Experiment 4: Software Defined Radio

Objective

This experiment explores the basic *Software Defined Radio* architecture which combines elements of wideband radio hardware and digital signal processing. We will use a hardware front end together with Matlab/Simulink to receive and demodulate AM and FM signals in real-time.

Introduction

In a traditional radio frequency (RF) receiver, hardware components such as filters, oscillators and mixers shape the RF signal received by the antenna, demodulate it and extract the modulating waveform. *Software Defined Radio*[1] (SDR) on the other hand, is a system in which all or at least some signal processing tasks are implemented in software running on a computer or an embedded system. Consequently, SDR is a flexible and reconfigurable system that can easily work with a multitude of transmission protocols and standards. As an example consider a current generation mobile phone. In order to be competitive, such a device has to work with GSM, CDMA, HSPA, EVDO, LTE, Wi-Fi, Bluetooth, NFC communication standards, must be capable of transmitting and receiving RF signals in the 700–2600 MHz frequency band and have a GPS receiver. Without the flexibility of an SDR, a mobile phone will be too *big*, *bulky* and *consume too much power*. Therefore, SDR has been and will continue to be the primary factor in the miniaturization of mobile communication devices.

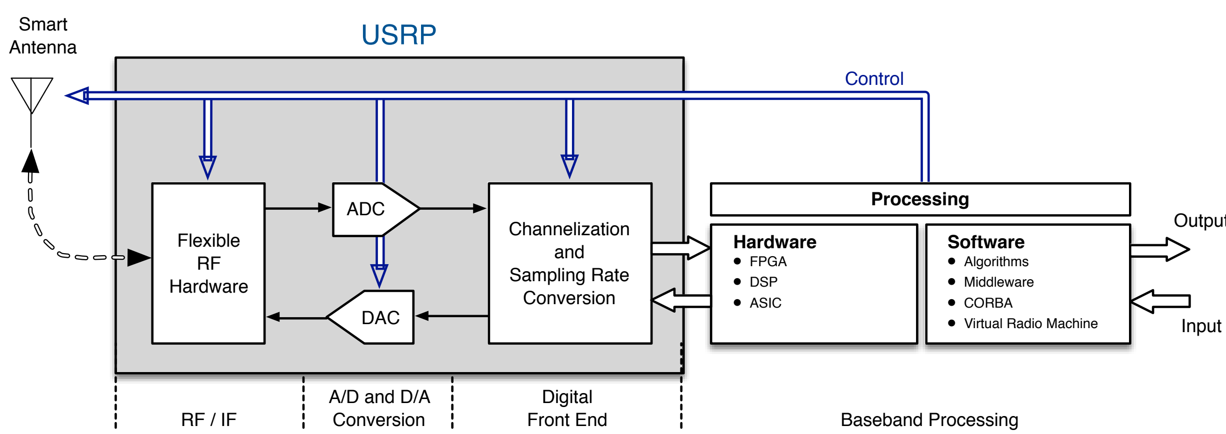

Figure 1: Basic SDR architecture [1].

An *ideal* SDR samples the RF signal at the receiver antenna directly using a high speed analog-to-digital converter (ADC), and process the digitized RF signal in software. However, with today's technology it is simply not feasible to digitize the RF signal at a sufficiently high sampling rate and resolution. Therefore, the current generation of SDRs use a hardware RF front end to convert

[1] A complete SDR consists of a transmitter and a receiver. In this experiment, however, we will focus exclusively on the receiver capability of the SDR.

the RF signal to an IF frequency (*superheterodyne* or *low-IF* receiver architectures) or directly to baseband (*zero-IF* receiver architecture). The baseband/IF-frequency signal is then digitized with high speed ADCs. The hardware RF front end unit is known as *Universal Software Radio Peripheral* (USRP). Figure (1) shows the architecture of a generic SDR.

Many SDR implementations use a zero-IF architecture where the received RF signal is directly down-converted to baseband before demodulation. In this experiment, we will use *Ettus Research N210 USRP* with architecture as shown in Figure (2).

