Modeling Real-Time Software Defined Radio Using Sampled Data Frequency Modulation (FM) Signals

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***Abstract*—The aim of this paper is to model a real-time desktop Software Defined Radio (SDR) using sampled data frequency modulation (FM) signals. With SDR technology, major part of hardware radio functionalities such as synchronization, demodulation, decoding or decryption can be implemented by means of software in a personal computer or embedded system. SDR has challenge of real-time demodulation as a result of component quality factor and sensitivity. The study considers component quality factor variation to demodulate sampled FM signal in real-time. This could be achieved by deploring initial knowledge in systems engineering, RF planning, ADC/DAC selection, software architecture selection and digital signal processing (DSP) hardware selection. This research is expected to reveal real-time model of SDR for monitoring broadcasting stations.**

Keywords—Software Defined Radio (SDR); Radio Frequency (RF); Digital Signal Processing (DSP).

I. Introduction

Radio communication is the science of communicating over a distance by converting sounds or signals to electromagnetic waves and radiating these through space [1]. Radio communication principles are applied in commercial over-the-air broadcasting, military communication, telephony, radar, border surveillance systems, and a host of other applications. In all of these applications, the common thread is the use of electromagnetic waves to convey information [2]. A radio communication system consists of radio transmitter, radio receiver(s) and the radio frequency channel. Since no material medium is required for the propagation of electromagnetic waves, the communication channel is free space. The information to be conveyed over the channel is impressed on the electromagnetic wave, called the carrier wave, using a process called modulation. The needed information is recovered from the information bearing carrier waves, at the receiver end; using a reverse process called demodulation [3]. The advent of digital signal processing technology and software technique has created new possibilities in radio communication. One of such possibilities is the emergence of software defined-radio receivers. Unlike traditional receivers, whose functionality is defined by the arrangement of hardware components within the receiver; the functionality of a software defined radio is software defined [4].

Conventional analogue receivers require hardware building blocks like intermediate frequency (IF) amplifiers, mixers and local oscillators. These are normally implemented in hardware, using electronic components such as diodes and transistors. In software-defined radio receivers, these basic functions are implemented in software [5]. Software Defined Radio (SDR) is a generic term which refers to radio systems in which almost all of the functionality associated with the Physical Layer (PHY) is implemented in software using Digital Signal Processing (DSP) algorithms [6]. An ideal SDR receiver would have a very small hardware front-end; only an antenna and a high speed GHz sampler that is capable of capturing and digitizing a wide band of radio frequencies. Any demodulation, synchronization, decoding or decryption required to recover information contained within a received signal would be performed in software that is executed on a superfast, dedicated processing device [4].

The use of software adds a new dimension of flexibility to radio receivers. For example, it is now possible to receive broadcasts from a number of stations simultaneously, using a digital computer running appropriate software [7]. The received signals can then be stored as digital files on the hard disk of the computer for analysis and other uses. This features is of use to journalists and broadcast regulatory bodies, that need to monitor a number of broadcasting stations at a time. Without software radio receivers, a number of conventional hardware based receiver will need to be tuned to different stations for proper monitoring.

Software defined radio receivers can also be designed to adapt to different modulation formats, without any change in hardware. For example, an FM software-defined radio can easily be reconfigured as an AM receiver by a simple change of software. This does not require any change of hardware component. In contrast, if we want to receive an FM broadcast using an analogue receiver, an FM receiver is required. We cannot use the same FM receiver as an AM receiver; an AM receiver is needed, in spite of the fact that both receivers have a number of hardware components (mixers, local oscillators and intermediate-frequency amplifiers) in common [8].

Many smartphones and similar devices currently have up to around 8 different radios optimized for receiving various signals from different frequency bands, such as those for WiFi (2.4GHz), LTE (Long Term Evolution, 800MHz), GSM (Global System for Mobile Communications, 900MHz), UMTS (Universal Mobile Telecommunications System, 2.1MHz), GPS (Global Positioning System, 1.5GHz), Bluetooth (2.4GHz), NFC (Near Field Communications, 13.56MHz), and FM Radio 100MHz). The ultimate solution here would be to utilize a single SDR that samples the spectrum at GHz rates to digitize and capture all signals from baseband to 2.5 or even 3GHZ, and to implement all of these receivers in software code.

