Increasing the Multi-position Signals Noise Immunity of Mobile Communication Systems based on High-order Phase Modulation

Mykhailo Klymash[1], Liubov Berkman[2], Serhiy Otrokh[3], Volodymyr Pilinsky[3], Oleksandr Chumak[4], and Olena Hryshchenko[2]

[1]*Lviv Polytechnic National University, Ukraine*
[2]*State University of Telecommunications, Kyiv, Ukraine*
[3]*National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine*
[4]*Military Diplomatic Academy named after Yevheniy Bereznyak*

Abstract

The article presents the results of a study of situations typical for 4G (Long Term Evolution - LTE) mobile communication systems, in which there are conditions for the use of the autocorrelation method for processing multi-position signals, and the noise immunity of demodulators that implement this method is determined. It has been proved using the theory of catastrophes that for modern mobile communication systems it is advisable to use energy methods with high-order phase-difference modulation (PDM), which will provide the system with the property of invariance to a certain class of electromagnetic interference (EMI). A comparative analysis of the application of systems with PDM of the first and second order has been carried out and it has been determined that in the case of autocorrelation reception of signals from PDM-1, it is necessary to ensure sufficiently stringent requirements for the stability of the frequency of the carrier wave. It was found that in the case of using PDM-1, the autocorrelation technique is much simpler, but the PDM-2 has a unique property of invariance to the frequency of the carrier wave, which neither coherent nor optimal incoherent methods have. An energy (autocorrelation) demodulator of signals with double PDM-1 is proposed, which has the property of relative or absolute invariance to changes in the frequency of the carrier wave, which can occur in digital information transmission systems during communication with rapidly moving objects. satellite communication systems, as well as fiber-optic communication systems, mobile broadband access with support for the fourth generation technology.

Keywords

Phase-difference Modulation, Autocorrelation Method, Multi-position Signals

1. Introduction

At present, in the case of using information transmission rates close to the capacity of communication channels, when calculating the noise immunity of a system, it is necessary to take into account not only white Gaussian noise, but also multiplicative noise distributed in the spectrum and time.

In this case, the use of correlation reception methods is not effective, since the possible variants of the sent signal are not known, but only their energies. Therefore, in this case, it is advisable to use energy methods of receiving signals.

A large number of optimal algorithms have been created in the theory of signal reception and processing. The best algorithm (according to the fundamental position of the theory of systems) under

XXI International Scientific and Practical Conference "Information Technologies and Security" (ITS-2021), December 9, 2021, Kyiv, Ukraine
EMAIL: klymash@journal.kh.ua (M. Klymash); berkmanlubov@gmail.com (L Berkman); 2411197@ukr.net (S. Otrokh); pww@ukr.net (V. Pilinsky); a_ch_i@ukr.net (O. Chumak); lgrischenko88@ukr,net (O. Hryshchenko)
ORCID: 0000-0002-1166-4182 (M. Klymash); 0000-0002-6772-1596 (L. Berkman); 0000-0001-9008-0902 (S. Otrokh); 0000-0002-2569-9503 (V. Pilinsky); 0000-0003-3876-8149 (O. Chumak); 0000-0001-8198-5056 (O. Hryshchenko)

certain reception conditions can be considered an algorithm that meets the criteria of some optimality depending on the established restrictions due to the characteristics of the channel and signal and the peculiarities of the communication system as a whole according to certain specified criteria [1].

The most adequate classification of conditions under which one or another optimal algorithm can be synthesized is based on what information about the signal is known before it arrives, that is, according to the degree of a priori uncertainty of the situation. There is a wide range of intermediate situations between a signal with a known initial phase and a signal with a completely unknown initial phase

The hierarchy of optimal algorithms is opened by coherent reception, which is optimal under conditions when the possible realizations of the transmitted signal are fully known. Optimal incoherent reception is optimal for signals with an unknown but uniformly distributed initial phase. If we go further by reducing the a priori information about the sent signal, we can to synthesize other reception methods that can be applied under appropriate conditions. In this case, the less we have a priori information about the parameters of the signal during its processing, the less noise immunity. Completing the hierarchy of good methods for receiving signals are methods using methods for processing multi-position signals [2] of unknown shape. These include algorithms for autocorrelation processing of phase-modulated signals. The essence and conditions of application of autocorrelation signal processing are given below.

2. Algorithms for autocorrelation processing of phase modulated signals

Let us consider two versions of the transmitted signal S_1(t) or S_2(t) (signals of unknown shape) and the known interval of their existence (0, τ). These signals can be presented as a sum of orthogonal transformation functions with bases $\{\varphi_i\}$ and $\{\psi_i\}$:

$$S_1(t) = \sum_{i=1}^{2\beta} a_i\,\varphi_i(t), \qquad S_2(t) = \sum_{i=1}^{2\beta} \beta_i \psi_i(t),$$

where 2β is the base of expected signals;

$$a_i = \int_0^{\tau} S_1(t)\,\varphi_i(t)dt;\ \beta_i = \int_0^{\tau} S_2\,(t)\psi_i(t)dt.$$

The signals S_1(t) and S_2(t) are called signals of unknown shape if there is no information about the coefficients a_i and β_i. Provided that the basis functions φ_i and ψ_i are known, the system of functions $\{\varphi_i\}$ defines the space of possible signal shapes $S_1(t)$, and the system of functions $\{\psi_i\}$ defines the space of possible signal shapes $S_2(t)$. We can assume that in this case the spaces of the expected signals are known, determined by the corresponding set of basis functions and the time interval of their existence.

