

Digital Signal Processing Using an RTL-SDR Dongle by the Example of FM Signal

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Abstract. The article describes the reception of frequency-modulated signals using a software-defined radio (SDR) based on hardware and software platforms of the RTL-SDR project and the following demodulation of the signal in the MATLAB. The operation principle and the mathematical model of the SDR dongle are considered. The mathematical model describes the process of signal receiving and processing that occurs in the receiver prior to the sampling of the input signal. The experimental part describes the process of receiving and processing the frequency-modulated signal of one of the Moscow radio stations presented as discrete samples of the in-phase and quadrature components in the MATLAB. The use of RTL-SDR dongle in conjunction with the MATLAB mathematical software allows software-based digital signal processing, which resulted in the reproduction of the transmitted audio information in the live broadcast.

Keywords: software-defined radio (SDR), digital signal processing, FM signal

Introduction

Software defined radio (SDR) is the technology allowing one to change software radio frequency parameters of the receiver. Over the past 20 years, SDR has attracted a lot of interest among researchers and developers [1]. Such devices differ in a possibility of implementation of functions of the physical layer in a program way that provides implementation of processing of different signal types without change of the hardware. When cheap devices appeared, interest in this technology increased even more as it permits creating a cheap radio operating in the range from tens megahertz to units of gigahertz.

This paper considers usage of RTL-SDR and MATLAB to receive and demodulate frequency-modulated signals.

RTL-SDR description

In general case, SDR includes: a receiving antenna, analog-to-digital converter (ADC), frequency converter, and single processing device. A single processing device can be programmable logic device (PLD) or signal processor. In the present case, the signals were processed using a personal computer.

During creation of SDR, it is important to understand what functions are performed hardware and what is possible to carry out software. The simplified block diagram of the RTL-SDR receiver can be presented in the successive joining of the two chips: Raphael Micro R820T and Realtek RTL2832U (Fig. 1).

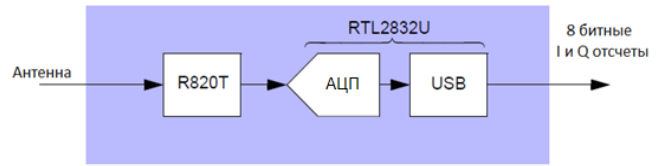


Fig. 1. The block diagram of RTL-SDR. (Antenna / ADC / 8-bit I and Q readings)

The chip R820T performs as radio receiver operating by superheterodyne principle in the frequency range from 24 MHz to 1850 MHz. The chip performs the following: amplification, bandpass filtration, transmission to the intermediate frequency 3.57 MHz [2], and low-frequency filtration. When working with R820T, it is necessary to set the central frequency f_c and amplification coefficient G .

It is known, that the chip RTL2832 contains the ADC with the sample rate of 28.8 MHz, digital oscillators, and decimation filters of lower frequencies. On the output of the chip there are formed and transmitted through USB interface 8-th bit readings of in-phase (I) and quadrature (Q) components of a signal. Sample rate of output reports is set software and can be up to 2.8 MHz.

Here the hardware part of SDR comes to an end and following operations such as filtration, demodulation, and signal detection are software realized.

Fig. 2 depicts a functional scheme of the RTL-SDR dongle [3].

The input signal $r(t)$ is transmitted into the system:

