Phased-locked signal detection system based on parallel optimal receivers by average risk criterion

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Abstract. This paper is devoted to the investigation of a developed sync system which is based on optimal receiver by average risk minimum criterion when detecting the reflected radar impulse under conditions of Gaussian and Johnson noises. M-sequence with single pulse phase-shift keying has been chosen as a reference signal. A transceiver has been implemented during the digital experiment. The use of developed self-tuning system allows applying the optimal methods of reflected radar signal detection when it is noncoherently received under conditions of Gaussian and non-Gaussian noises. It has been proved that the developed sync system has the signal detection quality advantage over the system based on matched filter.

1. Introduction
The development of radar signal detection systems, which allow defining the object at the long distance, is still a problem today [1]. Existing detection systems are generally based on the methods of correlation analysis and matched filtering with preliminary adaptive or nonlinear filtering [2]. The use of optimal reception methods requires the huge amount of a priori data on signal and noise. For example, the use of phase-shift keying (PSK) implies that receiver knows the single pulse duration, signal amplitudes, as well as the arrival time and initial phase of the first pulse [3]. This is impossible because of a priori uncertainty about a target range (the time of propagation in space) and the signal distortions under the conditions of different interferences. Therefore, the necessity arises to develop the sync system locking the first pulse initial phase.

For this purpose in the present work we suggest using maximal value of cross-correlation function (CCF) between the reference signal and the signal from the optimal receiver output. We considered a discrete random process with Johnson distribution as the noise since a variation of its parameters allows generating a sufficiently large class of distributions close to the distribution of real noise [4]. Moreover, the choice of Johnson distribution is convenient because these processes can be generated by inertialless nonlinear transformations of normal random processes, in particular discrete.

2. Synthesis of Optimal Algorithm
The task of forming the optimal reception algorithm for reflected radar signal in the sum with non-Gaussian noise is solved based on the following key assumptions [5]:

1. The signal \( y(t) \) is M-sequence with PSK, whose parameters (amplitude, duration, repetition period, the carrier frequency) are known except the message \( \lambda(t) \).
2. The noise is a discrete sequence coinciding in time with the signal samples and having the Gaussian or Johnson distribution. The noise intensity is so high, that the signal to noise ratio (SNR) is much less than unity. Thus, the signal accumulation is used for reliable information extraction.

3. The criterion of the average risk minimum is used as an optimality criterion for a simple loss function. Therefore, the algorithm of a posteriori probability density maximum in the form of likelihood ratio can be used as an optimum decision rule. In this criterion the optimal reception provides the minimum of total error probability.

During the present work we considered the optimal signal receiver under the conditions of additive non-Gaussian noise when SNR is quite small. In this case the noise is a random process described as an inertialless transform \( q(z_i) \) of Markov Gaussian process \( z_i \) with variance \( \sigma_i^2 \). The input process \( y(t) \) is assumed to be observed at discrete moments of time \( t_i : \)

\[
y_i = \begin{cases} 
  s_i + q(z_i), & \text{if } \Theta = 1, \\
  q(z_i), & \text{if } \Theta = 0, 
\end{cases} \quad i = 1, 2, ..., m.
\]

Parameter \( \Theta \) characterizes the presence \( (\Theta = 1) \) or absence \( (\Theta = 0) \) of the signal \( s_i \) in observed data. In turn the useful signal \( s_i \) is a harmonic signal with two states of phase differed by \( \pi \) depending on parameter \( \Omega \), which means the positive \( (\Omega = 1) \) or negative \( (\Omega = 0) \) pulse of M-sequence.

It is supposed the function \( q \) is known, and it has such unique inverse function \( q^{-1} = Q \), that

\[
z_i = \begin{cases} 
  Q(y_i - a_i \sin(\omega t)), & \text{if } \Theta = 1, \text{ and } \Omega = 1, \\
  Q(y_i - a_i \sin(\omega t + \pi)), & \text{if } \Theta = 1, \text{ and } \Omega = 0, \\
  Q(y_i), & \text{if } \Theta = 0.
\end{cases}
\]

where \( a_i \) is an amplitude of every single pulse; \( \omega \) is a cyclic frequency of radio pulse filling. Then initial \( w_0(z) \) and conditional \( w(z_{i+1} | z_i) \) probability densities are defined as follows [6]:

