Digital demodulators for analog signals: comparative analysis and simulation

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Abstract The paper examines digital demodulators for two commonly used techniques of modulating analog signals: amplitude modulation (AM) and frequency modulation (FM). The described demodulators can be used to perform the radio monitoring of narrowband signal ranges including FM broadcasting stations as well as license-free CB, LPD, PMR bands. The demodulators considered in this work are intended for programmable devices with limited memory and computing resources, for example, for STM32F407 microcontrollers and similar ones. The paper presents the analysis and simulation of demodulators for AM signals, FM signals with low modulation indices and for FM signals without restriction on the modulation indices. In addition, the authors demonstrate how to demodulate the phase-modulation signal using a quadrature demodulator. The number of operations that are available for demodulation is limited by IF multiplication and filtering. The simulation of the analyzed demodulation algorithms was carried out in the Scilab environment which is a free analogue of the Matlab environment. To explain the principle of operation of demodulators, block diagrams and graphs of signals in time and frequency domains are shown.

1. Introduction
To extract useful information from a radio signal, it must be demodulated. In a conventional receiving device, various electrical circuits with nonlinear components (for example, diodes) are used as demodulators. A separate demodulator is required for each different type of modulation. In the case of amplitude modulation, it is sufficient to select its envelope to demodulate such a signal. An ordinary semiconductor diode will accomplish this task [1]. When demodulating an FM signal in analog form, it is first converted to an amplitude modulated signal using a transformer, and then demodulated in the same way as an AM signal. Therefore, it turns out that when using exclusively analog electronic devices to modify the demodulator, it implies to change the circuit topology which entails additional difficulties in the implementation and operation of the device, and also complicates the task of miniaturization. The modern software-defined devices [2] for receiving and converting information give a solution by using an ADC (or frequency converters followed by an ADC) inserted after the input circuits instead of analog demodulator. This approach significantly expands the scope of receiving devices. Input circuits of SDR-receivers are similar to those of analog receivers. SDR receivers may be configured to perform direct conversion when the ADC sampling rate, as a rule, exceeds 100 MHz or one or two frequency conversions as the popular heterodyne Hack RF One [3].

Receivers are classified as narrow-band and wide-band according to the width of the processed frequency band. Narrowband receivers are mainly used to carry out radio communication sessions and control various devices. Broadband receivers are used for performing radio monitoring tasks as well
as some special tasks, an example, the study of properties of materials. The key difference between narrowband and wideband receivers resides in the signal processing device: narrowband ones may have a microcontroller while wideband ones use only FPGA [5].

Currently, narrowband signals are used in VHF radio broadcasting as well as for communication sessions in the CB, Airband, LPD, and PMR bands. The bandwidth data is given in table 1. It is seen from table 1 that even within the same license-free range various types of modulation can be used, which significantly complicates the use of analog receiving devices.

2. Simulation task
Now, let us consider a modulated signal at the output of an intermediate frequency amplifier. We choose the intermediate frequency not from a number of preferred values, but based on the channel bandwidth. Therefore, for a heterodyne receiver designed to receive VHF broadcasting the intermediate frequency cannot be less than 100 kHz. The most common ADCs, both built-in and external, have a sampling frequency of 0.4 to 5.0 MHz, which is the upper limit for the intermediate frequency. For the built-in ADC of the STM32F407VG microcontroller, the optimal sampling rate does not exceed 1 MHz. For that reason, it is advisable to choose an intermediate frequency of 150 to 200 kHz to avoid distortion due to aliasing. If we might not want to receive VHF broadcasting, we can choose a lower discretization frequency, for example, 96 kHz as this frequency is more convenient for output to the speaker via a DAC or audio codec.

While running simulation, the modulated waveform is considered at a low intermediate frequency. The IF range is limited to half the channel width at the bottom and half the sample rate at the top. The range of frequencies used for modulation of AM signals lies in the tone FM signal range $f_{\text{voice}} = 300$ to 3400 Hz, i.e. the channel width for dual-band AM modulation will be 6.8 kHz. The frequency deviation of a narrowband FM signal is 6.25 kHz. Receiving devices used for simulation do not feature high-speed ADCs (the sampling rate does not exceed 1 to 2 MHz). When using a sampling rate close to the maximum, the sample size may exceed the available space in the device memory, so we will choose $f_{\text{IF}} = 10$ kHz as the intermediate frequency. Taking into account that this frequency is not included in the list of intermediate frequencies, the device will need to be shielded from external interference; however, we note that only very powerful signals can cause significant interference at this and other close frequencies, but the wavelength of such oscillations is quite large and it also reduces the effect of such interference.

We choose the sampling frequency equal to 96 kHz, because in practice, successful signal recovery is possible if the maximum frequency in the signal spectrum is more than 3 to 5 times less than the sampling frequency. Another advantage of this sampling rate is the absence of the need to decimate the signal when outputting it, for example, through an audio codec.

Signal demodulation is performed using digital high-pass and low-pass filters [6] as well as frequency multiplication. The considered demodulation algorithms can be used for systems with limited resources as the major limit of such systems is the capacity of RAM, i.e. the suggested algorithms mainly refer to the systems including microcontrollers.
3. Demodulators

3.1. AM demodulator

When demodulating AM signals, we take into account the modulation frequency range and calculate the cutoff frequencies for the LPF and HPF.