$$r(t) = s(t) + N(t) \tag{1}$$

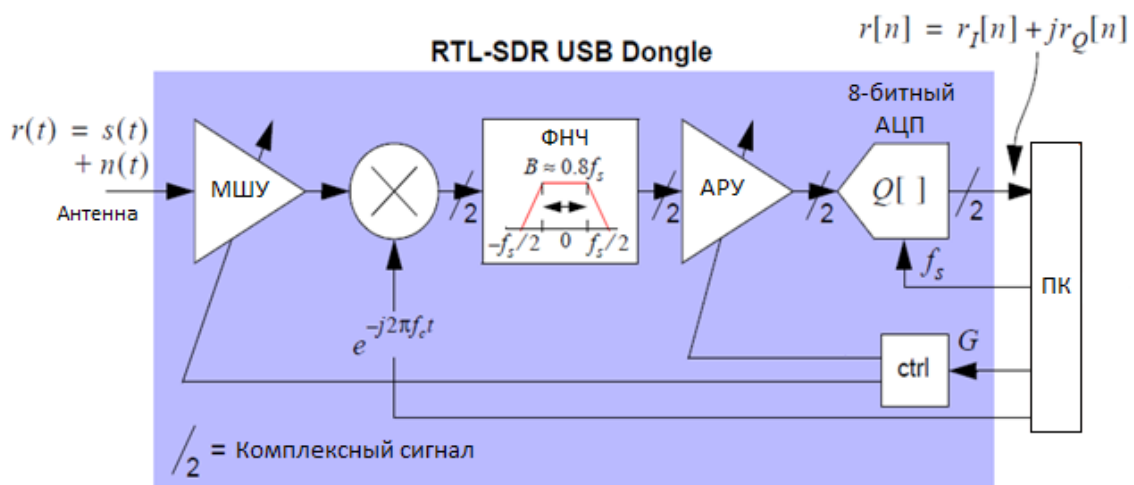


Fig. 2. The functional scheme of the RTL-SDR dongle. (Antenna / LNA / LPF / AGC / 8-bit ADC / Computer / Complex signal)

where $N(t)$ is the noise component of the signal, and $s(t)$ is the useful signal.

The input signal is transmitted onto the low-noise amplifier, which main objective consists in signal amplification without distortions. The amplified signal is mixed with the heterodyne signal s_r :

$$s_r = e^{-j2\pi f_c t}$$

Hence, there is a multiplication of the amplified input signal with a heterodyne signal operating at the negative carrier frequency. The illustration of this process is given in Fig. 3.



Fig. 3. The transmission of a signal into the zero frequency. (Shift to the left / Effective bandpass / discrete signal spectrum)

At the output of the mixer, the signal can be presented in a complex form, since [4]:

$$e^{j\theta} = \cos\theta + j\sin\theta.$$

After the mixer, a signal is transmitted to the built-in low-pass filter (LPF), where the actual and imaginary part of the signal is separately filtered, i.e., the filter discards the high-frequency part generated by multiplying the two signals.

In the discrete form, the signal can be described as follows [5]:

$$r[n] = G \cdot LP\{r(t)e^{-j2\pi f_c t}\}_{t=n/f_s},$$

where LP is the transfer function of a LPF.

In the frequency domain, the signal is described as

$$R(f) = G \cdot R(f+f_c) \cdot H_{LP}(f).$$

The last element of signal processing to receive reports on in-phase and quadrature components is an

8-bit ADC. An output signal from an ADC is described by the sum of signals:

$$r[n] + N[n] = (r_I[n] + jr_Q[n]) + (N_I[n] + jN_Q[n]).$$

An output signal, in the form of a flow of 8-bit readings is transmitted from a RTL-SDR dongle via the USB interface, which can be processed in the MATLAB.

The analysis of capabilities and prospects of the RTL-SDR application is described by the example of frequency-modulated signal reception and processing with MATLAB [6].

MATLAB used an optional installation package to work with RTL-SDR dongle – “Communications System Toolbox Support Package for RTL-SDR Radio”, where there are the means to carry out interaction with RTL-SDR, and digital signal processing library. This package allows receiving a digitized signal for which receiving it is necessary to set the carrier frequency and sampling rate. Then, a signal in the form of an array of complex numbers is transmitted to the discriminator, where the above operations are performed.

Frequency modulation is a type of analog modulation at which the information signal controls the frequency of the carrier fluctuation, at the same time a derivative of a phase deviation is proportional to an information signal [7]. A frequency-modulated signal is described by the expression:

$$x_c(t) = A_c \cos(2\pi f_c t + \varphi(t)) = A_c \cos\left(2\pi f_c t + 2\pi k_a \int_{-\infty}^t m(t) dt\right)$$

where k_a is the modulation coefficient, $m(t)$ is the modulating signal.

The received frequency-modulated signals are transmitted to a complex bandpass discriminator, also known as a quadricorrelator. At the output of the quadricorrelator, real and imaginary parts of the received signal are generated:

$$x'_c(t) = \cos(2\pi\Delta f t + \varphi(t)) + j\sin(2\pi\Delta f t + \varphi(t)) = x_I(t) + jx_Q(t),$$

where Δf is the error in frequency occurring at the signal transmission to the “zero” frequency.

The above expressions relate to continuous time systems, as they relate to discrete systems, further statements relate to the implementation of a digital signal processing system from the RTL-SDR dongle.

The following demodulator algorithm was implemented in the MATLAB.

