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CLARIFICATION OF THE ALGORITHM FOR ESTIMATING THE FREQUENCY OF THE SIGNAL RECEIVED BY THE SATELLITE COMMUNICATION SYSTEM IN A CONTINUOUS MODE UNDER THE INFLUENCE OF «NEIGHBORING CHANNELS»

Abstract. Satellite communication systems that use phase modulation of a signal designed to transmit useful information in a continuous mode face the problem of frequency uncertainty of the signal when used as intended. For demodulators of satellite modems of such systems operating with a continuous input signal, the most significant is the problem of synchronization in the frequency of carrier oscillations in the conditions of frequency uncertainty of the signal. This synchronization task is actually reduced to estimating the true parameters of the signal, namely the estimation of the carrier frequency. The complexity of the task of estimating the carrier frequency in a satellite channel with phase modulation is exacerbated by the presence of additional interfering actions of "neighboring channels" - signals with the same type of modulation and the same data rate. The paper specifies the algorithm for estimating the carrier frequency of the signal received by the satellite communication system in a continuous mode, taking into account the influence of "neighboring channels" of information transmission. This algorithm allows to estimate 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 continuous mode, taking into account the influence of "neighboring channels" of information with a minimum observation interval. It includes the steps of: calculating the readings of the amplitude spectrum of the received signal and counting the convolution of the obtained amplitude spectrum with frequency response UV; calculating the count of the derivative convolution and finding the initial estimate of the frequency; based on the obtained evaluation of the evaluation procedure based on the multiplication of the phase of the received signal and the calculation of the estimated carrier frequency of the received signal.In order to assess the effectiveness of this algorithm in the comparison of the effectiveness of the estimates provided by the proposed procedure and the estimates made on the basis of subtraction of the global maximum convolution of the amplitude spectrum of the received signal. The results of this assessment presented in the paper showed that the dependences of the normalized variance on practically do not differ. That confirms the efficiency and feasibility and practical value of the algorithm for estimating the carrier frequency given in the work, taking into account the influence of "neighboring channels" of useful signal transmission. A promising area for further study of the issues raised in the work is the adaptation of this algorithm to the carrier frequency estimation in combined phase synchronization systems that have the ability to increase the order of astatism, monitoring the carrier frequency (pilot signal), the phase of which is modulated by a deterministic Doppler signal.

Keywords: estimation of signal carrier frequency; minimum limiting variance of carrier frequency estimation; influence of "neighboring channels" of information transmission; fast Fourier transform function; signal frequency estimation algorithm.

Introduction

Satellite communication systems that use phase modulation of a signal designed to transmit useful information in a continuous mode face the problem of frequency uncertainty of the signal when used as intended. For demodulators of satellite modems of such systems operating with a continuous input signal, the most significant is the problem of synchronization in the frequency of carrier oscillations in the conditions of frequency uncertainty of the signal. This synchronization task is actually reduced to estimating the true parameters of the signal, namely the estimation of the carrier frequency. The complex signal envelope contains unknown values ν, ϕ, τ. That is, the task of synchronization is actually reduced to the assessment of the true parameters of the received signal – ν, ϕ, τ, knowledge of the parameters of which is necessary for demodulation of the signal [2].

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 estimate in a channel with low energy and 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 included, namely: phase synchronization and clock synchronization [3-5].

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 [6,7].

Sufficiently effective results of carrier frequency estimation can be obtained by applying a two-stage algorithm for estimating the carrier frequency of a phase-modulated signal of a satellite communication system when transmitting data in a continuous mode, taking into account the uncertainty of all signal parameters. Achieving the minimum observation interval in the given carrier frequency estimation algorithm is ensured by using the fast Fourier transform function [8].

In practice, the signal of the "neighboring channel" can exceed the signal level in the main channel by 7 dB, the difference in frequency of the "neighboring channel" from the main is a value equal to 1/4T [6]. The algorithm presented in [8] does not take into account the influence of "neighboring channels". That is, an effective assessment of the carrier frequency in a satellite channel requires consideration of the influence of adjacent channels. Which, in turn, necessitates the improvement of appropriate estimation algorithms.

Analysis of recent research and publications. The issue of determining the estimate of the carrier frequency of the signal received by the communication system in a continuous mode and the development of the procedure for conducting this assessment, taking into account the influence of various factors, a number of works.

The authors of [9] proposed an algorithm for joint estimation of carrier frequency, its synchronization and determination of carrier frequency shift in channels with additive white Gaussian noise. This algorithm uses a frequency filter followed by a selection of input pulses in order of importance, takes into account 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 issue of assessing the impact of "neighboring channels" in this work was not considered.

In [10] 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. Channel distribution is performed during the formation of signals of quadrature channels: in-phase channel is used to generate a phase-locked signal with spread spectrum, quadrature channel is used to transmit a clock signal. The synchronization algorithm proposed by the authors lacks data and procedures for calculating the impact of "neighboring channels", and does not take into account the evaluation interval.

In [11] a variant of technical implementation of high-speed carrier frequency recovery algorithm by direct phase adjustment method of reference generator with simultaneous elimination of phase ambiguity and allocation of frame synchronization using coordinated filters with Barker sequences is proposed. The use of this algorithm involves a preliminary assessment of the carrier frequency of the input signal, but without taking into account the interval of determination and evaluation of the impact of "neighboring channels".

