Two-Time Procedure for Calculation of Carrier Frequency of Phasomodulated in Communication Systems

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Abstract: The use in radio communication systems of phase modulation of a signal intended for the transmission of useful information in a continuous mode creates the problem of frequency uncertainty of the received signal by frequency.
In practice, it is not possible to implement frequency estimation in the conditions of chat uncertainty of the signal in the channel with low energy of the signal received in the continuous mode. Therefore, the estimation of the carrier frequency offset of the signal received relative to the nominal value is carried out before other synchronization procedures are included, namely: phase synchronization and clock synchronization. The paper generalizes the procedure and forms a two-step procedure for calculating the carrier frequency of the phase-modulated signal of a radio communication system for data transmission in a continuous mode, taking into account the condition of uncertainty of all signal parameters. Achieving the minimum observation interval in the given order of calculation of the carrier frequency is ensured by the use of the fast Fourier transform function. In order to analyze the effectiveness of this procedure, the process of estimating the carrier frequency of the phase-modulated signal of the radio communication system during data transmission in continuous mode and functional dependences of the maximum frequency in the signal spectrum and the minimum variance of carrier frequency estimation. This procedure allows a two-stage assessment of the carrier frequency according to the rule of maximum likelihood, taking into account the condition of uncertainty of all parameters of the signal received by the satellite communication system in a continuous mode with a minimum observation interval. Achieving the minimum observation interval in the given order of carrier frequency estimation is ensured by using the fast Fourier transform function and two estimation steps. The analysis of the efficiency of the estimation of the specified order was carried out on the basis of comparison of a ratio of the received minimum variance of an estimation of a carrier frequency and theoretically possible border of the minimum variance.
Keywords. Carrier frequency estimation, minimum estimation margin variance, frequency maximum estimation, fast Fourier transform function, signal frequency estimation algorithm.

1. Introduction

The use in radio communication systems of phase modulation of a signal intended for the transmission of useful information in a continuous mode creates the problem of frequency uncertainty of the received signal by frequency.
For demodulators of radio modems operating with a continuous input signal, when working in conditions of frequency uncertainty of the signal, the most significant problem is the synchronization of the carrier frequency. This synchronization task is actually reduced to estimating the true parameters of the received signal [1].
The best results can be obtained by a joint assessment of unknown signal parameters. However, in practice it is not possible to implement such an assessment in a low-energy satellite channel with high frequency uncertainty of the received signal.
Therefore, the estimation of the carrier frequency offset of the signal received relative to the nominal value is performed before other synchronization procedures are activated, namely: phase synchronization and clock synchronization.
The complexity of the task of estimating the carrier frequency in the satellite channel is exacerbated by the presence of additional interfering actions of "neighboring channels" - signals with the same type of modulation and the same data rate. It is known that satellite information transmission systems work, including in modes with random access of signal packets. That is, for them it is important to synchronize coherent phase demodulators operating in batch mode.
Significant difficulties arise in the implementation of evaluation algorithms in batch mode. This is due to the fact that in batch mode, the synchronization of the demodulator is carried out according to the preamble, the duration of which is rigidly fixed.
Given the fact that the estimation of the carrier frequency in continuous mode and batch mode is carried out in fundamentally different ways, it is advisable to develop methods for estimating in continuous and batch modes separately.
The methods of carrier frequency estimation and subsequent synchronization for this case, described in the previous works, are intended for demodulators of communication systems operating with time division multiplexing. The main disadvantage of these works is that we consider relatively small relative to the band of the input signal offset carrier oscillations, while in real modern communication systems, these offsets can be correlated with the clock frequency of the received signal [3,5].
In the presence of information about the parameters $\{d, \varphi, \tau\}$, the MP–estimate of the carrier frequency can

provide the minimum limiting variance, which will be determined by the lower Kramer-Rao boundary [2,3].

The process of estimating the carrier frequency should provide an estimate of the maximum frequency in the signal spectrum with a minimum variance of the carrier frequency estimate for the shortest possible estimation interval [3,4].

In turn, the development of new and improvement of existing evaluation algorithms based on the above process requires an analysis of the effectiveness of their application. Such an analysis must be performed in relation to the conditions, factors and parameters that determine the peculiarity of the transmission and reception of the phase-modulated signal by the phase-coherent satellite communication systems in a continuous mode.