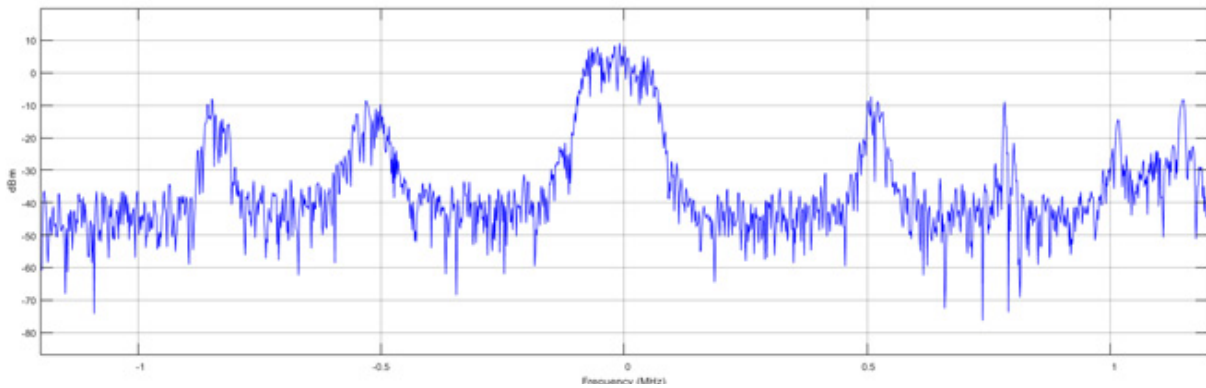


Fig. 4. The input signals spectrum.

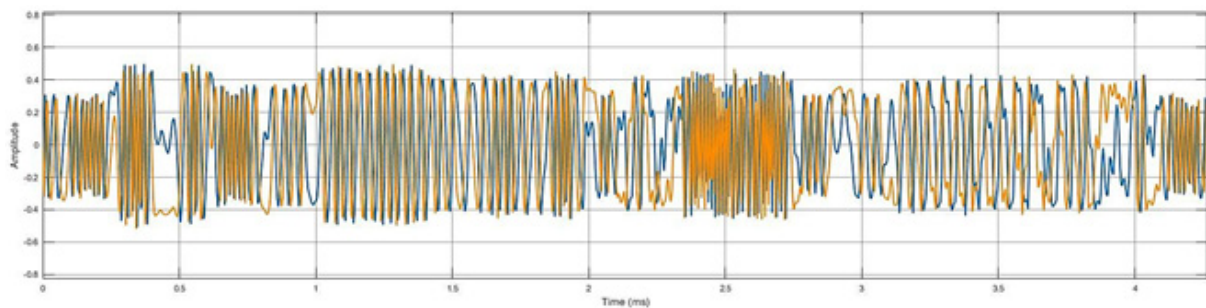


Fig. 5. I and Q components of the input signals.

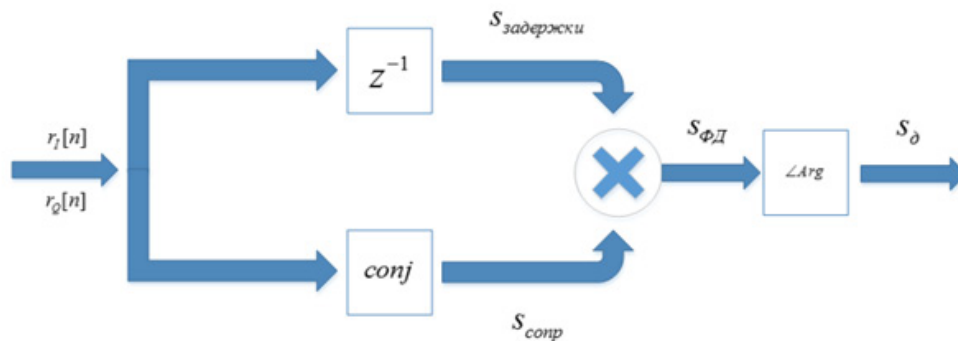


Fig. 6. The discriminator scheme. ($S_{delay} / S_{PD} / S_d$)

The signals output from the RTL-SDR can be expressed as follows:

$$r[n] = (r_I[n] + N_I[n]) + j(r_Q[n] + N_Q[n]).$$

The spectrum of input signals is shown in Fig. 4 [8]. The frequency of one of a popular radio stations in Moscow was used as the center frequency.

Two streams of discrete signals are transmitted to the discriminator input: quadrature and in-phase components of the signal (Fig. 5).

The discriminator performs two operations in parallel: generation of complex conjugated signals and generation of delayed signals per one cycle (Fig. 6).