SDR receivers can be designed to run on a number of hardware platforms. Such platforms include the following [9]: Field Programmable Gate Arrays (FPGAs), Digital Signal Processors, Application Specific Integrated Circuits (ASICs), and General Purpose Processors (GPP). The choice of hardware platform depends on a lot of factors, such as cost and the application. At its very simplest conceptual level, SDR comprises of an RF section (antenna, amplifiers and filters) and a very high speed Analogue-to-Digital Converter (ADC) and Digital-to-Analogue Converter (DAC) pair, interfaced with a powerful DSP processor and/or computing system, as illustrated in Figure 1. Samples are passed into and out of the DSP section via the ADC and DAC, respectively.

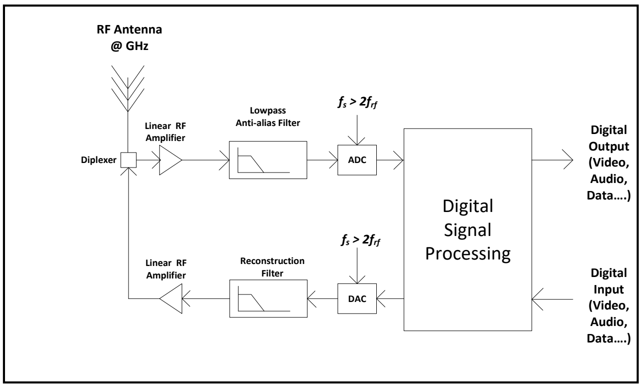

Fig. 1. *The components of the simple, conceptual, 'ultimate' Software Defined Radio (Bob et al, 2015)*

According to the Nyquist theorem (i.e. that one need to sample a signal at greater than twice the signal bandwidth to retain all information), sampling at say f_s=4GHz, would produce a baseband spectrum from 0 to 2GHz, or f_s /2. Thus, the SDR would be capable of transmitting and receiving all frequencies up to 2GHz, with the modulation and demodulation undertaken in the digital domain.

II. APPROACH

The study aim to deploy RTL-SDR receiver and MATLAB software. The RTL-SDR is a low-cost, easy to use USB device that receives RF radio signals. The front end of the RTL-SDR receives RF signals live off the air, downconverts them to baseband, digitizes them, and the device outputs samples of the baseband signal across its USB interface. It is a device made by NooElecand was originally designed to be used as DVB-T (Digital Video Broadcast – Terrestial) receivers, but it was discovered that they could be used as generic (receive only) SDRs by simply putting them into a different mode.

Over recent years, and probably since the late 1990s, SDR has been presented – even heralded – as the future solution and design for all RF receivers [10]. It is probably true to say that SDR has been promising solutions for quite a few years, but from 2014 has this become very low cost and widely available at the desktop level. In the past, SDR was more commonly associated with military and research applications, due to its (historically) high cost implementation [11].

MathWorks has a Hardware Support Package released recently which enables both MATLAB and Simulink to interface with, and control the RTL-SDR. With this add-on, samples output from the device can be captured and brought into software, enabling one to implement any kind of Digital Signal Processing (DSP) receiver or spectrum sensing system one desire in either a Simulink model or MATLAB code.

RF signals are received at the antenna, quadrature down converted by the RTL-SDR, and In Phase/Quadrature Phase (IQ) samples are presented to the computer running MATLAB. The receiver design is implemented using the appropriate DSP algorithms to demodulate the signal to baseband and extract the information signal. This might be audio, video, images, or data.

Subject to appropriate hardware configuration i.e. using the right antenna and signals being broadcast in our vicinity, the RTL-SDR allows us to receive not only FM radio signals, but also UHF/DTV signals, Digital Audio Broadcast (DAB) radio, GPS signals, 2G, 3G and 4G cellular signals, transmissions in the Industrial, Scientific and Medical (ISM) bands. RF signals from the electromagnetic spectrum that can be received by the device varies from FM radio (87.5MHz) to GPS system (1575MHz).

III. FREQUENCY MODULATION (FM) DEMODULATION TECHNIQUES

The conventional analogue receiver is based on the super heterodyne principle, which is illustrated in

Figure 2. The antenna receives the transmittedelectromagnetic waves, producing an electrical signal. The amplitude of the received signal is small, and needs to be amplified before any useful signal processing can be carried out. After amplification by the RF amplifier, the signal is then downconverted to a constant Intermediate Frequency (IF). The frequency downconversion is carried out by heterodyning the amplified RF signal with a locally produced sinusoidal oscillation. Further amplification is carried out in a tuned narrowband IF amplifier. The needed information is then extracted from the IF signal by the demodulator [12].