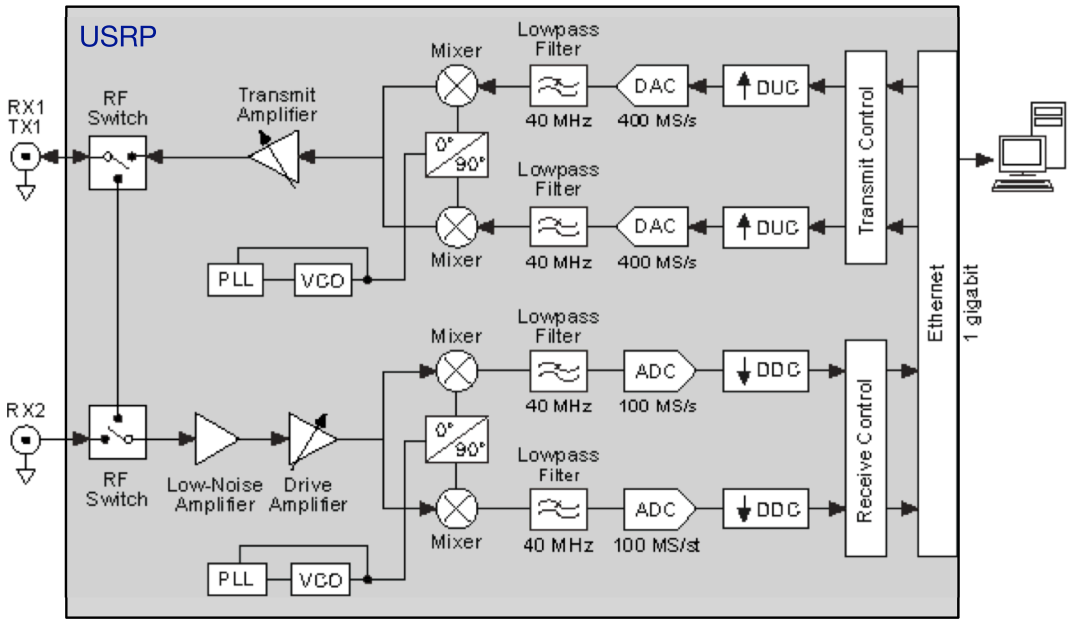

Figure 2: N210 USRP architecture with WBX wide bandwidth transceiver card [2].

The receiver (RX) subsystem of N210 USRP is based on lowpass filter modules with cutoff frequencies at 40 MHz, ADCs operating at 100 MS/s with 14-bit resolution achieving 88 dBc SFDR[2].

Digital down converter (DDC) units implemented on an FPGA convert the ADC output data to zero-IF (i.e., baseband) or a low-IF signal at a lower sampling frequency. The reduced sampling rate digital data stream is then transmitted to the host computer over a Gigabit Ethernet connection. Software running on the host computer performs signal processing and demodulates the received signal. Figure (3) shows the block diagram representing the receiver subsystem of N210.

There are many excellent SDR software, both free and commercial. One of the most popular is *GNUradio*, which is “a free and open-source software development toolkit that provides signal

[2] Spurious free dynamic range (SFDR) is the ratio of the rms value of the signal to the rms value of the worst spurious (unwanted) signal regardless of where it falls in the frequency spectrum. The worst spur may or may not be a harmonic of the original signal. SFDR is an important specification in communications systems because it represents the smallest value of signal that can be distinguished from a large interfering signal (blocker). SFDR can be specified with respect to full-scale (dBFS) or with respect to the actual signal amplitude (dBc), [3] [4].