If the distributions of the coefficients ai and β_i are known, then a simple maximum likelihood rule can be used to synthesize the optimal algorithm for receiving signals $S_1(t)$ and $S_2(t)$; if the distributions a_i and β_i are unknown, then the general maximum likelihood rule should be applied, according to which, out of two possible hypotheses $S_1(t)$ or $S_2(t)$, one should choose the one for which the maximum of the likelihood function will acquire a greater value.

For signals with the same energy, when it is known that

$$\sum_{i=1}^{2\beta} a_i^2 = \sum_{i=1}^{2\beta} \beta_i^2.$$

Signal $S_1(t)$ should be considered as transmitted if

$$\sum_{i=1}^{2\beta}\left[\int_0^{\tau} x(t)\varphi_i\,(t)dt\right]^2 > \sum_{i=1}^{2\beta}\left[\int_0^{\tau} x(t)\psi_i\,(t)dt\right]^2,$$

where i is a signal $S_2(t)$ when the inequality is opposite.

The mathematical expressions in square brackets of inequality (4) are the coefficients of the orthogonal transformation of the received signal according to the basis functions φ_i and ψ_i, and the sums of the squares of these coefficients (the left and right sides of (4) are equal to the energy of the received signal in the spaces functions $\{\varphi_i\}$ and $\{\psi_i\}$ respectively. Based on the remarks made, inequality (4) can be written as:

$$\int_0^\tau x_1^2(t)\,dt > \int_0^\tau x_2^2(t)\,dt,$$

where $x_1(t)$ and $x_2(t)$ is the estimate of the membership of the received signal in the $\{\varphi_i\}$ and in the space $\{\psi_i\}$.

Based on inequality (5), the following algorithm for estimating the signal arriving at the receiver is proposed. First, you need to calculate the energy of the received signal, in the spaces of the first and second possible signal realization, and assume that a signal has arrived, in the space of which the calculated energy is greater. In this regard, acceptance algorithms based on the application of criteria (4) and (5) are called energy or autocorrelation. The last name of the algorithm follows from the fact that in the case of its application in the receiver, it is necessary to calculate the convolution of the received signal with its time-delayed copy with a different delay time or, otherwise, with a different time offset (in (5) this offset is equal to zero). These algorithms can be applied to signals with different types of signal modulation. To obtain the corresponding separate algorithm, one should apply the basis functions corresponding to the applied type of modulation [3] to calculate inequality (4).

The considered algorithms can be effective not only in the case of an unknown waveform, but also in the case of variable waveform signals. However, algorithms can only be used for signals whose changes occur within a certain space of signal implementations. With phase difference modulation (PDM-1), this means that the signals must be repeated with sign accuracy over an interval of two bursts. This, in particular, implies rather stringent requirements for the stability of the frequency of the carrier wave when using the autocorrelation method for receiving PDM-1 signals.

Autocorrelation demodulators of signals with PDM-1 attract attention with their extreme simplicity, since their implementation does not require either coherent reference waves extractor devices as in coherent demodulators, or correlators with quadrature reference waves, as in optimal incoherent demodulators [4]. But it should be borne in mind that potentially autocorrelation demodulators are inferior in noise immunity to coherent and optimal incoherent. In contrast, the noise immunity of autocorrelation (energy) demodulators depends not only on the ratio h2 of the signal energy to the spectral power density of the noise, but also on the base of the received signal-to-noise mixture, which, in turn, depends on the bandwidth F of the receiver input filter. The larger the base 2FT, the lower the noise immunity at the same valueh2. The more complex the signal, the greater its dimension and the more other identical conditions are the probability of error. These are the features of the autocorrelation method of receiving. At the same time, in the case of receiving narrow-band signals with a base of $B \approx 2$, autocorrelation demodulators are slightly inferior to the optimal incoherent ones with respect to noise immunity. When comparatively assessing the noise immunity of coherent and maximum incoherent demodulators, on the one hand, and autocorrelation ones, on the other, it should be taken into account that the former have an advantage only when the conditions for their optimality and performance are met. If these conditions are not met and it is necessary to provide a priori reception of a signal of unknown shape, then the autocorrelation demodulator can provide a lower probability of error. Therefore, we can conclude that the autocorrelation technique (as a method arising from the generalized maximum likelihood rule) provides a minimum error probability under the condition of uniformly distributed unknown parameters (conversion coefficients of a signal of an unknown shape).

Algorithms for autocorrelation processing of signals with PDM-1 directly follow from the general maximum likelihood rule and, in this sense, are optimal for signals of unknown shape. The functional diagram of the energy demodulator can be proposed based on a similar optimal signal processing algorithm with PDM-2. As in the case of optimal incoherent reception, signal energy demodulator with PDM-2 is superior in noise immunity to the equivalent autocorrelation demodulator with PDM-1. At the same time, the noise immunity of these types of demodulators depends on the stability of the frequency of carrier oscillation. At the same time, there is no such dependence in the PDM-2 autocorrelation demodulator.