2. Literature Survey and problem statement

The algorithm for estimating the carrier frequency of a phase-modulated signal transmitted in a continuous mode, based on the MP–estimation, presented in [5], allows estimating the maximum frequency in the signal spectrum with the minimum estimation variance for the minimum short interval. The presented algorithm requires an analysis of its efficiency, the results of which in this work are disclosed and not fully presented. Analysis of recent research and publications. The issue of estimating the carrier frequency of the signal received by the communication system in a continuous mode, developing a procedure for conducting this evaluation, and evaluating its effectiveness is devoted to a number of works. The authors of [6] proposed an algorithm for joint estimation of carrier frequency, its synchronization and determination of carrier frequency shift in channels with additive white Gaussian noise. The proposed algorithm uses a frequency filter followed by sampling of input pulses in order of importance, considers the previous distribution of evaluation parameters and includes recommendations for re-sampling to solve the degeneracy problem and fine-tune the estimated values of the input signal frequency. The specified algorithm does not provide definition of the minimum variance of an estimation, and in work there is no material concerning an estimation of its efficiency at application on purpose.

In the article [7] the method of sequence synchronization proposed by the authors is considered, which expands in the conditions of significant excess of the noise level over the level of the information signal. For synchronization the service channel which works on one frequency with information is used. The synchronization algorithm proposed by the authors does not contain data and calculation procedures that take into account the estimation interval and the minimum estimation variance. The results of the evaluation of the efficiency of the proposed algorithm presented in the paper do not fully reveal its possibility to evaluate the phase-modulated signal of the satellite communication system. In [8], a variant of technical implementation of a high-speed carrier frequency recovery algorithm by the method of direct phase adjustment of the reference generator with simultaneous elimination of phase ambiguity and allocation of frame synchronization using matched filters with Barker sequences is proposed. The use of this algorithm involves a preliminary estimate of the carrier frequency of the input signal, but without determining and considering the estimation interval and estimation variance.

The author of [9] proposes an approach to reduce the error of estimating the carrier and symbol frequency of signals with digital modulation by methods based on the analysis of the frequency characteristics of the signal. The approach is based on the calculation of the first derivative of the spectral density function and the search for zero by the iterative method of the erroneous position. The results of the evaluation of the proposed approach presented in this paper do not fully reveal its possibilities for use in radio communication systems.

In [10], based on the relative correlation characteristics of the pseudo-noise sequence, an algorithm for estimating the carrier frequency was developed, using a preamble with the specified sequence. The evaluation results of this algorithm, presented in the work, showed its relative efficiency in terms of estimation accuracy, savings in system resources and stable in the unstable state of the communication channel. The issues of reducing the interval of carrier evaluation and evaluation of the efficiency of the system in estimating the frequency in the work were not considered.

In [11,12] the issues of increasing the accuracy of estimating the carrier frequency of the received signal, increasing the speed of the carrier frequency estimation system, storage resource of the signal receiving system in the unstable state of the input signal receiving channel and low signal-to-noise ratio are considered. The algorithms presented in the paper do not provide for the determination of the minimum variance of the estimate, and there is no material in the works to fully evaluate its effectiveness when used in satellite communication systems.

Thus, the analysis of the efficiency of the order of estimating the carrier frequency of phase-modulated signal of phase-coherent radio communication systems transmitting a signal in continuous mode, which can estimate the maximum frequency in the signal spectrum at minimum variance of carrier frequency estimation for the shortest estimation interval is an urgent scientific task.

As a criterion by which the above analysis can be performed, we choose the ratio of the variance of the estimates obtained by using the proposed order of the two-step estimation procedure in accordance with the theoretical boundaries of such variances.

3. Proposed Methodology

The purpose of applying the method and algorithms that will be used to achieve the scientific problem defined in the article is to obtain the results of estimating the carrier frequency of the phase-modulated signal of phase-coherent radio communication systems that transmit the signal in continuous mode. To achieve this goal, the paper identifies the following steps and steps, which are presented below.