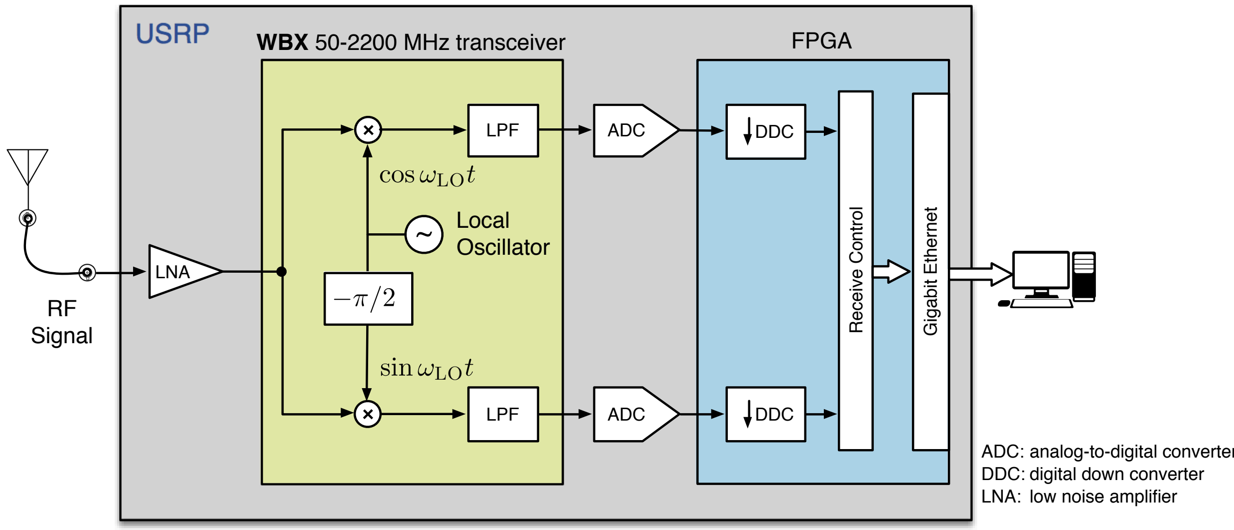

Figure 3: Receiver subsystem of Ettus Research N210 USRP.

processing blocks to implement SDRs. It can be used with readily-available low-cost external RF hardware to create software-defined radios, or without hardware in a simulation-like environment. It is widely used in hobbyist, academic and commercial environments to support both wireless communications research and real-world radio systems" [5].

Matlab/Simulink is an alternative SDR software platform. In particular, Simulink provides blocks for popular USRP devices including N210. These blocks interface Simulink with the USRP hardware. Once the signal is in the Simulink workspace, standard Matlab functions and Simulink blocks are used to create receiver models that process and demodulate signals received from the USRP.

In this experiment, we will use Matlab/Simulink as the SDR software. An Ettus research N210 USRP will feed Simulink models with complex-valued data (I- and Q-channel data) at 200 kHz sampling rate.

Note: There are many excellent and widely accessible references and tutorials on SDR hardware and software. Please refer to the reference section of this document for further information.

Equipment

In this experiment you will use the following equipment and software:

- Ettus Research N210 USRP with LX receiver or WBX transceiver modules.
- TERK indoor amplified AM/FM antenna; cable AM antenna.
- HP 8662A signal generator.
- Computer with Linux operating system.
- Matlab/Simulink 2014b.

Procedure

A. Receiving AM Broadcast Signals

> **Important:** AM broadcast signals span the 540–1610 kHz frequency band. The single most important factor affecting the quality of received AM signals is an antenna that is compatible with AM broadcast frequencies. AM signals require long antennas such that the received signal will be strong and have high SNR. If the SNR of the received signal is low, then the AM receiver will perform poorly.
>
> In this experiment, the cable strung across the ceiling of ENG 311 will function as an external AM antenna. In part due to the location of ENG 311, this setup will be barely adequate to receive AM broadcast signals with carrier frequencies at the upper end of the AM broadcast spectrum.

Step A.1 Open the Simulink model Exp4_AMReceiver.slx. The top-level signal flow diagram of the AM Receiver Simulink model is shown in Figure (5). The **SDRu Receiver** block supports communication between Simulink and the USRP device; it brings data from N210 USRP to Simulink workspace at a sampling frequency of 200 kHz.