If in the case of PDM-1 the autocorrelation technique is attractive mainly for its simplicity, then in the case of PDM-2 the autocorrelation technique, which in this case is one of the submaximal modifications of the algorithm for receiving the corresponding signals of an unknown shape, has a unique property of invariance to the frequency of carrier waves. This property is absent in the method of coherent and maximally incoherent reception. Therefore, autocorrelation algorithms for receiving signals from PDM-2 are important in mobile networks. It is advisable to use them in channels with an undefined signal frequency [5].

Consider the factors influencing the conditions typical for channels with an undefined frequency. Such conditions arise due to the instability of the frequency of the master oscillators. In all links of the communication system, an indefinite frequency of carrier oscillations occurs at the beginning of any communication session, during the entire reception interval during short-term communication sessions, in the case of information transmission in a pulsed or burst mode, especially if packets are formed by different transmitters or in different communication lines, and also in all other cases when the signal history is either absent or very short-lived before the start of processing. Uncertainty in the signal frequency, in addition, is a consequence of the Doppler effect, which occurs during communication with fast moving objects or in the case of relaying signals through a mobile repeater. When a communication object moves, unexpected changes in the frequency of the carrier waves can occur, which are difficult to compensate for in a short time using automatic frequency control devices. In some cases, frequency self-tuning is also impossible to implement in continuous data transmission systems, if the latter operate using channels with variable parameters.

Thus, when transmitting digital information by different communication channels, conditions arise under which the receiver must process a signal with an unknown or inaccurately known frequency of the carrier wave - channels with an undefined signal frequency. For such channels and conditions, when using signals from the second-order PDM, it is better to use the autocorrelation method of reception.

Autocorrelation modems with PDM-2 are characterized by the property of relative or absolute invariance to changes in the indefinite frequency of carrier oscillations. They are used in digital information transmission systems in communication systems with fast moving objects, in satellite communication systems, as well as in fiber-optic communication systems, mobile broadband access with support for LTE technology [6].

Let us consider the class of optimal autocorrelation (energy) demodulators of signals from the first order PRM.

Let us use the evaluation criterion (5) to synthesize the corresponding algorithm for receiving signals from the PDM-1. In this case, the variants of the signal of an unknown shape on the interval of two parcels can be described by the relations:

$$\left.\begin{aligned} S_1(t) &= \begin{cases} f(t), & 0 < t < T, \\ f(t-T), & T < t < 2T; \end{cases} \\ S_2(t) &= \begin{cases} f(t), & 0 < t < T, \\ -f(t-T), & T < t < 2T; \end{cases} \end{aligned}\right\}$$

where *f(t)* is an unknown function. To analyze the signals $S_1(t)$ and $S_2(t)$, select the following basic functions:

$$\left.\begin{aligned} &\text{for } S_1(t) \\ &\varphi_i(t) = (1/T)\sin i\omega_0 t, \quad 0 < t < T, \\ &\varphi_i^*(t) = (1/T)\cos i\omega_0 t, \quad T < t < 2T; \\ &\text{для } S_2(t) \\ &\psi_i(t) = \begin{cases} (1/T)\sin i\omega_0 t, & 0 < t < T, \\ (-1/T)\sin i\omega_0 t, & T < t < 2T, \end{cases} \\ &\psi_i^*(t) = \begin{cases} (1/T)\cos i\omega_0 t, & 0 < t < T, \\ (-1/T)\cos i\omega_0 t, & T < t < 2T, \end{cases} \end{aligned}\right\}$$

where $\omega_0 = 2\pi/T$.

Basis functions (7) define two spaces corresponding to two variants of the transmitted signal, one of which has a phase jump of all frequency components by 180 °, and the other has no phase jump. These two spaces do not overlap.

In addition to the indicated distribution of the transmitted PDM signals into two non-intersecting spaces, another distribution can be proposed, in which these spaces have different frequency components. Since the signal $S_1(t)$ on the interval *(T, 2T)* is the same as on the interval *(0, T)*, then paired harmonics π/T will be present in the decomposition of the signal into harmonic components, and in a similar decomposition of the signal $S_2(t)$, which repeats the signal on the interval with the opposite sign, there will be all odd harmonics [7].

