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Parameter Justification of a Signal Recognition Algorithm Based on Detection at Two Intermediate Frequencies

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Abstract

Introduction. The signal recognition task for the purposes of RF spectrum management can be solved using a signal recognition algorithm with detection at two intermediate frequencies. This algorithm is based on time–frequency analysis using fast Fourier transform (FFT) and signal envelope processing. Due to the relative simplicity of transformations, this algorithm is implemented on commercially available field programmable gate arrays and allows processing received signals in near real-time. However, the justification of the algorithm parameters providing effective signal recognition by the criterion of minimizing the signal-to-noise ratio (SNR) has not performed so far.

Aim. Justification of parameters of the developed signal recognition algorithm, providing the minimum required SNR at the algorithm input.

Materials and methods. The efficiency of the developed algorithm was estimated by computer simulation in the MATLAB environment.

Results. The influence of the parameters of functional blocks and received signals on the efficiency of the developed algorithm was investigated. For chirp, simple pulse, binary, and quadrature phase shift keying signals, the following parameters are recommended: a pulse duration of 5…20 µs; a chirp rate of 0.8…24 MHz/µs; a code duration of 0.5…1 µs. For these signal parameters, the parameters of the algorithm ensuring its efficiency according to the given criterion are as follows: the number of FFT points equals 1024; the Hamming weight window; bandwidths of bandpass filters are 4 MHz; signal envelope amplitude averaging coefficient equals 0.15…0.25.

Conclusion. The algorithm with the scientifically valid parameters can be used for recognition of signals at the input minimum SNR for the given types and parameters of signals.

Keywords: time-frequency analysis, fast Fourier transform, weight window, signal envelope, bandpass filter

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Introduction. RF spectrum management is used to control the radio-electronic situation and regulate the use of radio frequencies [1, 2]. Modern radio sources make use of different types of signals. Therefore, recognizing the signal modulation type is a critical task for RF spectrum management [3–5]. This task can be solved by various algorithms using spectral analysis based on fast Fourier transform (FFT) [6–13], wavelet transform [14, 15], high-order cumulants [16, 17], cyclostationary spectral analysis [18, 19], time-frequency distribution [20, 21], and convolutional neural networks [22, 23].

The advantage of algorithms using FFT-based spectrum analysis [6–13] over other algorithms [14–23] consists in their simplicity in terms of technical implementation [24, 25]. Currently, various approaches are employed to implement a high-speed FFT block on commercially available field programmable gate arrays [26, 27]. A review of such algorithms [6–13] found the algorithm [12, 13] to have an advantage over the algorithms [6, 7] in terms of the number of signal types and the algorithms [8–11] to be beneficial in terms of the signal-to-noise ratio (SNR) values required to recognize phase shift keying signals.

A comparison of the probability of correct recognition of down-chirp, up-chirp, simple pulse (SP), binary (BPSK), and quadrature phase shift keying (QPSK) signals depending on the SNR for the developed algorithm was carried out in [12, 13]. However, the justification of the algorithm parameters providing efficient signal recognition has not been performed. Further, we assume that the efficiency can be estimated by the criterion of minimizing the SNR required to recognize each of the specified signals.

Given the above, this work aims to justify the parameters of the developed signal recognition algorithm [12, 13], which ensure the minimum required SNR at the algorithm input.

Description of the developed algorithm. The algorithm is briefly described by a structural diagram (Fig. 1), which includes the following functional blocks: signal partitioning block SPB; weight window block WWB; FFT block; carrier frequency determination block CFDB; frequency analysis block FAB; generator G; delay line DL; frequency converter FC; frequency doubling block FDB; bandpass filters BPF1 and BPF2; envelope detectors ED1 and ED2; decision-making block DMB. The ranges of the input signal frequencies, intermediate frequencies and double intermediate frequencies are denoted by $\Delta f_{\text{in}}, \Delta f_{\text{IF1}}$, and Δf_{IF2}, respectively.