\[
w_0(z) = \frac{1}{\sigma_z \sqrt{2\pi}} \exp \left\{ -\frac{Q^2(y_0)}{2\sigma_z^2} \right\} |Q'(y_0)|,
\]

\[
w(z_{i+1} | z_i) = \frac{|Q'(y_{i+1})|}{\sigma_z \sqrt{2\pi(1 - R^2)}} \exp \left\{ -\frac{[Q(y_{i+1}) - Q(y_i)R]^2}{2\sigma_z^2(1 - R^2)} \right\},
\]

where \( R \) is a correlation coefficient. The optimal receiver is built by modelling the likelihood ratio [7]. Since the signal contains two types of useful message, it is necessary to implement two optimal algorithms for \( \Omega = 1 \) and \( \Omega = 0 \). So the overall likelihood equation looks as follows

\[
\Lambda_m = \frac{w_0(z_0, \Theta = 1) \prod_{i=1}^{m} w(z_{i+1}, \Theta = 1 | z_i, \Theta = 1)}{w_0(z_0, \Theta = 0) \prod_{i=1}^{m} w(z_{i+1}, \Theta = 0 | z_i, \Theta = 0)}.
\]

Equation (1) fully defines the receiver scheme presented in figure 1. The signals from the adder output go to the total adder and then to the solver whose answer is "signal_1" or "signal_2" depending on whether incoming message crosses threshold \( l_{m1} \) or \( l_{m2} \) respectively, and 0 otherwise.

3. Synchronization Algorithm Synthesis

An implementation of the optimal receiving algorithm is only possible with the precise \( a \ priori \) data on the first pulse arrival. Therefore, it is proposed to use the parallel processing of the received signal
and its copies shifted in time by the sample from each other in the range of half number of samples per pulse. From the simple processor output the restored sequence goes to the correlator calculating the maximal value of CCF between the reference and restored signals (figure 2). Then, the correlator and appropriate processing channel with the largest possible CCF are defined. The clock shift at the chosen channel guarantees the best quality of restoration and synchronization.

![Figure 1. The optimal receiver block diagram.](image1)

**Figure 1.** The optimal receiver block diagram.

**4. Digital Implementation of Sync System**

The developed algorithms of optimal reception and sync system have been implemented in LabView software set up on the National Instruments platform PXI 1075. Figure 3 shows the maximal values of different CCFs when parallel processing the reference signal and 12 signal copies shifted in time by sample from the previous one. CCF is maximal when the initial phases of the reference and received signals coincide. The optimal processing algorithm is launched at this moment and performs the best.

![Figure 2. Block diagram of sync system.](image2)

**Figure 2.** Block diagram of sync system.

**Figure 3.** The determination of the largest possible CCF between the reference signal and received signal with the time shift.

Figure 4 shows the signal and noise mixture at the receiver input, and the signal from the phase-locked output. In order to estimate the restoration quality we have obtained the dependencies of the normalized CCF (NCCF) vs. SNR for the developed system and compared them with matched filter under white Gaussian noise (WGN) and different types ($S_B$, $S_L$ and $S_U$) of Johnson noise (figure 5).

![Figure 4 showing signal and noise mixture.](image4)

**5. Conclusion**

The optimal restoration algorithm for radar signal, represented as M-sequence with PSK, has been developed for operation under conditions of Gaussian and non-Gaussian noise. The implementation of suggested algorithm requires the use of precious *a priori* data on received signal initial phase. Thus, the self-tuning system, which is based on the parallel processing of several signal copies shifted in time, has also been designed.

The use of optimal algorithm leads to the gain in signal restoration by 10 dB for WGN and 2 dB for $S_L$ and $S_U$ Johnson noise in comparison with the use of matched filters. The worst masking effect
belongs to $S_B$ Johnson noise. At the same time the use of optimal algorithm in this case does not lead to the significant gain in signal restoration.

![Figure 4](image)

**Figure 4.** The result of developed system operation: (a) mixture of signal and WGN mixture at the input; (b) restored signal. SNR = 5 dB.

![Figure 5](image)

**Figure 5.** The dependencies of NCCF vs. SNR at the output of matched filter (MF) and optimal receiver (OR) for (a) WGN and $S_B$ Johnson noise; (b) $S_L$ and $S_U$ Johnson noise.

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