In conventional analogue super heterodyne receivers, channel selection is achieved by maintaining a constant frequency difference between the frequency of the local oscillator and that of the desired channel.

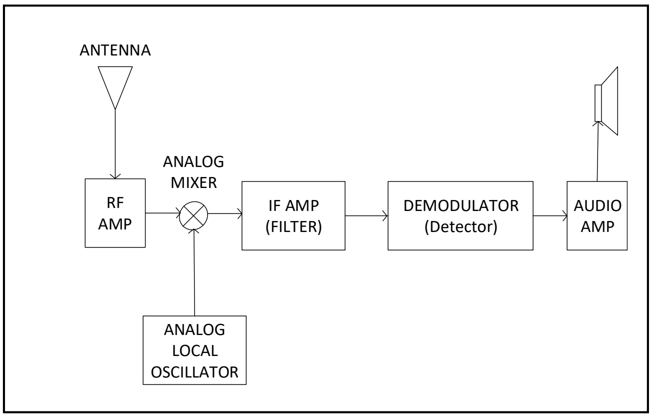

Fig 2. *Block diagram of a conventional receiver (Hosking, 2003)*

The design of the demodulator depends on the type of modulation techniques employed. In AM broadcast receivers, the diode detector is the most commonly used. In FM receivers, the demodulators commonly used include the following [13]: Foster SeelyDiscriminarors; The Ratio Dectectors; The Phase Locked Loop; Quadrature Detector; and Zero Crossing Detector.

IV FREQUENCY MODULATION (FM) DEMODULATION USING DIFFERENTIATION

One of the standard methods used to demodulate FM signals involves taking the derivative of the received signal. For the transmitted (and perfectly received!) signal $s_{fm}(t)$, a new differentiated signal denoted as $s_{fm}{}'(t)$ (where the dash' denotes the derivative) is generated by the receiver.

Considering the generic FM modulated information signal,

$$s_{fm} = A_c cos\left(\omega_c t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i\,(t)dt\right) \qquad (1)$$

Where A_c is the amplitude of the carrier wave, ω_c is the angular rotational frequency of the unmodulated carrier wave of frequency f_c , K_{fm} is the max frequency deviation of the carrier wave from the nominal frequency f_c, $s_i(t)$ is the modulating waveform.

Differentiating Eq. (1) using the chain rule results in:

$$s'_{fm}(t) = \frac{d}{dt} s_{fm}(t)$$

$$= -A_c \frac{d}{dt}\left[\omega_c t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i\,(t)dt\right] sin\left(\omega_c t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i(t)dt\right)$$

$$= -A_c\left[\omega_c + 2\pi K_{fm} s_i(t)\right] sin\left(\omega_c t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i(t)dt\right) \qquad (2)$$

(Blue represents the amplitude component while red represents the high frequency component)

When an FM signal is differentiated, there is a resulting information envelope (the amplitude component in Eq. (2)) multiplied by a high frequency component.

It is clear that the amplitude of the envelope is directly proportional to the amplitude of the information signal. Although it has a DC offset (ω_c, and gain of $2\pi K_{fm}$ resulting from the FM modulation constant, the amplitude fluctuations will still match those of $s_i(t)$).

A complete design of this type FM receiver will require appropriate components to select the frequency band of interest. In modern Integrated Circuit (IC) FM receivers (such as the commercial device in NXP Semiconductor), this process is performed by downconverting the RF signal from ~100MHz to an IF (such as 10MHz), followed by another downconversion stage to 0.5MHz or less, followed by the FM demodulator circuit. Many other methods for FM reception exist, including the simple slope overload and phase detectors.

V METHODOLOGY

The two main components used in the RTL_SDR receivers are a DTV tuner [14] is most commonly used, although some RTL-SDRs utilize the Elonics E4000) and the Realtek RTL283U DVB-T Coded Orthogonal Frequency Division Multiplex (COFDM) demodulator. Figure 3 shows a signal processing flow diagram of the main stages that are carried out on the RTL-SDR. RF signals entering the tuner are downconverted to a low-IF using a Voltage Controlled Oscillator (VCO). The VCO is programmable, and is controlled by the RTL2832U over an Inter-Integrated Circuit (I^2C) interface. After an Active Gain Control (AGC) stage, which dynamically adjusts the amplitude of the input signal to suit the operating range of the device [15], the IF signal then requires to be brought down to baseband. The classical method of doing this is to pass the IF signal through an anti-alias filter, sample the output with an ADC, and then downconvert it to baseband using quadrature Numerically Controlled Oscillators (NCOs) (i.e. a sine and a cosine oscillating at the IF frequency).