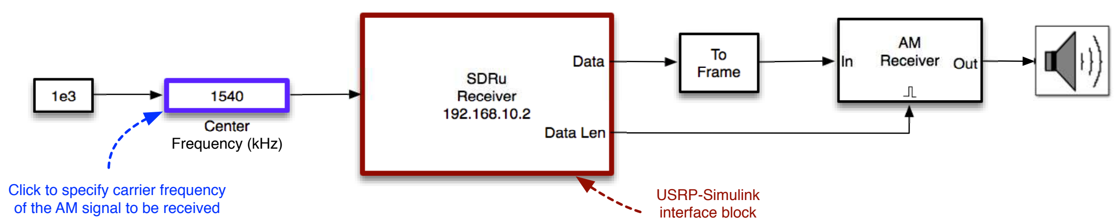

Figure 4: AM Receiver top-level signal flow diagram.

Click on the **Centre Frequency** block. The edit fields indicate the *lower limit*, the *current value*, and the *upper limit*. You can change the block parameter in two ways: by manipulating the slider, or by entering a new value in the *current value field*.

You can tune the AM receiver by adjusting the **Centre Frequency** to match the carrier frequency of the station you want to receive. It is difficult to precisely tune the centre frequency using the slider. Therefore, change the center frequency by entering a new value in kHz in the *current value field*. For example, to tune the USRP to receive an AM station broadcasting at the carrier frequency 1540 kHz enter the value 1540 in the *current value field*. **Note:** The constant block set to **1e3** indicates that the center frequency value is in **kHz**.

Click on the **AM Receiver** block and study the receiver structure.

Step A.2 Connect the receiver input of the USRP labeled **RF2**, to the **Ext. AM** port of the antenna box. Connect the **Sound Output** port of the computer to the external speaker. Tune the **AM Receiver** to 1540 kHz (CHIN Radio, multilingual). Run the Simulink model. At this point you should hear the demodulated AM signal on the speakers. Observe the signal spectra at the input and output of the **AM Receiver** block.

While the Simulink model is running tune the **AM Receiver** to 1610 kHz (CHHA Radio, Spanish language community radio).

Step A.3 In addition to the AM radio stations broadcasting at 1540 and 1610 kHz carrier frequencies, you can also listen to the AM broadcast at 85 MHz carrier frequency broadcast from the signal generator in the Communications Laboratory. Connect the receiver input of the USRP to the **FM** port of the antenna box. Power the TERK antenna—the gain adjustment dial on the antenna column will light up when the unit is powered. Open the **Centre Frequency** block. Change the *current value* field to 85000 kHz. You may need to adjust *upper limit* field to change the **Centre Frequency** value to 85000 kHz.

Problem A.1 The AM signal you received and demodulated in **Step A.3** is generated at 50% modulation level. If we change the modulation level to 70%, what difference would you observe in the demodulated signal?

Extra-Curricular Problem Identify the artist(s) and the song in **Step A.3**.

B. Receiving FM Broadcast Signals

Step B.1 Open the Simulink model Exp4_FMReceiver.slx. The **FM Receiver** can be tuned to different FM stations as in **Part-A**. Since the FM radio broadcast signals span the 87–108 MHz frequency band, the constant block is now set to **1e6** such that the **Centre Frequency** values are in **MHz**. Click on the **FM Receiver** block and study the receiver structure.

Step B.2 Connect the receiver input of the USRP to the **FM** port of the antenna box. Tune the **FM Receiver** to 96.3 MHz (CFMZ-FM Toronto, classical music). Run the Simulink model. At this point you should hear the demodulated FM signal on the speakers. Change the gain setting of the external antenna for best reception. Observe the signal spectra at the input and output of the **FM Receiver** block.

Step B.3 The **FM Receiver** model can receive several different FM stations. Tune the **FM Receiver** to stations that broadcast in *stereo* and in *mono*, and observe the differences in the spectra of their respective baseband signals (known as the FM-MPX signal). For example, CBLA-FM (99.1 MHz, CBC Radio 1) broadcasts in mono whereas CBL-FM (94.1 MHz, CBC Radio 2) broadcasts in stereo. **Note:** The Appendix provides a complete list of AM and FM radio station in Toronto area.