3.1. Formalization of the problem for the development of the evaluation procedure

The main task of the analysis of the efficiency of the order of carrier frequency estimation is to use mathematical modeling methods to determine how the variances of estimates obtained

as a result of using the proposed in [5] two-stage estimation procedure in accordance with theoretical boundaries.
During the simulation we will generate calculations of the complex envelope of the received signal [5, 13]:

$$Z_n = e^{j\left(2\pi\nu \frac{n}{F_d}\right)} \sum_k d_k h\left(\frac{n}{F_d} - kT - \tau\right) + \omega_n$$

Where:
F_d – is the sampling frequency of the signal.
ω_n – deduction of positive Gaussian noise.
It was assumed that the value ν is characterized by a uniform distribution in the range where $[-\nu_{max}, \nu_{max}]$, when $\nu_{max} = \frac{1}{T}$. The signal is generated with a random initial phase φ evenly distributed over the range $[-\pi, \pi]$. The value τ is generated from the sensor of random numbers with a uniform distribution and varies in range $[0, T]$.
Nyquist filter rounding factor $a = 0.4$. Simulations are performed for three modulation cases, namely FM-2, FM-4 and FM-8. The sampling frequency during the simulation was chosen so that the condition of the ratio is met $F_d T = 8$.
The choice of such a ratio of the sampling frequency and the clock frequency of the captured signal is explained as follows. When the phases are multiplied for FM-8, the spectrum is expanded 8 times. To stop the effect of overlapping spectra, the sampling frequency of the complex envelope of the received signal must be not less than 8 times the clock frequency of this signal.
Consider a two-stage procedure for estimating the carrier frequency of the FM signal [5,13 – 16].

3.2. The first step of evaluation

In the first step, an MP estimation of the carrier frequency of the signal received on the basis of the vortex is performed. 2. The computational procedure of the first stage is as follows:
1. The N_f elements of the Z_k complex Fourier transform of the signal received in accordance with the standards of the FFT algorithm were calculated:

$$Z_k = \frac{1}{N_f} \sum_{n=0}^{N_f - 1} Z_n exp\left(-\frac{j2\pi nk}{N_f}\right).$$

Where:
z_n – the calculation of the complex envelope of the received signal;
$k = 0,1,..., N_f - 1$
2. Calculated readings of the amplitude spectrum of the receiving signal:

$$G_k = |Z_k|$$

3. The conversion of the obtained amplitude spectrum to the type of the spectrum of the band signal was performed:

$$SR_k = \left\{ \frac{G_k + \frac{N_f}{2}, k = 0,1,..., \frac{N_f}{2} - 1}{G_k + \frac{N_f}{2}, k = \frac{N_f}{2}, \frac{N_f}{2} + 1, ..., \frac{N_f}{2} - 1} \right\} \quad 1)$$

4. Calculations of amplitude spectrum convolution from the frequency response of the matched filter (MF) were calculated:

$$SW_m = SR_{m+\frac{N_f}{2}} + \sum_{k=1}^{M_1 - 1} H_k \left[SR_{m+\frac{N_f}{2}+k} + SR_{m+\frac{N_f}{2}-k} \right]. \quad (2)$$

Where:
$m = -N_{max}, ..., N_{max}$
$N_{max} = \left[\frac{V_{max}}{F_d} * N_f \right].$
N_k – counting the amplitude-frequency characteristics (AFC) of MF.
For N_{max} you can write:

$$N_{max} = \left\{ cos\left[\frac{\pi}{4a} \left| \frac{2k}{K} \right| - 1 + a \right] \right\}$$

Under the conditions – $\frac{|k| \le M_0}{\frac{M_0 \le |k| \le M_1}{|k| \ge M_1}}$.
Where:
$m_d = F_d T;$
$M_0 = \left[\frac{1-a}{2 m_d} N_f \right];$
$M_1 = \left[\frac{1+a}{2 m_d} N_f \right].$
5. The values of the carrier frequency offset of the signal received relative to the nominal value were calculated:

$$\bar{\nu}_0 = arg\left\{ \underset{-N_{max} \le m \le N_{max}}{Max} \{SW_m\} \right\} * \frac{F_d}{N_f}. \quad (3)$$

In the process of modeling the procedure of the first stage, the following parameters were selected: the length of the observation interval was K = 256 and 512 information symbols.
The length of the fast Fourier transform (FFT) is undoubtedly related to the length of the observation interval $N_f = m_d K$.
In our case $m_d = 8$. Therefore, for K = 256 = 2048 and K = 512 corresponds to = 4096.
Here and in the future in the implementation of computational procedures in continuous mode, the choice of values of K by the degree of two is due to the relative simplicity of the implementation of FFT algorithms of length 2n, where n is a positive integer.