Thus, in the case of using the PDM, the basis of the subspace of the signal *$S_1(t)$* is made up of even frequency harmonics, and the basis of the subspace of the signal *$S_2(t)$* is odd:

$$\left.\begin{aligned} S_1(t) &= \sum_{i=1}^{\beta} a_{2i}\, sin\, 2i\frac{\pi}{T}t + b_{2i}\, cos\, 2i\frac{\pi}{T}t; \\ S_2(t) &= \sum_{i=1}^{\beta} a_{2i-1}\, sin(2i-1)\frac{\pi}{T}t + b_{2i-1}\, cos(2i-1)\frac{\pi}{T}t. \end{aligned}\right\}$$

Let us determine the optimal criterion for receiving signals of an unknown shape with a PDM. For this, we rewrite general criterion (4) as follows:

$$\sum_{i=1}^{\beta}\left\{\left[\int_0^{2T} x(t)\varphi_i(t)dt\right]^2 + \left[\int_0^{2T} x(t){\varphi^*}_i(t)dt\right]^2\right\} >$$
$$> \sum_{i=1}^{\beta}\left\{\left[\int_0^{2T} x(t)\psi_i(t)dt\right]^2 + \left[\int_0^{2T} x(t){\psi^*}_i(t)dt\right]^2\right\}$$

Compared to (4) in relation (9), the integration interval is twice as large, since in the case of using PRM, each information symbol is determined by two signaling messages. Substituting (7) into (9), we get:

$$\sum_{i=1}^{B}\left\{\left[\int_0^{T} x(t) sini\omega_0\, tdt + \int_T^{2T} x(t) sini\omega_0 tdt\right]^2 +\right.$$
$$\left.+\left[\int_0^{T} x(t) cosi\omega_0 tdt + \int_T^{2T} x(t) cosi\omega_0 tdt\right]^2\right\} >$$
$$> \sum_{i=1}^{B}\left\{\left[\int_0^{T} x(t) sini\omega_0\, tdt - \int_T^{2T} x(t) sini\omega_0 tdt\right]^2 +\right.$$
$$\left.+\left[\int_0^{T} x(t) cosi\omega_0 tdt - \int_T^{2T} x(t) cosi\omega_0 tdt\right]^2\right\}$$

After bringing the right and left sides of expression (10) to the square and reduction of similar terms, we get:

$$J = sgn \sum_{i=1}^{\beta}\left[\int_0^T x(t) sin\, i\omega_0 tdt \int_T^{2T} x(t)\, sini\omega_0 tdt + + \int_0^T x(t) cos\, i\omega_0 tdt \int_T^{2T} x(t)\, cosi\omega_0 tdt\right].$$

From the obtained result, it follows that the sum of the products of the input signal transformation coefficients at two intervals is proportional to the scalar product of signals on two adjacent sending, that is, (11) can be written as:

$$J = sgn \int_0^T x(t)x(t-T)dt,$$

which coincides with the algorithm for autocorrelation reception of signals with a single PDM. Thus, the use of an optimal algorithm for receiving signals of an unknown shape, which implements the general maximum likelihood rule, when using PDM-1 determines the structure of the autocorrelation signal processing circuit shown in Fig. 1

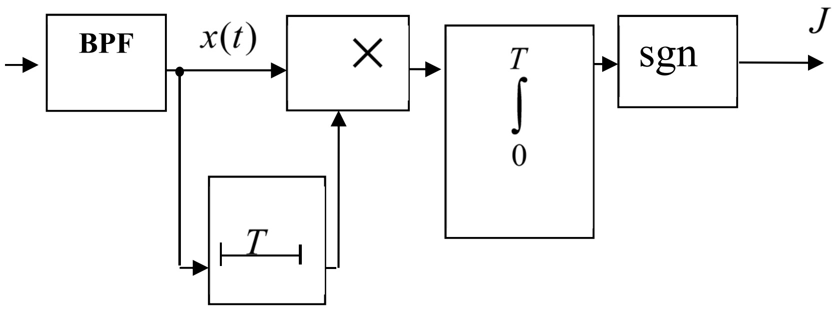

Figure 1: Functional diagram of an optimal autocorrelation demodulator of signals with a single PDM

The input signal goes to a bandpass filter (BPF), which is designed in the autocorrelation demodulator to perform two functions:

firstly, for the usual frequency selection function of the useful signal. Such selection is necessary in cases where the demodulator input arrives at the baseband signal of the transmission system with FDC (frequency distribution of channels) and in other cases. To implement the same function, a similar input bandpass filter is used at the input of coherent and good incoherent demodulators;

secondly, the input bandpass filter provides a limitation of the spectrum (and, consequently, the power) of the fluctuation noise entering the demodulator input, since in the case of using the autocorrelation method of signal reception, in contrast to the correlation methods - coherent and optimal incoherent, the noise immunity depends on the width frequency bands (and, as a consequence, - power) of noise, and not only from its spectral density [8].

At first glance, it may seem that the signal autocorrelation processing algorithm based on relation (12) does not provide for band pass filtering of the signal. However, if we turn to relation (9), from which equation (12) is obtained, then we can conclude that β harmonic components should be applied for an equivalent signal x(t)representation. Therefore, the input signal is limited to the frequency band F=β/T.

Practically the bandwidth of the filter in the circuit in Fig. 1 to receive signals from the PDM should be chosen as a compromise: on the one hand, this bandwidth should be as narrow as possible to reduce the effect of noise, and on the other hand, wide enough so that linear signal distortions and the so-called inter symbol interference do not significantly reduce the noise immunity. In autocorrelation demodulators of narrowband PM signals, the base FT values are usually selected in the range from one to two, and most often, input filters with an $F \approx 1{,}5\ T$. bandwidth are used. Regarding the effect of intersymbol interference on the noise immunity, it should be noted that not only the bandwidth of the input filter of the demodulator is important, but also the entire end-to-end frequency response [9].