Step B.4 Tune the **FM Receiver** to 96.3 MHz. Observe the [59, 75] kHz frequency band in the spectrum of the FM-MPX signal. The signal you observe is a subcarrier within the FM-MPX baseband signal, allowing the radio station to broadcast additional services as part of its transmitted signal. In Canada this subcarrier signal is known as *Subsidiary Communications Multiplex Operation*[3] (SCMO). The SCMO subcarrier, which is most commonly set at 67 kHz above the main carrier, can transmit additional program material such as alternate audio/language tracks, telemetry data and background music.

Step B.5 Open the Simulink model Exp4_FMandSCMOReceiver.slx. Click on the **FM Receiver** block and study the demodulator structure for the SCMO subcarrier.

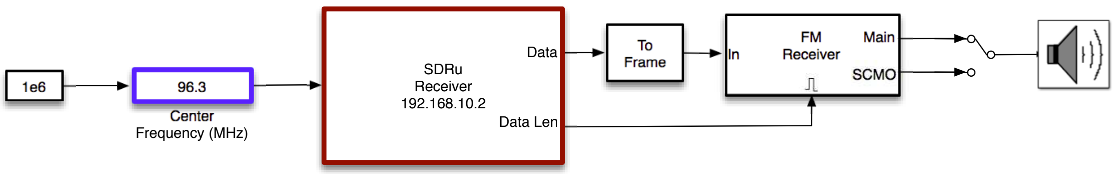

Figure 5: AM Receiver top-level signal flow diagram.

Run the Simulink model. The switch at the output of the **FM Receiver** block selects the *main program* or the *secondary program* transmitted with the SCMO subcarrier (if there is one).

Identify other radio stations with SCMO subcarrier signals, tune the **FM Receiver** to those stations and listen to the *secondary program* transmitted with the SCMO subcarrier. **Note:** CBC Radio 1 broadcasting at 99.1 MHz is another FM station with a strong SCMO subcarrier signal.

Problem B.1 Study the **FM Demodulator** block. Discuss how the signal processing operations carried out within this block can successfully demodulate an FM signal.

Problem B.2 Study the **Stereo Decoder** block. Discuss the functions implemented by the **19 kHz Peaking Filter**, **Create 38 kHz Tone**, **Deemphasis Filter** and **Stereo Separation** blocks.

Problem B.3 In **Step B.5** you tuned to radio stations which transmit a *secondary program* with the SCMO subcarrier. What is the difference you observed/heard in listening to the *main program* and the *secondary program* material. Explain potential reasons for the difference you observed/heard.

Problem B.4 Explain the advantages and disadvantages of transmitting a *secondary program* using the SCMO subcarrier.

[3] *Subsidiary Communications Authorization* (SCA) in the United States.

References

[1] Software Defined Radio Scheme: Adopted by LtCdr Topi Tuukkanen, Project Manager, Finnish Software Radio Demonstrator from various scientific articles, studies, conference papers etc. in public domain; http://commons.wikimedia.org/wiki/File:SDR_et_WF.svg.

[2] Ettus Research, www.ettus.com/kb/detail/usrp-bandwidth.

[3] W. Kester, "MT-003: Understand SINAD, ENOB, SNR, THD, THD+N and SFDR so You Don't Get Lost in the Noise Floor," Analog Devices, retrieved March 14, 2015, http://www.analog.com/media/en/training-seminars/tutorials/MT-003.pdf,

[4] "What is Spurious-Free Dynamic Range?" National instruments, http://digital.ni.com/public.nsf/allkb/7C77898F35A951E086256BF100686FED.

[5] http://en.wikipedia.org/wiki/List_of_radio_stations_in_Ontario.

Resources

SDR: Books

- E. Venosa, F.J. Harris and F.A.N. Palmieri, *Software Radio: Sampling Rate Selection, Design and Synchronization*, Analog Circuits and Signal Processing Series, Springer, 2011.
- E. Grayver, *Implementing Software Defined Radio*, Springer, 2012.
- M. Dillinger, K. Madani and N. Alonistioti, *Software Defined Radio: Architectures, Systems and Functions*, Wiley, 2003.