In the simulation process, the ratio changed E_b/N_0 in the considered range in steps of 0.25 dB. At each evaluation, the evaluation algorithm E_b/N_0 was implemented N_s = 1000 times.
The normalized variance was calculated as follows [4,17]:

$$\bar{\sigma}_\nu^2 T^2 = \frac{1}{N_S} \sum_{i=1}^{N_S} \left[\left(\nu_i - \bar{\nu}_0(i) \right) \right]^2 .$$

Where:
ν_i – the offset of the carrier frequency of the signal received during the i - th implementation of the estimation algorithm;
$\bar{\nu}_0(i)$ – the value of the estimate of this offset in the i-th implementation of the estimation algorithm;
N_s – number of experiments.

The dependence of the normalization of the variance of the carrier frequency estimate on the ratio E_b/N_0 obtained from the simulation results for K = 256 and 512, shown in Fig.1.
In Fig.1. solid lines represent the normalized boundaries corresponding to the given conditions $\bar{\sigma}_\nu^{2*} T^2$ [18,19].
It should be noted that the variance of the estimation of the frequency of the carrier oscillation of the FM signal obtained during the evaluation procedure of the first stage, almost coincides with the corresponding limiting variance.

3.3. The second step of the assessment

In the second step, the modulation is removed and the frequency of the maximum in the signal spectrum is estimated.
The following operations were performed to estimate the frequency of the considered maximum.
1. The N_f elements of Y_k the complex Fourier transform of the signal y_n in accordance with the standard FFT algorithm were calculated.

$$y_k = \frac{1}{N_f} \sum_{n=1}^{N_f - 1} y_n * exp\left(-\frac{j 2\pi nk}{N_f} \right)$$

Where $k = 0,1,..., N_f - 1$

2. The count of the amplitude of the spectrum was calculated [19,20]:

$$y_k = \frac{1}{N_f} \sum_{n=1}^{N_f - 1} y_n * exp\left(-\frac{j 2\pi nk}{N_f} \right)$$

3. The count was calculated W_k by converting the amplitude spectrum to the spectrum G_k of the band signal using the transformation (2).
4. Determined the number of spectral counting M_p, such that:

$$M_p = arg\left\{ \frac{max}{-N_i + \frac{N_f}{2} \le k \le N_i + \frac{N_f}{2}} \{W_k\} \right\}$$

Where N_i some fixed value.

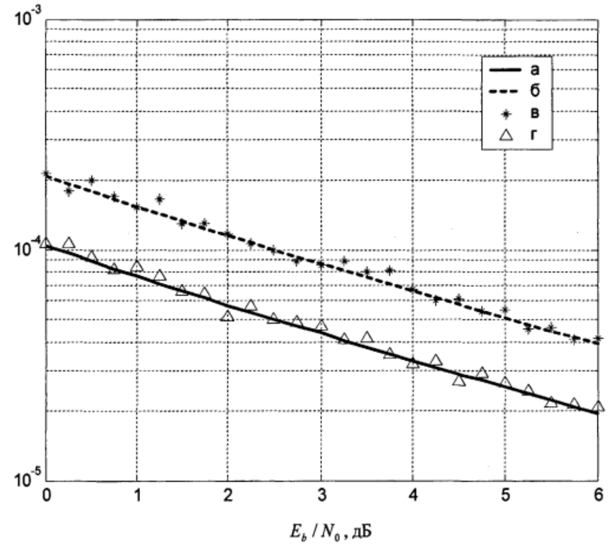

Figure 1. Type of modulation -FM-4:
Standardization of MHD estimates of carrier frequency ($\sigma_\nu^{2*} T^2$), a - K = 512; b - K = 256.
Normalization of the variance of the carrier frequency estimates ($\sigma_\nu^{2*} T^2$), in - K = 256, g - K = 256.