When recognizing signals, a linear least-square approximation of the average carrier frequency values (ACFVs) of the signal falling into the processing windows in FAB is carried out. The signal envelopes at intermediate and double intermediate frequencies in the ED1 and the ED2 are also processed. The ACFV of the signal in the processing window f_i can be calculated as follows:

$$f_i = \sum_{m=1}^{M} f_m / M, \qquad (1)$$

where f_m are frequencies in the processing window, at which the signal spectrum value is above the given detection threshold and above half of the

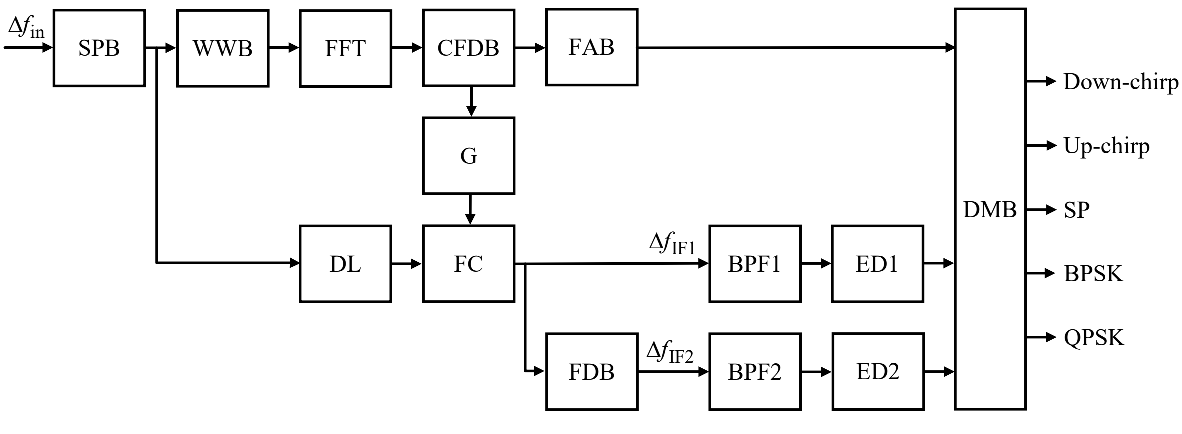

Fig. 1. Structural diagram of the signal recognition algorithm with detection at two intermediate frequencies

spectrum maximum and M is the number of these frequencies. Signal recognition is performed after detecting the signal and calculating the ACFV in the CFDB in at least two processing windows. To recognize signals of different types, the following parameters are used: the slope coefficient of the approximated straight line *a,* its variance σ^2, signal envelope dips at intermediate $K1$ and double intermediate frequencies $K2$.

For chirp signals, the modulus of the coefficient *a* characterizes the chirp rate, and its sign – the direction of chirp rate (Fig. 2, *a, b*). For down-chirp and up-chirp signals, the coefficient *a* takes a negative and positive value, respectively.

For an SP signal, the coefficient *a* takes a zero value, since the spectrums of the signal falling into the processing windows have the same shape (Fig. 2, *c*). In addition, when receiving an SP signal, the envelope at the intermediate frequency at the ED1 output has no dips (Fig. 3, *a*).

For BPSK and QPSK signals, the coefficient *a* takes a value close to zero, since the spectrum shape of these signals falling into the processing windows depends on the phase shift value, code duration, and processing window length (Fig. 2, *d, e*). The signal envelope at the intermediate frequency at the ED1 output has dips for both types of signals (Fig. 3, *b, d*). After frequency doubling, the BPSK signal envelope at the ED2 output has a smooth shape, and there are dips for the QPSK signal (Fig. 3, *c, e*).

The threshold values of signal envelope dip detection at two intermediate frequencies at the ED1 and ED2 outputs are set as

$$U_{\text{thr}} = k_{\text{av}} U_{\text{av}}, \quad (2)$$

where k_{av} is the signal envelope amplitude averaging coefficient, and U_{av} is the signal average envelope amplitude value.

The principle of the algorithm operation is described in greater detail in [12, 13].

Experimental methodology. To minimize the required SNR at the algorithm input, we used MATLAB to investigate the following algorithm parameters and their influence:

– the number of FFT points N_{FFT} on selecting threshold values of the slope coefficient and variance;