A fundamentally important element of the PDM-1signals autocorrelation demodulator is a memory element or a signal delay line for the duration of a message T. Rather stringent requirements are imposed on the delay duration. In systems with autocorrelation reception of first-order PDM signals, the relationship between the frequency of the carrier wave and the duration of the message cannot be arbitrary. On an interval of duration T, an integer number of periods of the carrier frequency oscillation must fitω, that is $\omega T = 2\pi k$, where k is an integer. Only in this case, the signal shape will be the same on two adjacent transmission intervals, which is a necessary condition for the optimality of the algorithm for receiving PDM-1 signals of an unknown shape. Deviations from the ratio $\omega T = 2\pi k$, are caused by the instability of the frequency ωor delay T, lead to a decrease in noise immunity, and in the case of significant deviations, to the loss of the demodulator's performance. Frequency $\Delta\omega$and delay ΔT acceptable deviationscan be determined from the ratio

$$\Delta\varphi_{acc} = \Delta\omega T + \omega\Delta T + \Delta\omega\Delta T,$$

where $\Delta\varphi_{ac}$ cis the permissible parasitic phase shift between the carrier oscillation softhead jacent elements of the PDM-1 signal.

To maintain a sufficiently high noise immunity value $\Delta\varphi_{acc}$ should not exceed the fraction (5.10)% of the minimal lowed phase jump, which is π in the case of a single PDM, is $\pi/2$ in the case of a double, is $\pi/4$ in the case of a three fold, etc. It should be noted that, as follows from (13), the frequency and delay deviations can compensate each other if they have different signs. This, in particular, is the basis for the methods of adaptive correction of instability with fixing the nominal value of one of these parameters, for example, determine $\Delta\varphi_{acc}$ under the condition ΔT or $\Delta\varphi_{acc}$ under the condition $\Delta\omega$. While maintaining the exact frequency of the carrier vibration ($\Delta\omega$), the permissible instability of the delay duration ΔT_{acc} is determined from the relation:

$$\Delta T_{доп} = \Delta\varphi_{доп}/\omega.$$

It follows from the corresponding relationship that it is advisable to reduce the frequency of the carrier wave in order to weaken the requirements for the stability of the delay line. In this regard, autocorrelation demodulators sometimes use the transfer of the spectrum of the received signal to a lower intermediate frequency. The "transfer to zero frequency" is limiting case of such a transformation is, i.e., the scheme for the implementation of this algorithm is equivalent to the scheme of the optimal incoherent demodulator [10].

In addition to the algorithm using relation (12) and the scheme of its implementation shown in Fig.1, there are other equivalent algorithms and schemes for autocorrelation processing of signals from PDM-1, which do not require direct calculation of the correlation coefficient of the received signal.

In the digital implementation of the receiver, it is convenient to apply an algorithm based on criterion (12) and the circuit shown in Fig. 1. The question of the implementation of this scheme depends on the available element base for a specific frequency range and transmission rate. The autocorrelation demodulator uses the same correlator as the coherent and optimal incoherent demodulator. The difference is that the reference oscillation in this case is the preliminary sending of the received mixture of the useful signal with the noise. Therefore, it is not desirable to use key multipliers in an autocorrelation demodulator - this leads to a noticeable loss of noise immunity. A multiplier in an autocorrelation receiver circuit, if it is implemented in an analog way, is a relatively complex unit. There are no peculiarities in digital implementation.

Usually, in autocorrelation demodulator circuits, integrators are replaced by low-pass filters (LPF), at the output of which a modulation signal with certain distortions is obtained. The corresponding modification of the main circuit of the autocorrelation demodulator is shown in Fig. 2. Such circuits, in contrast to circuits with reset integrators, are efficient without clock synchronization, but provide less noise immunity. To increase the noise immunity, the signs of oscillations at the output of the low-pass filter should be recorded at certain points in time. The moment of determining the signal symbol depends, in particular, on the frequency characteristics of the channel and the modem and is associated with the clock pulse of the clock synchronization device (CSD).

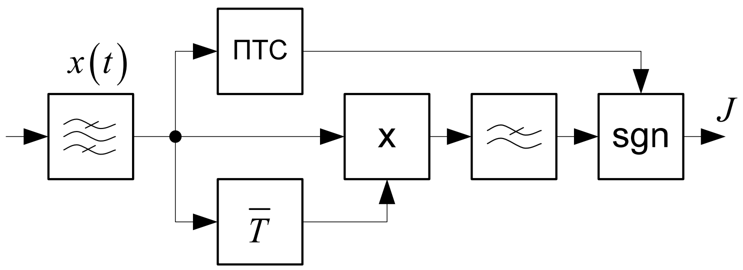

Figure 2: Scheme of a modified autocorrelation demodulator of signals with a single PDM-1

Let's consider some other schemes of autocorrelation processing of signals from PRM-1. To do this, let us return to relation (9) or (10).