Let us consider a tone-amplitude-modulated signal (TAMS) with an amplitude modulation factor $k_{AM}$.

$$s(t) = \cos(2\pi f_{IF}t) \cdot [1 + k_{AM} \cos(2\pi F_t)]. \quad (1)$$

Then we multiply the signal at the IF by the IF frequency:

$$s(t) = \frac{k_{AM}}{2} \cos(2\pi (f_{IF} - F_t)t) + \cos(2\pi f_{IF}t) + \frac{k_{AM}}{2} \cos(2\pi (f_{IF} + F_t)t). \quad (2)$$

When multiplied by frequency, side components of the multiplication of harmonic cosine oscillations appear. In order to get rid of them, we use a low-pass filter with a cutoff frequency slightly higher than the maximum frequency of the modulating signal: $f_{c, LPF} = 3.5$ kHz. The result of filtering operation will be a signal:

$$s_1(t) = \frac{1}{2} + \frac{k_{AM}}{4} \cos(2\pi F_t). \quad (3)$$

To recover a mean value free signal, it is necessary to use a high-pass filter with a cutoff frequency equal to the lowest frequency of the modulating signal. We choose $f_{c, HPF} = 300$ kHz.

Let us consider the block diagram and the signal in the frequency domain after performing each of the actions (figure 1). We choose an AM signal modulated by harmonic oscillations with a frequency of 1.2 and 2.5 kHz with partial amplitude modulation coefficients of 0.65 and 0.3, respectively (figure 2 and figure 3).

![Figure 1. AM demodulator block diagram.](image)

The proposed model of AM demodulator is particularly suitable for demodulating two-sideband, single-sideband, and balanced amplitude modulation signals, which makes it possible to use it in the amateur radio SW band.

3.2. NFM demodulator

NFM (Narrow FM) signal has a small frequency deviation. These signals feature the small value of the FM index $m_{FM}$, that being the case, the amplitude spectrum of such a signal will be similar to the amplitude modulation signal (AMS) spectrum. However, the key difference lies in the phase spectrum. FM signals with low modulation indices are currently not widely used because of low noise immunity.
Nevertheless, it is essential to consider a separate demodulator for such signals as a special case of converting an FM signal into a single sideband AM signal. As an example, let us consider the tone FM signal with a low modulation index.

\[
\sin(2\pi m f_{\text{IF}} t + 2\pi m \sin(2\pi f_t t)) = \cos(2\pi f_{\text{IF}} t) + \frac{m}{2} \cos(2\pi (f_{\text{IF}} + F)t) - \frac{m}{2} \cos(2\pi (f_{\text{IF}} - F)t) .
\]

Taking into account that the amplitude spectrum of the FM signal is symmetrical about the center frequency, we use a high-pass filter with a cutoff frequency equal to the center frequency of the signal (figure 4). After filtering, we get an AMS with a suppressed carrier frequency (figure 5), for which we can use the demodulation method for AM signals.

### 3.3. Quadrature demodulator

The Quadrature demodulator is a universal demodulator for AM, FM and PM signals [7]. The basic principle behind Quadrature demodulator is that the signal is decomposed into imaginary and real parts. In other words, we create from two arrays with one array by multiplying the original array of samples by arrays of samples of sinusoidal and cosine oscillations with a frequency equal to the intermediate frequency (figure 6). It is essential to note that for a sampled signal it is most correct to evaluate it using the frequency normalized to the sampling rate. When, after multiplying two arrays are obtained, we
proceed to their filtering that is completely analogous to that of a simple AM demodulator: first with a digital low-pass filter, and then with a digital high-pass filter in order to produce mean value free signal. If the demodulated signal is frequency modulation, then an array of complex numbers arguments is determined, and further this array is differentiated. In case of phase modulation, no differentiation is required. In case of amplitude modulation, it is needed to create an array of modules of complex numbers. A distinguishing characteristic of this demodulator is the fact that it can demodulate an FM signal with any FM index [8], unlike the simplest demodulator for narrowband FM signals. Example of FM signal demodulating is given below (figures 7-10).

![Quadrature demodulator block diagram.](image)

**Figure 6.** Quadrature demodulator block diagram.

![Quadrature demodulator input FM signal](image)

**Figure 7.** Quadrature demodulator input FM signal (modulation frequency is 2 kHz, modulation index is 2).

![Quadrature demodulator input FM signal amplitude spectrum.](image)

**Figure 8.** Quadrature demodulator input FM signal amplitude spectrum.

![Quadrature demodulator output FM signal](image)

**Figure 9.** Quadrature demodulator output FM signal (modulation frequency is 2 kHz).

![Quadrature demodulator output FM signal amplitude spectrum.](image)

**Figure 10.** Quadrature demodulator output FM signal amplitude spectrum.
4. Conclusion
The considered digital demodulators can be used in software-defined receivers with a low intermediate frequency and preliminary analog signal filtering. The findings are summarized as below:

- When demodulating an AM signal, it seems most expedient to use a non-quadrature AM demodulator, since it is more efficient both in memory and in the time of demodulation. The obtained advantages are achieved by a 2-fold reduction in the number of filtering and multiplication operations, as well as the absence of squaring and square root operations.
- A demodulator for an FM signal with a low modulation index is currently not practical since signals with low FM indices are not used in practice, and when demodulating a signal with the FM index of 0.2 or more, significant distortions appear in the demodulated signal.
- Quadrature demodulator is a universal demodulator for any analog type of modulation. It is advisable to use it for demodulation of frequency or phase modulation signals with any modulation index in any band listed in table 1. The authors’ opinion is consistent with the fact of the widespread use of quadrature demodulators in practice.

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