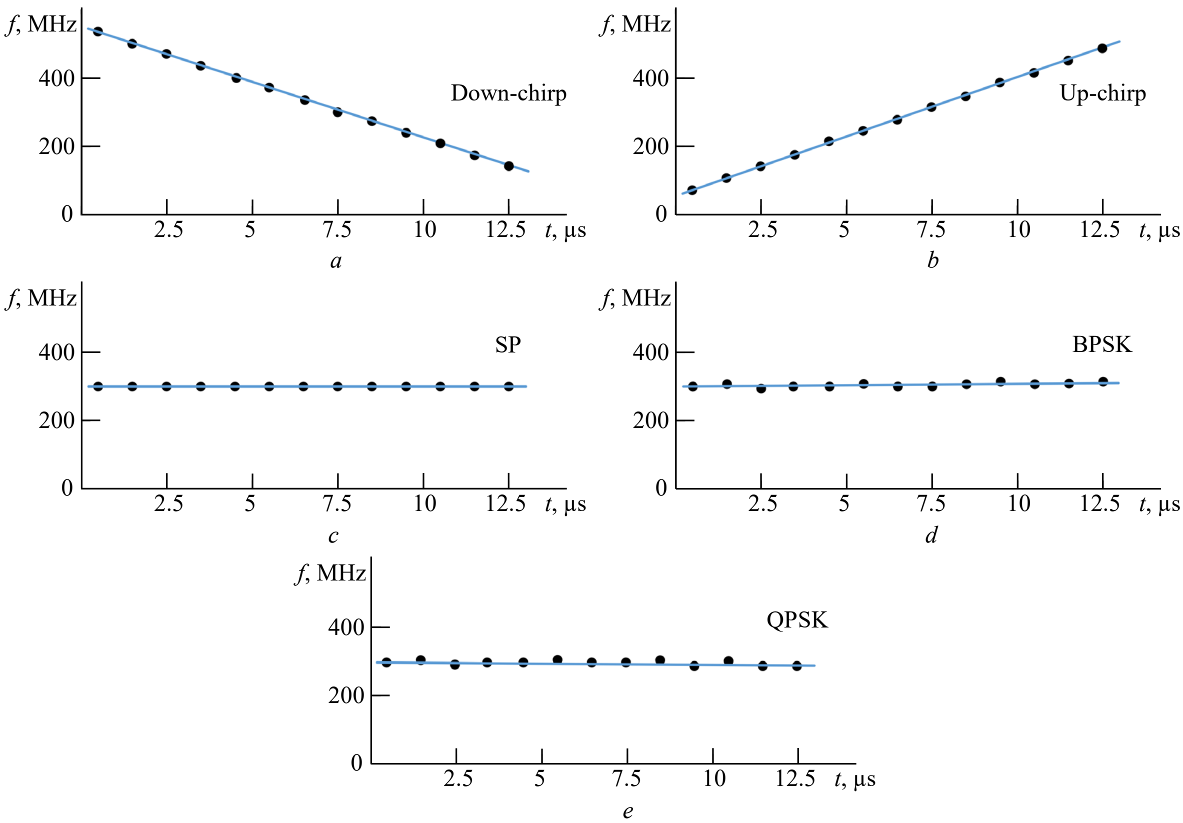

Fig. 2. Linear approximation of the average carrier frequency values of the signal falling into the processing windows