In square brackets on the left side of (10) are the sums of the coefficients of the orthogonal transformation of the received signal on two adjacent transmission intervals. Consequently, the sum of the squares of the values in square brackets is proportional to the energy of the sum of the signals on two adjacent messages. Similarly, in square brackets on the right side of (10) are the differences in the coefficients of the expansion of the received signal on two adjacent messages. Therefore, the sum of the squares of these differences is proportional to the energy of the difference between the signals in two adjacent messages. Thus, (10) can be represented as:

$$\int_T^{2T}[x(t)+x(t-T)]^2dt > \int_T^{2T}[x(t)-x(t-T)]^2dt.$$

The equivalence of (15) and (12) is obvious. Inequality (15) can be represented as a relation for determining the transmitted binary symbol similarly to (12):

$$J = sgn\left\{\int_0^T[x(t)+x(t-T)]^2dt - \int_0^T[x(t)-x(t-T)]^2dt\right\}.$$

The demodulator circuit corresponding to algorithm (16) is shown in Fig. 3. Regarding the noise immunity, as well as the requirements for the stability of the carrier frequency of the signal and the duration of the demodulator delay, presented in Fig. 1 and Fig.3, are equivalent. However, in the demodulator, presented in Fig. 3 there is no module for multiplying signals on adjacent sendings. Instead, the sum and difference of these sendings are sent to the quadrator (KB) and integrated. The results obtained are compared in a subtraction scheme. If the energy of the sum of the signals is large, then it is concluded that there is no phase difference and the symbol +1 is transmitted, but if the energy of the signal difference is of greater importance, then it is concluded that there is a phase difference and the symbol -1 is transmitted. In practice, quadrators and integrators can be implemented using an inertial quadratic detector [11].

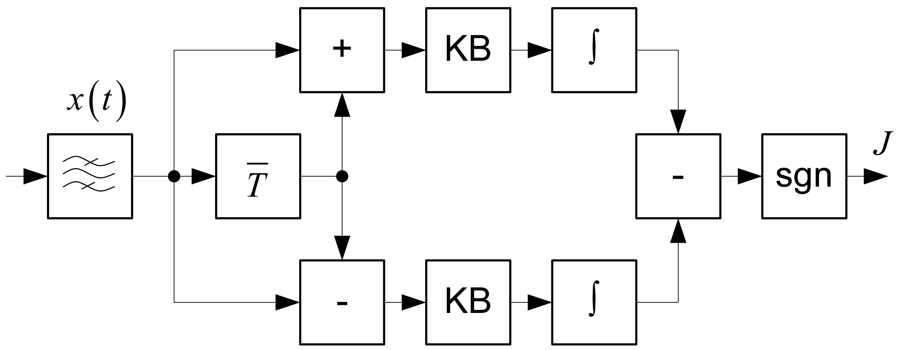

Figure 3: Scheme of the optimal energy demodulator of signals with a single PDM

In the case of an analog implementation of the autocorrelation technique, the algorithm (16) and the scheme for its implementation, Fig. 3 may turn out to be better than the above algorithm. In the case of digital implementation, it is more convenient to apply algorithm (12) and the scheme shown in Fig. 3. Nevertheless, the question of implementation should be decided depending on the available element base for a specific frequency range and transmission rate. We now turn to the consideration of autocorrelation reception of signals from multiple PDM. Note that with this method of reception, the same regularities take place as with other processing methods: in the case of an increase in the number of possible values of the phase difference and a corresponding increase in the transmission rate, the noise immunity decreases noticeably; in the case of a transition from a single PDM to a double one with a constant transmission rate, the noise immunity slightly decreases, etc. In practice, autocorrelation modems with double PDM are most often used, which allows, at the same transmission rate as modems with single PDM, to almost halve the required frequency band with insignificant energy losses.

In the case of double PRM, two systems of information phase differences are usually used: 1) $\pi/4$, $3\pi/4$, $5\pi/4$ and $7\pi/4$, or 2) $0,\pi/2,\pi$ and $3\pi/2$. . In both cases, the manipulation Gray code is used. These systems are shown in Fig. 4 in vector form. To synthesize algorithms for autocorrelation demodulators of signals from PRM-1 using the manipulation Gray code, it is more convenient to use general algorithms for decoding multi-position signals from PRM, in which the transmitted binary symbols are represented through the sine and cosine of the received phase difference [12].

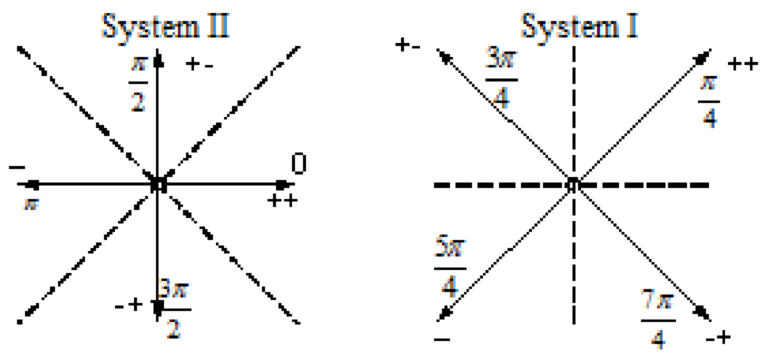

Figure 4: Vector diagrams of double PDM

When using the first signal system (Fig. 6), the demodulation algorithms for the first and second binary subchannels are:

$$\left.\begin{aligned} J_{1n} &= sgn \int_{(n-1)T}^{nT} x(t)x^{*}(t-T)dt \\ J_{2n} &= sgn \int_{(n-1)T}^{nT} x(t)x(t-T)dt \end{aligned}\right\}$$

where the asterisk denotes the Hilbert transform.