In MATLAB, the conjugated signal is generated by the *conj* function, and the delayed signal is formed by the *delayseq* function [6]. Then the signals s_d and s_{conj} are multiplied. In the result, a signal of a phase detector s_{FD} described by the expression [9]:

$$s_{FD}[n] = s_d[n] \times s_{conj}.$$

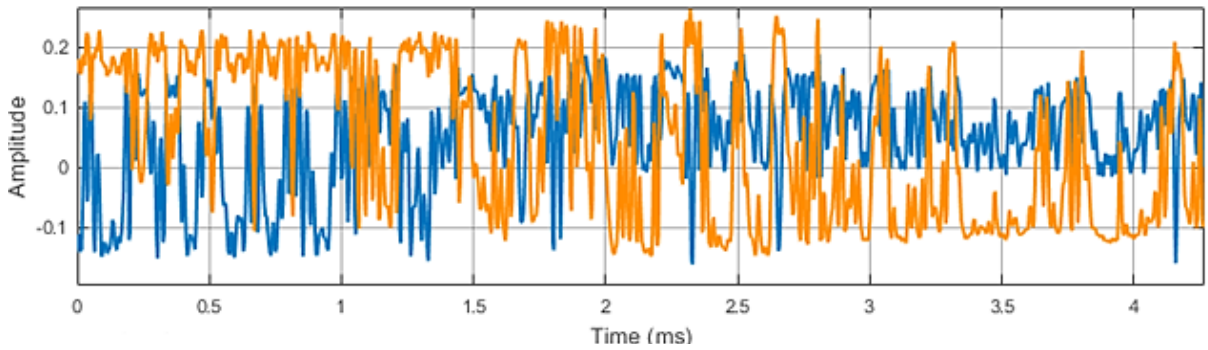


Fig. 7. The S_{FD} signal.

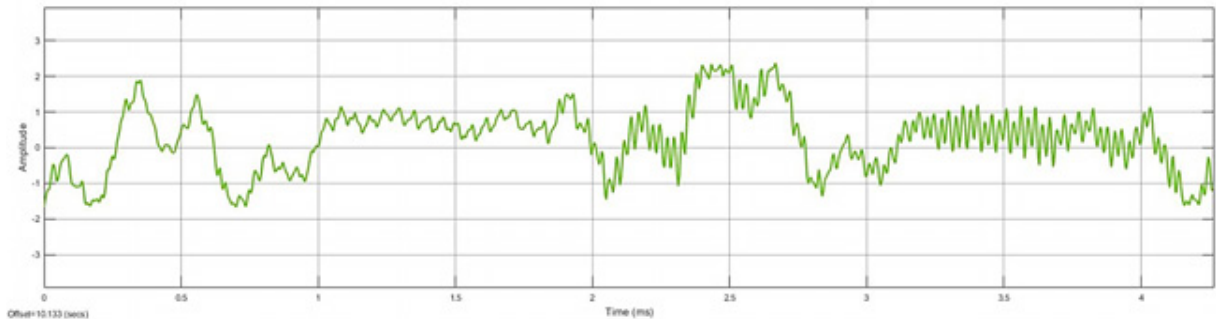


Fig. 8. The signal in the discriminator output.

The arctangent from the ratio of the imaginary component s_{FD} to the real one equals the instantaneous phase and corresponds to the information component of the received. MATLAB allows one to calculate the arctangent using the function *atan*, to which real and imaginary components of s_{FD} is transmitted as arguments. This operation is performed for each member of the set. In the output of the discriminator, the current signal value can be recorded as follows:

$$s_d(t) = \angle s_{FD}(t) .$$

As a result, a discrete signal will be generated at the output of the system $s_d[n]$:

$$s_d[n] = \angle \{(r_I[n] - r_Q[n]) \times (r_I[n - 1] - r_Q[n - 1])\} .$$

Then the signal is remodified and reproduced on audio speakers using the function *sound* [10]. The output signal of the system is shown in Fig. 8.

As a result when carrying out the above-stated actions during the experiment from PC loudspeakers the music corresponding to that radio station, which carrier frequency was selected as central for RTL-SDR receiver, was reproduced.

Conclusion

In this article, the device and mathematical model of RTL-SDR dongle are considered. The demodulation algorithm of the FM signal generated by the radio station and received with the help of RTL-SDR dongle is considered with the following digital signal processing in the MATLAB modeling system. The results showed that the use of RTL-SDR dongle in combination with MATLAB allows employing configurable algorithms of digital signal processing for radio communication needs.

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