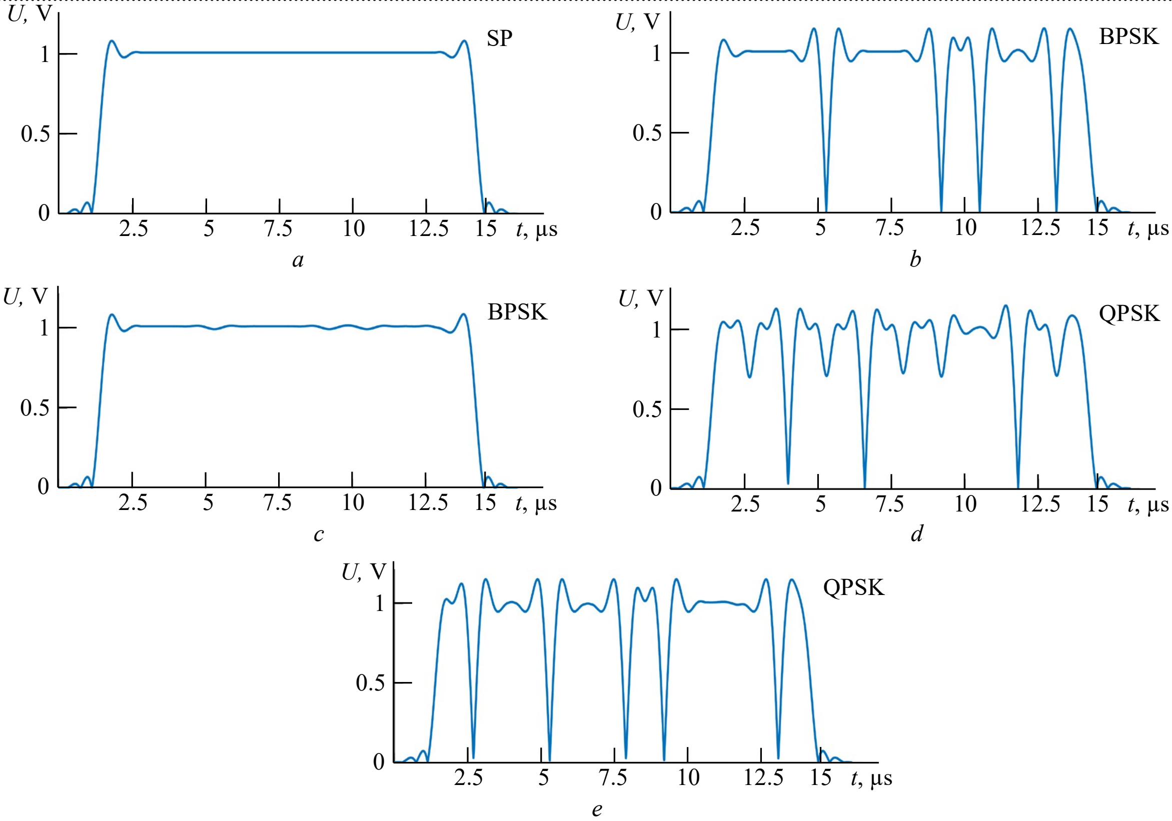

Fig. 3. Signal envelopes at intermediate (left) and double intermediate frequencies (right)

– the number of FFT points N_{FFT} and weight window type on the dependencies of the probability of correct recognition of down-chirp, up-chirp, SP, BPSK, and QPSK signals on the SNR;

– threshold values of signal envelope dip detection U_{thr} and bandwidths of bandpass filters used in the algorithm Δf_{BPF1} and Δf_{BPF2} on the dependencies of the probability of correct recognition of SP, BPSK, and QPSK signals on the SNR.

In estimating the above influence, the minimum SNR value q_{thr} ensuring the probability of correct recognition not less than 0.9 is used.

Selection of parameter variation ranges for input signals and the algorithm. We performed a statistical simulation of constructing the linear approximation of the signal falling ACFVs into the processing windows to estimate the influence of N_{FFT} on the selecting threshold values of the slope coefficient and variance. Since the probabilities of correct recognition of down-chirp and up-chirp signals do not differ significantly, only up-chirp signal is investigated as a chirp signal in [12].

The input signal is a mixture of a signal and additive white Gaussian noise (AWGN) with the zero mean value and unit standard deviation. It is assumed that the pulse duration exceeds the length of the longest processing window by more than a factor of 2. We set the following initial data.

Parameters of the useful signals: pulse duration of chirp and SP signals – from 5 to 20 μs in increments of 0.05 μs; code duration of BPSK and QPSK signals – from 0.5 to 1 μs in increments of 0.1 μs; carrier frequency of SP, BPSK, and QPSK signals – from 10 to 490 MHz in increments of 10 MHz (the product of the code duration of BPSK, QPSK signals and their carrier frequency have to be an integer number of waves); amplitude – random from 0 to 5; initial frequency value of chirp signals – 10 MHz; deviation of chirp signals – from 4 to 480 MHz; chirp rate $\gamma = 0.8\ldots24$ MHz/μs in increments of 0.05 MHz/μs; initial phase of signals – random; number of codes of BPSK and QPSK signals – 20; phase shift law of BPSK and QPSK signals – random.

Fixed parameters of the developed algorithm: sampling rate – 1 GHz; frequency range of the input signal $\Delta f_{in} = (0...500)$ MHz; number of processing windows – 10; intermediate frequency range $\Delta f_{IF1} = 50 \pm \Delta f_c$ MHz, where Δf_c –

FFT-based carrier frequency determination error; double intermediate frequency range $\Delta f_{\text{IF2}} = 2(50 \pm \Delta f_{\text{c}})$ MHz. The threshold value of signal detection against the AWGN background in the processing windows is set based on the probability of false alarm 10^{-7} [28].

Optimizable parameters of the developed algorithm: number of FFT points in processing window $N_{\text{FFT}} = 512$; 1024; 2048; weight window types – rectangular, Hamming, Blackman; signal envelope amplitude averaging coefficient $k_{\text{av}} = 0.05\ldots0.45$; bandwidth of bandpass filters BPF1 and BPF2 $\Delta f_{\text{BPF1}} = \Delta f_{\text{BPF2}} = 2$; 4; 6 MHz.

