which was then input to the Tektronix TDS 2024C Oscilloscope as well as the input of the NooElec Ham It Up Upconverter. The oscilloscope was AC coupled an externally triggered by the carrier signal generator. The NooElec Ham It Up Upconverter was set in the up-convert mode and input to the NooElec NESDR SMART Software Defined Radio which was connected to the computer running the “AM_FM_DEMOD_SCRIPT” MATLAB Script. An image of this test setup is shown in Figure 6.

First the signal to noise ratio of the system was tested and measured through the following equation.  
\[
\text{Signal to Noise Ratio} = \text{Signal (dB)} - \text{Noise Floor (dB)}
\]

This test was performed in quarter increments on a logarithmic scale from 10 mVpp to 1 Vpp, shown in Figure 7.
Next the bandwidth of this system was tested for both sine and square wave inputs that were incrementally swept across a range of frequencies. Since one of the final steps of the system in the normal operating mode is decimation from a sampling rate of 240 KHz to 48 KHz and lowpass filtering with a cutoff frequency of 20 KHz the system was tested with multiple configurations, which are listed below.

Test Configurations:

- Sampling Rate = 240 KHz, Decimation 48 KHz LPF 20 KHz
- Sampling Rate = 240 KHz, No Decimation
- Sampling Rate = 2.4 MHz, No Decimation

Lastly the rise and fall times of received and demodulated pulse waves were tested and compared against the input modulating signals. The parameters tested were:

Input - Pulse Wave (1 Vpp, 1KHz, 50% Duty Cycle, Leading: 9 ns, Trailing 9ns).

**Analysis**

The signal to noise ratios obtained were between 65 – 100 dB. As shown in the following table.

<table>
<thead>
<tr>
<th>Vpp</th>
<th>Signal (dB)</th>
<th>Noise (dB)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010</td>
<td>-25</td>
<td>-90</td>
<td>65</td>
</tr>
<tr>
<td>0.025</td>
<td>-18</td>
<td>-90</td>
<td>72</td>
</tr>
<tr>
<td>0.050</td>
<td>-10</td>
<td>-80</td>
<td>70</td>
</tr>
<tr>
<td>0.075</td>
<td>-8</td>
<td>-80</td>
<td>72</td>
</tr>
<tr>
<td>0.100</td>
<td>-6</td>
<td>-80</td>
<td>74</td>
</tr>
<tr>
<td>0.250</td>
<td>3</td>
<td>-85</td>
<td>88</td>
</tr>
<tr>
<td>0.500</td>
<td>9</td>
<td>-85</td>
<td>94</td>
</tr>
<tr>
<td>0.750</td>
<td>12</td>
<td>-85</td>
<td>97</td>
</tr>
<tr>
<td>1.000</td>
<td>15</td>
<td>-85</td>
<td>100</td>
</tr>
</tbody>
</table>

When testing the bandwidth, it was observed that system had a bandwidth of half the sampling rate, per the Nyquist Theorem, for sine waves so long as they were not filtered out. The results obtained for square waves were much lower, with a bandwidth of approximately 10 KHz. This restriction of bandwidth was determined to be from the loss of higher order harmonics of the square wave to the system. Shown in Figures 7-9 are images out the demodulated square waves received for the three different configurations at 1000Hz.
In the figures shown, it is observed that by removing the decimation of the square wave, signal bandwidth is improved between configurations 1 and 2. Another observation made is that increasing the sampling rate with no decimation yielded similar bandwidth between configurations 2 and 3 which was an unexpected result but increased the noise on the signal as expected.
When testing rise and fall times, as indicated in the red boxes in Figure 10, rise and fall times of approximately 12 µs were achieved by the system which corresponds to a maximum frequency of approximately 13 KHz per the following calculation.

![Figure 11: Rise and fall times](image)

The results show that the software and SDR can detect a signal to noise ratio between 65-100 dB which corresponds to modulating signals with a peak to peak voltage in the range of 10 mVpp-1 Vpp, higher than this level led to distortion. The bandwidth was tested at multiple configurations, showing that the overall system could detect any sinusoidal waves whose frequency was within half of the sampling rate. Square waves were shown to have a limited bandwidth of 13KHz due to the loss of higher order harmonics at frequencies above this range. Together these results prove that the concept of SDR based FM modulated remote sensing of capacitance data using a low power transmitter is feasible.
3. Conclusions

The applications for software defined radio has only begun to be explored [2]. This project designed and tested a low cost portable spectrum analyzer, capable of detecting and measuring remote sensor generated radio frequencies in real time using an SDR. This project will continue with the code written, spectrum analyzers developed, and existing SDR technology to analyze a signal generated by a local oscillator built at the University of Southern Maine and determine how the MEMS sensor capacitance varies over time [8].

Acknowledgments

Authors acknowledge the fellowships and funding received from USM, and UROP (Undergraduate Research Opportunities Program) and the Maine Space Grant Consortium (MSGC).

References