4. To more accurately estimate the frequency of the maximum of the signal spectrum y_n a dichotomous search procedure is used, which is used to estimate the carrier frequency of the FM signal in batch mode.
The signal spectrum at the output of the phase multiplication circuit can be inferred from the signal spectra presented in Fig.2 and Fig. 3.

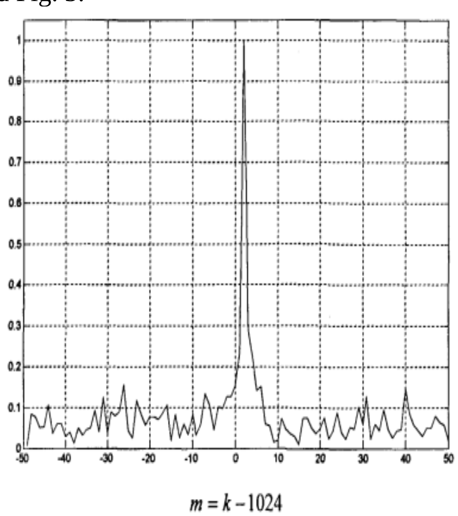

Figure 2. Normalized amplitude spectra of the signal at the output of the phase multiplication circuit.

Type of modulation - FM-2, E_b/N_0 = 3 dB, ν = 0

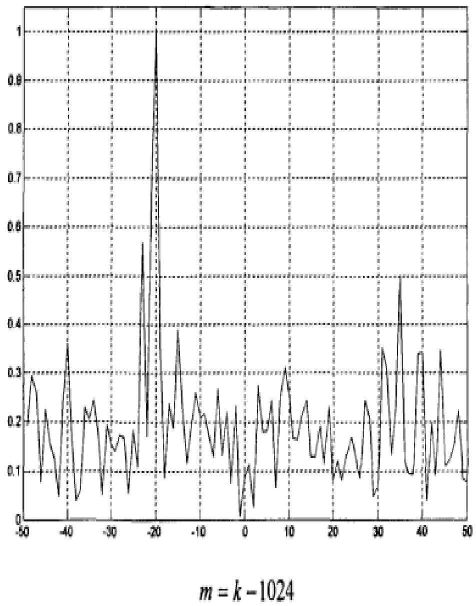

Figure 3. Normalized amplitude spectrum signal at the output of the phase multiplication circuit.
Type of modulation - FM-4, E_b/N_0 = 3 dB, ν = 0

In fig. normalized spectra of signals obtained during simulation in the implementation of the procedure of phase multiplication for signals FM-2 and FM-4 are presented.
The spectra obtained around the point M_p for N_f = 4096. and k = -50,…, 50.
The graphs have clear spectral maxima, by estimating which the estimate of the second stage is calculated.
Thus, after completing the procedure of the second step, the final estimate of the frequency of the carrier oscillation of the FM signal is calculated as follows:

$$\bar{\nu} = \bar{\nu}_0 + \frac{1}{M_\varphi} f_{M_i}$$

Where:
f_{M_i} – the estimate obtained during the implementation of the above iterative procedure;
M_i – the number of iterations of the dichotomous search procedure;
M_φ – the volume of the signal alphabet.

4. Conclusion

The paper summarizes the evaluation procedure and forms on its basis a two-step procedure for estimating the carrier frequency of the phase-modulated signal of a radio communication system in data transmission in continuous mode, taking into account the uncertainty of all signal parameters.
This procedure allows a two-stage assessment of the carrier frequency according to the rule of maximum likelihood, taking into account the condition of uncertainty of all parameters of the signal received by the satellite communication system in a continuous mode with a minimum observation interval.
Achieving the minimum observation interval in the given order of carrier frequency estimation is ensured by using the fast Fourier transform function and two estimation steps:
- the step of determining the minimum variance of the carrier frequency estimate;
- the step of estimating the maximum frequency in the signal spectrum.
The analysis of the efficiency of the estimation of the specified order was carried out on the basis of comparison of a ratio of the received minimum variance of an estimation of a carrier frequency and theoretically possible border of the minimum variance.
The results of modeling according to the proposed order and their analysis showed the practical feasibility of the presented functional dependencies and the relevance of the proposed order to estimate the carrier frequency of the signal received by the radio communication system in continuous mode.
These results may have perspective in the spectral analysis of the definition of random digital signals, as evidenced by the results published in [21].

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