Linear approximation of the ACFVs is performed after detecting the signal on the AWGN background in at least two processing windows. The simulation result for 10^4 measurements is presented in Tab. 1. The threshold values of slope coefficient and variance are selected to ensure that the values of the distribution function of the slope coefficient and its variance be not less than 0.99.

Tab. 1 allows us to draw the following conclusions:

1. For chirp signals, the value σ^2 increases as N_{FFT} increases at the fixed sampling rate. This is because an increase in the processing window length leads to a broadening of the chirp signal spectrum width. As a result, the error of linear approximation of the ACFVs increases. The slope coefficient a characterizes the chirp rate; therefore, the value a is constant for a different number of FFT points.

2. For SP, BPSK, and QPSK signals, the values $|a|$ and σ^2 decrease as N_{FFT} increases at the fixed sampling rate. This is because an increase in the processing window length leads to an increase in frequency resolution. As a result, the accuracy of determining the signal falling ACFVs into the processing windows increases.

Influence of the parameters of functional blocks and received signals on the algorithm efficiency

*Influence of the number of FFT points***.** To estimate the influence of the number of FFT points on the probabilities of correct recognition of chirp, SP, BPSK, and QPSK signals, depending on the SNR, $N_{\text{FFT}} = 512$; 1024; 2048 are selected. The required SNR at the algorithm input is generated by changing the corresponding value of the signal amplitude. BPSK and QPSK signals have 20 codes with phase shift laws $[0\ \pi\ \pi\ 0\ 0\ 0\ \pi\ \pi\ 0\ \pi\ \pi\ \pi\ 0\ 0\ \pi\ \pi\ 0\ \pi\ 0\ \pi]$ and $[0\ \pi\ \frac{\pi}{2}\ \frac{3\pi}{2}\ 0\ \frac{3\pi}{2}\ \frac{\pi}{2}\ 0\ 0\ \frac{\pi}{2}\ \pi\ \frac{3\pi}{2}\ 0\ \pi\ 0\ \pi\ 0\ \frac{3\pi}{2}\ \pi\ \frac{\pi}{2}]$, respectively. The threshold values of signal envelope dip detection at two intermediate frequencies are set by formula (2) based on the coefficient $k_{\text{av}} = 0.2$. The simulation result for 10^3 measurements with randomly selected signal parameters from the above ranges is shown in Fig. 4.

The following conclusions can be drawn based on the analysis of the results obtained:

1. For chirp signals, increasing N_{FFT} requires a higher value q_{thr}. This is due to the increase in the spectrum width of the processed chirp signals in the

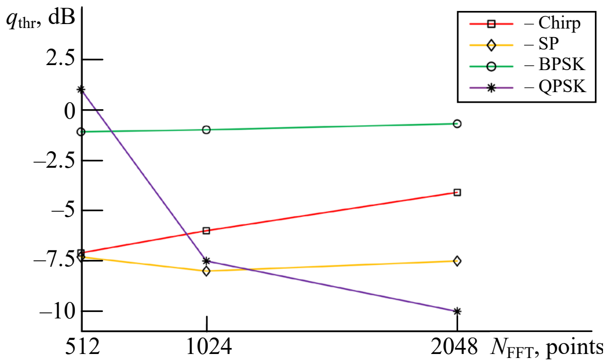

Fig. 4. Dependencies of the minimum SNR value providing the probability of correct recognition not less than 0.9 on the number of FFT points

Tab. 1. Threshold values of slope coefficient and variance for a different number of FFT points

Signal type	Threshold values					
	$N_{\text{FFT}} = 512$		$N_{\text{FFT}} = 1024$		$N_{\text{FFT}} = 2048$	
Chirp	$a > 0.75$	$\sigma^2 \le 1.0$	$a > 0.75$	$\sigma^2 \le 1.75$	$a > 0.75$	$\sigma^2 \le 3.0$
SP	$\lvert a \rvert \le 0.3$	$\sigma^2 \le 0.5$	$\lvert a \rvert \le 0.15$	$\sigma^2 \le 0.15$	$\lvert a \rvert \le 0.1$	$\sigma^2 \le 0.1$
BPSK	$\lvert a \rvert \le 0.45$	$\sigma^2 \le 0.9$	$\lvert a \rvert \le 0.25$	$\sigma^2 \le 0.3$	$\lvert a \rvert \le 0.15$	$\sigma^2 \le 0.2$
QPSK	$\lvert a \rvert \le 0.45$	$\sigma^2 \le 0.9$	$\lvert a \rvert \le 0.25$	$\sigma^2 \le 0.3$	$\lvert a \rvert \le 0.15$	$\sigma^2 \le 0.2$

processing window. For this reason, the error of determining the ACFV calculated by formula (1) at low SNR increases. As a result, to ensure the same accuracy in determining the ACFV when recognizing chirp signals, a higher SNR value is required.