A schematic of a demodulator that implements algorithm (17) is shown in Fig. 5.

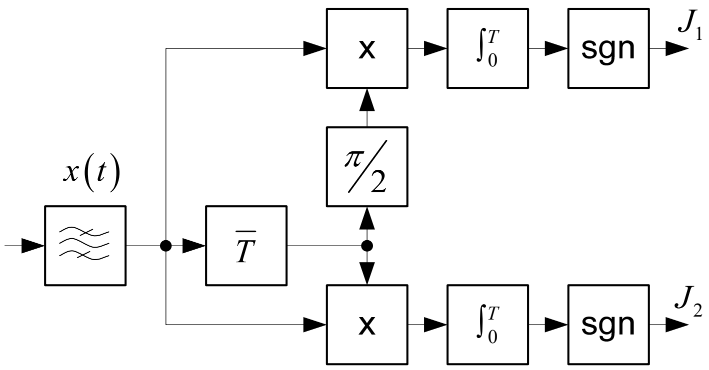

Figure 5: Scheme of an autocorrelation demodulator of signals with double PRM with phase difference $\pi/2$

In the case of using another signal system, the autocorrelation processing algorithm will take the form:

$$\left.\begin{aligned} J_{1n} &= sgn\left[\int_{(n-1)T}^{nT} x(t)x(t-T)dt + \int_{(n-1)}^{nT} x(t)x^{*}(t-T)dt\right]; \\ J_{2n} &= sgn\left[\int_{(n-1)T}^{nT} x(t)x(t-T)dt - \int_{(n-1)T}^{nT} x(t)x^{*}(t-T)dt\right]. \end{aligned}\right\}$$

The considered autocorrelation demodulators of signals with two-fold PRM contain a phase rotator on$\pi/2$, which performs the functions of a Hilbert transformer. This phase rotator should be broadband and phase shift by$\pi/2$ for all frequency components of the received signal. It is more expedient to use phase differences $\pi/4$, $3\pi/4$, $5\pi/4$, and $7\pi/4$, since in this case the demodulator circuit can be slightly simplified. At the same time, to implement such phase differences, it is necessary to use a slightly more complex modulator, since in this case the carrier wave can have eight phase values. But you can choose such a ratio between ω and T, in which the carrier oscillation will have only four phases: 0, $\pi/2$,π and $3\pi/2$, and the demodulator can be built according to the simplest scheme for a two-fold PDM, shown in Fig. 6.

To do this, in the demodulator, it is necessary to shift the phase of the oscillations of each message, which is performed automatically under the condition

$$\omega T = 2\pi k + {}^{\pi}/_{4},$$

In general, it should be noted that in autocorrelation demodulators, by changing the signal delay duration, one can switch to receiving different signal systems (with different values of the minimum phase difference). The same effect can be achieved by changing the frequency of the carrier wave without changes in the autocorrelation demodulator circuit [13].

For a two-fold PRM, as well as for a one-fold, it is possible to synthesize operation algorithms and circuits of energy demodulators, similarly to (16), (15) and Fig. 3. For example, for a system of signals with phase differences $0,\pi,\pi/2$ and $3\pi/2$, the demodulator circuit without signal multipliers has the form shown in Fig. 6.

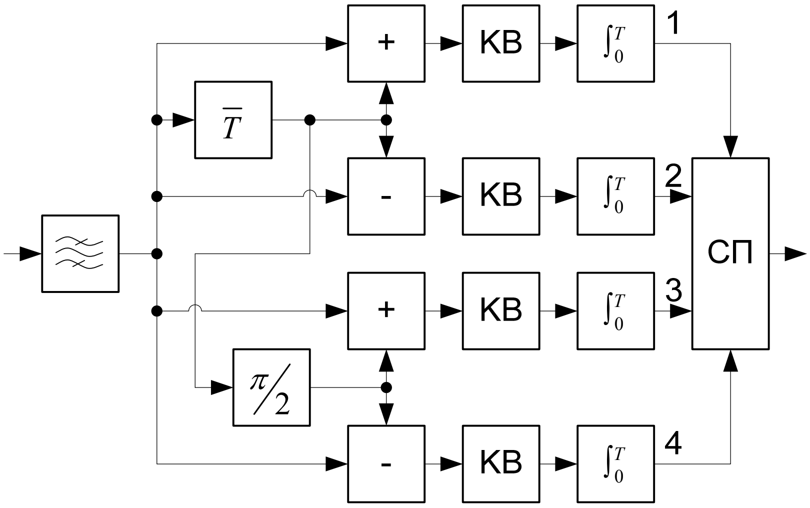

Figure 6: Diagram of an energy (autocorrelation) demodulator of signals with double PRM with phase differences of $0,\pi,\pi/2$ and $3\pi/2$

In the energy demodulator, Fig. 6, four processing steps are readied - according to the number of signal variants. In the comparison circuit (CC), the step at which the largest signal value occurs is determined. If the largest signal occurs at the first step, then it is considered that there is a zero phase difference; if at step 2, the phase difference is equalπ; if at steps 3 and 4, the phase differences are equal to$\pi/2$ and $3\pi/2$, respectively.