SDR: Web Links

- http://en.wikipedia.org/wiki/Software-defined_radio.
- G. Youngblood, "A Software Defined Radio for the Masses, Part 1–4", *QEX (American Radio Relay League)*, http://www.arrl.org, 2002–2003.

SDR: Hardware/Software

- http://www.rtl-sdr.com. Excellent site for applications using the RTL-SDR. **Important:** RTL-SDR is a very inexpensive software defined radio based on the RTL2832U chipset. You can purchase it on *Amazon* or *ebay* for less than Cdn $20 (inc.
- http://rtlsdr.org. This Wiki site collects information concerning the use of RTL-SDR. Good starting point for anyone who wants to use RTL-SDR with links to all relevant web sites.
- http://gnuradio.org. The place to go to learn everything about *GNUradio*.
- http://sdrsharp.com. SDR# (SDRSharp) is a popular, simple, fast and extensible SDR program. It either comes bundled with RTL-SDR or can be downloaded from this website for free.
- Ettus Research: http://www.ettus.com.

Appendix: Toronto Area Radio Stations

Modulation	Call sign	Frequency	Owner	Format	Mono/Stereo	SCMO	Comments
AM	CJCL	590	Rogers Communications	sports			
	CFTR	680	Rogers Communications	news			
	CFZM	740	ZoomerMedia	pop standards			
	CJBC	860	Ici Radio-Canada Première	public news/talk (French)			
	CFRB	1010	Bell Media Radio	news/talk			
	CHUM	1050	Bell Media Radio	sports			
	CJRU	1280	Ryerson University	campus radio			
	CHKT	1430	Fairchild Radio	multilingual			
	CHIN	1540	CHIN Radio/TV International	multilingual			
	CHHA	1610	S.L. Latin American Com.Centre	community radio (Spanish)			
	CHTO	1690	Cnd Hellenic Toronto Radio	multilingual			
FM	CIND-FM	88.1	Rock 95 Broadcasting	indie rock	S		
	CIRV-FM	88.9	Frank Alvarez	multilingual	S	Y	weak SCMO
	CIUT-FM	89.5	University of Toronto	campus radio	S	Y	weak SCMO
	CJBC-FM	90.3	Ici Musique	public music (French)	S		
	CJRT-FM	91.1	CJRT-FM Inc.	jazz	S		
	CHIN-1-FM	91.9	CHIN Radio/TV International	multilingual			weak signal
	CKIS-FM	92.5	Rogers Communications	CHR	S		
	CFXJ-FM	93.5	Newcap Broadcasting	urban music	S		
	CBL-FM	94.1	CBC Radio 2	public music	S	Y	
	CJKX-FM-2	95.9	Durham Radio	country	S		
	CFMZ-FM	96.3	ZoomerMedia	classical	S	Y	
	CKHC-FM	96.9	Humber College	campus radio			weak signal
	CHBM-FM	97.3	Newcap Broadcasting	classic hits	S		
	CHFI-FM	98.1	Rogers Communications	soft adult contemporary	S		
	CKFG-FM	98.7	Intercity Broadcasting Network	multilingual	S		
	CBLA-FM	99.1	CBC Radio One	public news/talk	M	Y	strong SCMO
	CKFM-FM	99.9	Bell Media Radio	hot adult contemporary	S	Y	weak SCMO
	CHIN-FM	100.7	CHIN Radio/TV International	multilingual	S		
	CJSA-FM	101.3	Diversity Media Group	multilingual	S		
	CIRR-FM	103.9	Evanov Communications	LGBT-targeted CHR	S		
	CHUM-FM	104.5	Bell Media Radio	hot adult contemporary	S		
	CHOQ-FM	105.1	Cooperative Radio-Toronto	community radio (French)	S		
	CHRY-FM	105.5	York University	campus radio			weak signal
	CKAV-FM	106.5	Aboriginal Voices	First Nations	S	Y	weak SCMO
	CILQ-FM	107.1	Corus Entertainment	classic rock	S	Y	weak SCMO

Table A.1: Toronto area AM and FM stations [5].

Note: In Table (A.1) AM station frequencies are in kHz and FM station frequencies are in MHz.