2. For an SP signal, the value $N_{\text{FFT}} = 1024$ requires the lowest value q_{thr}. This is due to the contradiction between frequency resolution and duration of the processed signal at the fixed number of processing windows. Increasing the frequency resolution allows a more accurate determination of the average signal carrier frequency value. However, the probability of false signal envelope dip detection at the intermediate frequency under the influence of noise increases due to an increase in the duration of the processed signal. Thus, value $N_{\text{FFT}} = 1024$ represents a compromise between the considered contradiction for the SP signal.

3. For an BPSK signal, increasing N_{FFT} requires a higher value q_{thr}. This is due to the fact that the number of processing windows is fixed, and increasing N_{FFT} leads to a longer duration of the processed signal. As a result, the probability of false signal envelope dip detection at double intermediate frequency due to noise is increased.

4. For a QPSK signal, increasing N_{FFT} requires a lower value q_{thr}. This is due to the fact that, along with an increase in the processing window length, the energy of the signal falling into the processing window increases, and the signal is detected at a lower SNR. Therefore, signal envelope dips can be formed not only in phase shifts but also elsewhere due to the noise.

Thus, as N_{FFT} decreases, the value q_{thr} for recognizing the QPSK signal increases significantly (when N_{FFT} decreases from 2048 to 512 by about 11 dB). As N_{FFT} increases, the value q_{thr} increases for chirp signal recognition, while being not significantly different for SP and BPSK signals. Therefore, the value $N_{\text{FFT}} = 1024$ for the considered parameters of the signals and the algorithm is optimal in terms of the SNR value required to recognize each signal.

Influence of the weight window type. To estimate the influence of the weight window type on the probabilities of correct recognition of chirp, SP, BPSK, and QPSK signals depending on the SNR, the input signal is weighted at $N_{\text{FFT}} = 1024$ by the following windows: rectangular, Hamming, and Blackman. The simulation result for 10^3 measurements with randomly selected signal parameters from the above ranges is presented in Tab. 2.

Tab. 2. Dependencies of minimum SNR value providing the probability of correct recognition not less than 0.9 on the weight window types

Signal type	q_{thr}, dB		
	Rectangular	Hamming	Blackman
Chirp	–2.2	–6.0	–6.7
SP	–8.0	–8.0	–8.0
BPSK	–1.0	–1.0	–1.0
QPSK	–7.8	–7.5	–6.6

Following the analysis of the results obtained, the following conclusions can be drawn:

1. Compared to the rectangular and Hamming windows, the Blackman window allows recognition of chirp signals at a lower SNR. One can explain this by the decrease in amplitude at the beginning and end of the weight window, which reduces the spectrum width of the chirp signal falling into the processing window. As a result, the ACFVs under the influence of noise at low SNR are determined more accurately.

2. When weighting by rectangular, Hamming, and Blackman windows, the required SNR values for recognizing SP and BPSK signals differ insignificantly. This is because SP signal weighting by Hamming and Blackman windows changes only the main lobe width without shifting the spectrum central frequency. For a BPSK signal, a phase shift π between the codes leads to summation or subtraction of their spectrums. Therefore, the weight window does not significantly affect the accuracy of determining the ACFV.

3. Compared to the rectangular window, Hamming and Blackman window weighting requires a higher SNR value to recognize the QPSK signal. This is because the decrease in amplitude at the beginning and end of the weight window at phase shifts on π and $\pi/2$ leads to a decrease in the accuracy of determining the ACFV.

Thus, when processing a chirp signal, the Hamming window requires a significantly lower SNR than the rectangular window. When processing a QPSK signal, this window requires a lower SNR compared to the Blackman window. In other cases, the Hamming window is comparable to other windows. Therefore, it is reasonable to apply the Hamming window for the developed algorithm.

Influence of threshold values of signal envelope dip detection. To estimate the influence of threshold values of signal envelope dip detection at two intermediate frequencies determined by (2) on the probabilities of correct recognition of SP, BPSK, and QPSK signals depending on the SNR, $k_{av} = 0.05\ldots0.45$ in increments of 0.05 at $N_{FFT} = 1024$ is selected. At $k_{av} < 0.05$, the value q_{thr} for PSK signals reaches unacceptably high values. At $k_{av} > 0.45$, there is a high probability of QPSK signal envelope dip detection at two intermediate frequencies under the influence of noise. At the SNR value of 10 dB and $k_{av} = 0.5$, the probabilities of correct and false detection of signal envelope dips at the intermediate frequency are 1 and $3 \cdot 10^{-4}$, respectively, equaling 1 and 0.1406 at the double intermediate frequency. The simulation result for 10^3 measurements with randomly selected signal parameters from the above ranges is shown in Fig. 5.