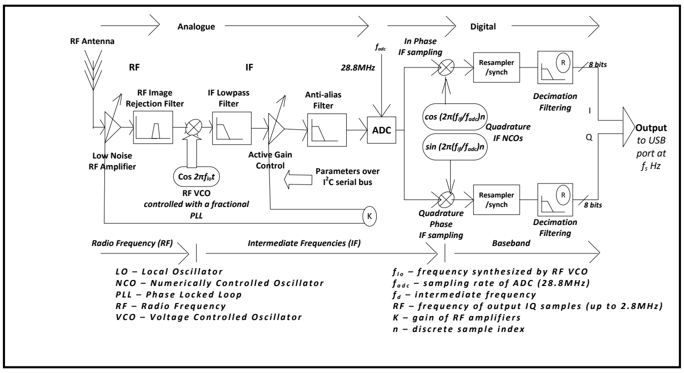

Fig.3.*Block diagram showing the internal architecture of the R820/RTL2832U RTL-SDR (Bob et al, 2015)*

Real RF signals received by the RTL-SDR are quadrature demodulated to baseband before they are sampled – this means that the baseband samples entering MATLAB and Simulink RTL-SDR receiver designs have both In-phase and Quadrature-phase components i.e. they form a complex signal.

When an RF FM signal ($s_{fmRF}(t)$) is received by the RTL-SDR, it is mixed with a complex exponential at frequency f_{lo} (representing the overall local oscillator frequency in the RTL-SDR) to demodulate the signal to complex baseband, as illustrated in Figure 4. Here, the spectra of the various stages of the RTL-SDR downconversion process are shown.

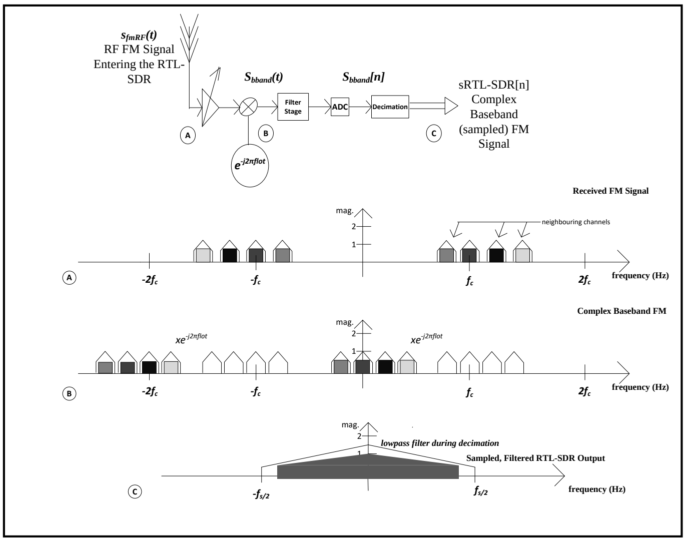

Fig.5.*The RTL-SDR receiving an FM signal, downconverting it to complex baseband, and gives sampled filtered output*

When a frequency offset exists between the original modulating carrier f_c and the local oscillator used during the demodulation process f_{lo}, a frequency shift of f_Δ occurs in the complex baseband output

Assuming that the RTL-SDR receives the transmitted signal $s_{fm}(t)$, from Eq. (1), because a perfect radio channel is assumed, the signal output from the RTL-SDR can be modelled as:

$$s_{RTL-SDR}(t) = LPF[s_{bband}(t)] = LPF\left[s_{fmRF}(t)e^{-j\omega_{lo}t}\right] \quad (3)$$

Where $e^{-j\omega_{lo}t}$ represents the complex oscillator inside the RTL-SDR

Ideally the frequency of the local oscillator used to demodulate the signal and the frequency of the original modulating carrier would be same, as this means that the RF signal will be perfectly demodulated to baseband. This is unlikely to happen however, and when it does not, meaning that the complex baseband signal is still modulated onto a low frequency 'carrier' (not a carrier in the conventional RF sense, but a low, non-zero frequency). We denote this carrier as

$$f_\Delta = f_c - f_{lo} \text{ or equivalently}, \omega_\Delta = \omega_c - \omega_{lo} \quad (4)$$