In the process of implementing the considered autocorrelation demodulators of four-position PM signals, one should fulfill the same requirements and apply the same approaches as in relation to demodulators of two-position signals. In particular, in the case of an analog implementation, integrators are usually replaced with a reset by low-pass filters with a reading at their outputs at the moments caused by clock pulses, and in the case of a digital implementation, digital memory registers are used instead of delay lines and digital correlators [14-17].

3. Conclusions

The considered algorithms can be effective not only in the case of an unknown waveform, but also in the case of variable waveform signals. However, algorithms can only be used for signals whose changes occur within a certain space of signal implementations. With phase difference modulation (PDM-1), this means that the signals must be repeated with sign accuracy over an interval of two bursts. This, in particular, implies rather stringent requirements for the stability of the frequency of the carrier wave when using the autocorrelation method for receiving PDM-1 signals.

Autocorrelation modems with PDM-2 are characterized by the property of relative or absolute invariance to changes in the frequency of the carrier vibration, they are used in digital information transmission systems in communication systems with fast moving objects, in satellite communication systems, as well as in fiber-optic communication systems, mobile broadband access with support for LTE technology [6].

Thus, when transmitting digital information by different communication channels, conditions arise under which the receiver must process a signal with an unknown or inaccurately known frequency of the carrier wave - channels with an undefined signal frequency. For such channels and conditions, when using signals from the second-order PRM, it is better to use the autocorrelation method of reception.

References

[1] V. B. Tolubko, L. N. Berkman, S. I. Otrokh, V. I. Kravchenko // Manipulation coding of signal n-dimensional multi-position constellations on the basis of regular structures that are optimal in terms of noise immunity/ Kyiv: Telecommunication and information technologies – 2017 – No 3 (56) – p.5-11 (in Ukrainian).

[2] V.Tolubko, L. Berkman, S. Otrokh, O. Pliushch, V.Kravchenko //Noise Immunity Calculation Methodology for Multi-Positional Signal Constellation s/ 14th IEEE International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET'2018): Conference Proceedings. – Lviv, 20-24 of February, 2018. – p.#436.

[3] Yu. Okunev //Digital transmission of information with phase-modulated signals./ M .: Radio and communication, 1991 -- 295 p. (in Russian).

[4] L. Levin, M. Plotkin// Digital information transmission systems./M.: Radio and communication. 1982 -- 216 p. (in Russian).

[5] V. Tikhvinsky, S. Terentyev //Mobile networks LTE: technologies and architecture / M .: Eco-Trends. – 2010 p.192-196. (in Russian).

[6] V. Steklov, L. Berkman, S. Mnischenko, L.Tarasenko, Information method for calculating the channel capacity of the intelligent network control system // Odessa: Proceedings of UNIIRT, No. 4 (16), 1998. – P.29-32.

[7] Yu. Lev, On the choice of the criterion for the efficiency of information distribution in communication networks. - K .: Collection of scientific papers KONIIS, vol. 5. - 1976. - P. 79-83.

[8] A.Fomin, A. Khoroshavin, I.Shelukhin, Analog and Digital Synchronous-Phase Meters and Demodulators / Ed. A.F. Fomin. - M .: Radio and communication, 1987.- 248 p.

[9] V. Netes, Basic principles of organizing self-healing networks based on synchronous digital.

[10] Yu. Okunev, Phase difference modulation theory. - M .: Communication, 1979 .- 215 p.

[11] A. Kozelev, O. Loshkareva, Long-distance high-speed fiber-optic transmission systems // Foreign radioelectronics. -1991. - No. 11. – P.28 - 45.

[12] M. Schwartz, Communication networks: protocols, modeling and analysis. - M .: Nauka, part 2, 1992 .- 272 p.

[13] V.Steklov, L.Berkman - Kiev: Tekhnika, 2002.- 792 p.

[14] B.Zhurakovskyi, S.Toliupa, Otrokh, H. Dudarieva, V. Zhurakovskyi, Coding for information systems security and viability //CEUR Worshop Proceedings, 2021,Vol -2859, P. 71–84.

[15] Recommendations ITU-T Y.2019 (2010). Content delivery functional architecture in NGN.

[16] Recommendations ITU-T Y.2091 (2008). Terms and definition for Next Generation Networks.

[17] Recommendations ITU-T Y.2221 (2010). Requirements for support of ubiquitous sensor network (USN) applications and services in the NGN environment.

[18] Recommendations ITU-T Y.2701 (2009). Security Requirements for NGN release 1. Sklyar B. Digital communication / B. Sklyar. – M.: Williams, 2004. – 104 p.

[19] V. Gordienko, M. Tveretsky, Multichannel telecommunication systems / - Moscow: Hotline - Telecom, 2005. - 230 p.

[20] W.Stallings. Wireless communication lines and networks / Stallings Williams. - M.: Communication, 2003. - 639 p.