From the analysis of the obtained results, we can draw the following conclusions:

1. For an SP signal, an increase in the k_{av} coefficient leads to an increase in the q_{thr} value. The reason is that an increase in the coefficient k_{av} leads to a higher probability of signal envelope dip detection at the intermediate frequency due to the influence of noise.

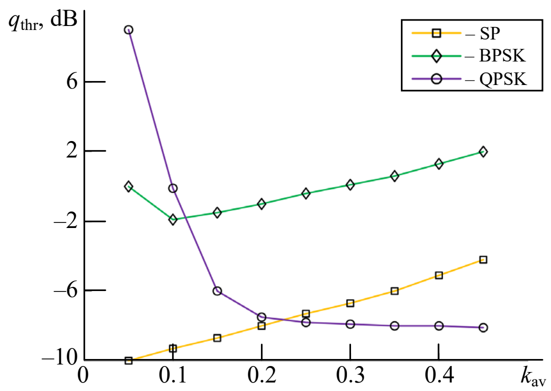

Fig. 5. Dependencies of the minimum SNR value providing the probability of correct recognition not less than 0.9 on the signal envelope amplitude averaging coefficient

2. For a BPSK signal, the coefficient $k_{av} = 0.1$ requires the lowest q_{thr}. When the k_{av} coefficient increases from 0.05 to 0.1, the value q_{thr} decreases and increases at $k_{av} > 0.1$. This is explained by the fact that the presence of envelope dips at an intermediate frequency and the absence of envelope dips at the double intermediate frequency are used to recognize a BPSK signal. As a result, an increase in the k_{av} coefficient from 0.1 to 0.45 increases the probability of signal envelope dip detection at both intermediate and double intermediate frequencies.

3. For a QPSK signal, the q_{thr} value decreases along with an increase in the k_{av} coefficient. This is due to the fact that an increase in the k_{av} coefficient increases the probability of signal envelope dip detection at the two intermediate frequencies. It can also be observed from the graph that at $k_{av} > 0.25$, the value q_{thr} takes a value approximating –8.0 dB. This is because the envelopes are distorted due to the effects of noise at low SNR values. As a result, signal envelope dips can be formed not only in phase alternations but also elsewhere due to noise.

Thus, to provide a compromise between the values of recognition sensitivity of all three signal types, it is reasonable to select the coefficient $k_{av} = 0.15\ldots0.25$.

Influence of bandwidths of bandpass filters used in the algorithm. To estimate the influence of bandwidths of bandpass filters used in the algorithm on the probabilities of correct recognition of SP, BPSK, and QPSK signals P_{CR} depending on the SNR, $\Delta f_{BPF1} = \Delta f_{BPF2} = 2;\ 4;\ 6$ MHz at $N_{FFT} = 1024$ are selected. The following parameters of initial signals are set: duration of SP signal – 5 µs; code duration of BPSK and QPSK signals – 0.5 µs; phase shift law of BPSK and QPSK signals – 13-bit Barker's code and 16-bit Frank's code, respectively. The threshold values of signal envelope dip detection at two intermediate frequencies are set by formula (2) based on the coefficient $k_{av} = 0.2$. We randomly selected the remaining parameters from the ranges given above. The simulation results (10^3 measurements for each SNR value) are presented in Figs. 6–8.

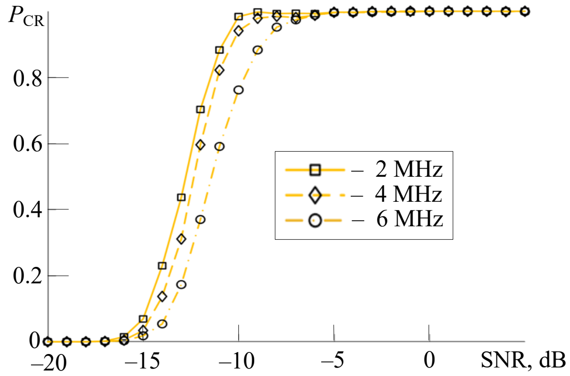

Fig. 6. Dependencies of the probability of correct recognition of SP signal on the SNR for different bandwidths of BPF1 and BPF2