We can express the downconverted signal using Euler's Formula ($e^{j\omega t} = \cos(\omega t) + j\sin(\omega t)$):

$$s_{bband}(t) = s_{fmRF}(t)e^{-j\omega_{lo}t}$$
$$= s_{fmRF}(t) \times (\cos(\omega_{lo}t) - j\sin(\omega_{lo}t)) \quad (5)$$
$$= A_c\cos\left(\omega_c t + \theta_{fm}(t)\right) \times (\cos(\omega_{lo}t) - j\sin(\omega_{lo}t)),$$

Where $\theta_{fm}(t) = 2\pi K_{fm} \times \int_{-\infty}^{t} s_i(t)dt$

(6)

Multiplying out Equation (5) gives:

$$s_{bband}(t) = A_c\cos\left(\omega_c t + \theta_{fm}(t)\right)\cos(\omega_{lo}t) - jA_c\cos\left(\omega_c t + \theta_{fm}(t)\right)\sin(\omega_{lo}t) \quad (7)$$

Using product to sum trigonometric rules:

$$\cos(u)\cos(v) = \frac{1}{2}[\cos(u-v) + \cos(u+v)]$$

$$\cos(u)\sin(v) = \frac{1}{2}[\sin(u+v) - \sin(u-v)]$$

Equation (7) becomes:

$$s_{bband}(t) = \frac{A_c}{2}\left[\cos\left(\omega_c t + \theta_{fm}(t) - \omega_{lo}t\right) + \cos(\omega_c t + \theta_{fm}(t) + \omega_{lo}t)\right] - j\frac{A_c}{2}\left[\sin\left(\omega_c t + \theta_{fm}(t) + \omega_{lo}t\right) - \sin(\omega_c t + \theta_{fm}(t) - \omega_{lo}t)\right] \quad (8)$$

(Green represents baseband components while red represents high frequency components)

The high frequency components are attenuated by the low pass filters within the RTL-SDR, leaving only the complex baseband signal which is expressed in the continuous time domain for simplicity (the signal $s_{RTL-SDR}(t)$ can be created with a DAC as shown in Figure 4).

$$s_{RTL-SDR}(t) = \frac{A_c}{2}\left[\cos\left(\omega_c t + \theta_{fm}(t) - \omega_{lo}t\right) + j\sin\left(\omega_c t + \theta_{fm}(t) - \omega_{lo}t\right)\right] \quad (9)$$

Which can be simplified by substituting

$\omega_\Delta = \omega_c - \omega_{lo}$ for the 'baseband' complex carrier:

$$s_{RTL-SDR}(t) = \frac{A_c}{2}\left[cos\left(\omega_\Delta t + \theta_{fm}(t)\right) + jsin\left(\omega_\Delta t + \theta_{fm}(t)\right)\right] \quad (10)$$

The baseband carrier, $\omega_\Delta$orf_Δ, is very close to 0Hz, or may be zero if $f_{lo}= f_c$. Substituting $\theta_{fm}(t)$ from Eq. (6) into Eq. (10) gives:

$$s_{RTL-SDR}(t) = \frac{A_c}{2}\left[cos\left(\omega_\Delta t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i\,(t)dt\right) + jsin\left(\omega_\Delta t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i\,(t)dt\right)\right]$$

$$= \frac{A_c}{2} e^{-j(\omega_\Delta t + 2\pi K_{fm} \times \int_{-\infty}^{t} s_i(t)dt)} \quad (11)$$

The RTL-SDR presents this complex FM signal as baseband samples to MATLAB and Simulink; spectra of the signal is illustrated in Figure 4(c). This is what is demodulated to recover the information signal by implementing a differentiate-divide demodulator in MATLAB.

The RTL-SDR Hardware Support Package is installed on the MATLAB/Simulink program. The *RTL-SDR Receiver* Simulink block becomes available for use in the Simulink Library and also the Hardware Support Package adds support to MALTAB in the form of the comm. SDRTL Receiver System Object. Both of these facilitate direct communication with the RTL-SDR attached to the computer and allow key parameters such as the RF center frequency f_c, the sampling rate f_s, and the tuner gain K to be set. A frequency correction value can be entered through both interfaces to compensate for any hardware tolerance issues associated with the device. The differentiate-divide demodulator is implemented in MATLAB.

Conclusion

Software Defined Radio (SDR) technology is emerging day by day. The study could address signal synchronization and time circuitry challenge. SDR designer could support signal repeating system to mitigate attenuation and fading during broadcasting. However, environmental challenges such as rain fade against propagated signal could be minimized. However, Knowledge-based activities such as commercial programme and paid announcement could be introduced during broadcasting at the software define radio terminal. Further study will be investigated on software define radio circuitry quality factor.

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