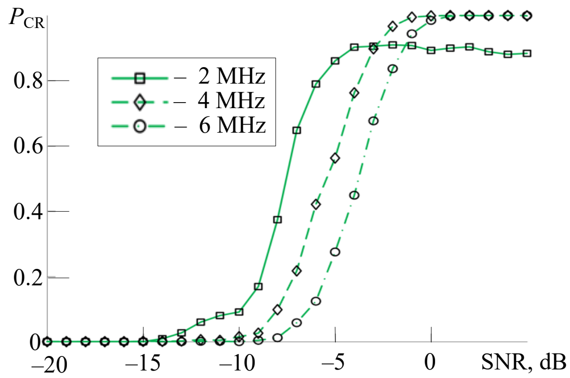

Fig. 7. Dependencies of the of the probability of correct recognition of BPSK signal on the SNR for different bandwidths of BPF1 and BPF2

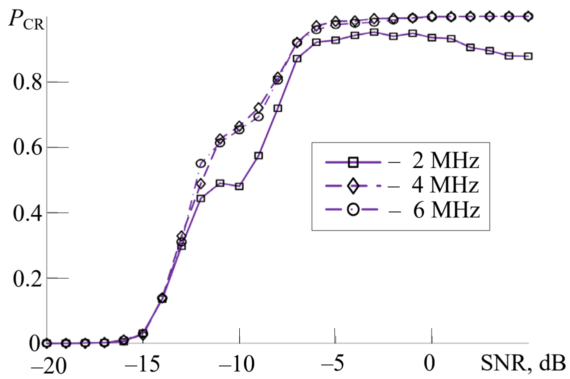

Fig. 8. Dependencies of the of the probability of correct recognition of QPSK signal on the SNR for different bandwidths of BPF1 and BPF2

From the analysis of the obtained results, we can draw the following conclusions:

1. For all signal types, the q_{thr} value increases with increasing filter bandwidths Δf_{BPF1} and Δf_{BPF2}. The reason is that an increase in the BPF1 and BPF2 bandwidths increases noise at the ED1 and ED2 outputs. Therefore, a higher SNR value is required to obtain acceptable signal envelopes at the detector outputs.

2. At filter bandwidths Δf_{BPF1} and Δf_{BPF2} equal to the spectrum width of BPSK and QPSK signals (2 MHz), the probability of correct recognition does not reach unity even at an SNR value of 5 dB. This is because the FFT-based carrier frequency determination error leads to a shift in the intermediate frequency of the signals after the frequency converter from the central frequency of BPF1. In addition, doubling the frequency results in a doubling of the specified error at the double intermediate frequency. Therefore, the filters do not allow enough frequency components to pass through, which creates envelope dips at the intermediate and double intermediate frequencies. Accordingly, the signal envelope shape is distorted.

Thus, at the given parameters of the investigated signals for $P_{CR} \ge 0.9$, the bandwidths of BPF1 and BPF2 in the developed algorithm should be not less than the sum of the double FFT frequency resolution and the maximum spectrum width of the recognized signals. In this case, the FFT frequency resolution is 0.98 MHz, the spectrum width of SP, BPSK, and QPSK signals are 0.2, 2 and 2 MHz, respectively. Hence, it is reasonable to select $\Delta f_{BPF1} = \Delta f_{BPF2} = 4$ MHz.

Conclusion. For the developed algorithm to recognize down-chirp, up-chirp, SP, BPSK, and QPSK signals, the influence of the algorithm parameters on the input SNR value required to provide the probability of correct signal recognition $P_{CR} \ge 0.9$ was investigated. As a result, we show that the required input SNR is minimal for all signals at the following parameters of the algorithm: number of FFT points $N_{FFT} = 1024$; weight window – Hamming; signal envelope amplitude averaging coefficient $k_{av} = 0.15 \ldots 0.25$; bandwidths of bandpass filters $\Delta f_{BPF1} = \Delta f_{BPF2} = 4$ MHz.

Author's contribution

Tran Huu Nghi, computer modeling; processing of modelling results; paper editing; formulating conclusions.
Aleksey S. Podstrigaev, supervision of scientific work; setting tasks; paper editing; formulating conclusions.
Nguyen Trong Nhan, literature analysis; paper editing.

Danil A. Ikonenko, literature analysis; paper editing.

All authors participated in the discussion of the results and in the preparation of the paper.

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