The author of [12] 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. This approach allows to ensure the relative accuracy of frequency estimation to 10-7 with a slight increase in the number of computational operations, but the issue of increasing system speed and directly taking into account the impact of "neighboring channels" against the background of reducing the estimation interval is not considered.

In [13], 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 question of the influence of the carrier assessment interval on the efficiency of the system and the question of the assessment of the influence of "neighboring channels" were not considered in the work.

In [14, 15] 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. It is proposed to use a pseudo-noise sequence in the development of an algorithm for estimating and restoring the carrier frequency. The issues of assessment of the impact of "neighboring channels" and reduction of the assessment interval in these works are not considered.

Certain results of the assessment of the impact of neighboring channels are presented in [16]. But in this work there is no consideration during the evaluation of all signal parameters, and the lack of an algorithm to reduce the evaluation interval, which generally affects the quality of the results.

Analysis of the impact of "neighboring channels"

The influence of "neighboring channels" on the efficiency of estimating the carrier frequency of the FM signal will be estimated by the method of mathematical modeling. During the simulation, the samples of the complex envelope of the received signal were generated, which are presented in the following form [2, 8, 17]:

$$z_n = \exp\left(j\left(2\pi\nu \cdot n/F_d\right)\right) \cdot \sum_k \left(n/F_d - kT - \tau\right) + \\ +2,24 \cdot \left(z_n^+ + z_n^-\right) + w_n, \qquad (1)$$

where $$z_n^+ = \exp\left(j\left(2\pi\left(\nu + 1.4 \cdot T\right) \cdot n/F_d + \phi^+\right)\right) \times \\ \times \sum_k d_k^+ h \cdot \left(n/F_d - kT - \tau^+\right);$$

$$z_n^- = \exp\left(j\left(2\pi\left(\nu - 1.4 \cdot T\right) \cdot n/F_d + \phi^-\right)\right) \times \\ \times \sum_k d_k^- h \cdot \left(n/F_d - kT - \tau^-\right);$$

The influence of "neighboring channels" on the complex envelope of the signal was taken into account during the simulation in expression (1) through the value of 2.24. The value of which means the fact that the levels of adjacent channels exceed the level of the main channel by 7 dB (20lg (2.24) = 7) [4]. As before, assume that the values of ϕ, ϕ^+, ϕ^- are independent and evenly distributed in the range $[0, 2\pi]$. Values τ, τ^+, τ^- independent, evenly distributed in the range $[0, T]$ of random variables. The transmitted data d_k, d_k^+, d_k^- were generated from three independent random number sensors.

As an example in Fig. 1 shows a fragment of the normalized amplitude spectrum of one of the received signal implementations obtained during the simulation [16]. In this Fig. 1 *i* the abscissa reflects the sequence number of the amplitude of the spectrum obtained by FFT length 2048. In Fig. 2 shows the result of calculating the convolution of the amplitude spectrum of the signal with the amplitude-frequency characteristic of the matched filter (AFCh MF) [16]. In this case, the maximum convolution of the amplitude spectrum of the signal received from the AFCh MF is far enough from the actual frequency of the carrier oscillation of the signal of the main channel.

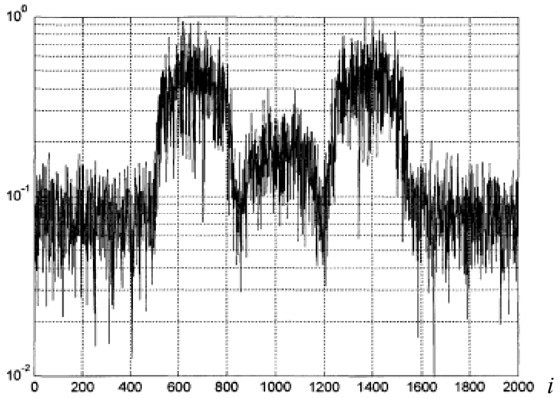


Fig. 1. Normalized amplitude spectrum of the received signal. $N_f = 2048$, type of modulation FM-2, $E_b/N_0 = 0$ dB, $\nu = 0$

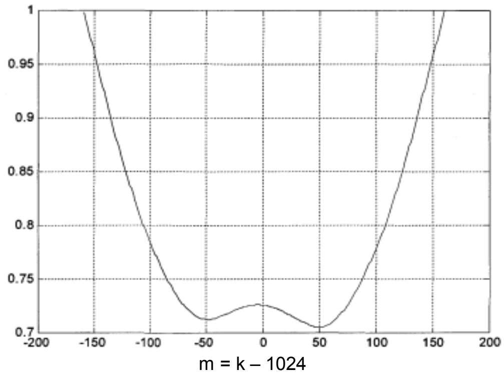


Fig. 2. Normalized convolution of the amplitude spectrum of the signal received from the AFCh MF, taking into account the influence of "neighboring channels"

The identified case differs significantly from that presented in [8] in the absence of "neighboring channels" (Fig. 3). In this case, the implementation of the procedure of the first stage of the estimation algorithm based on finding the abscissa of the global maximum convolution of the amplitude spectrum of the signal received from AFCh MF gives an erroneous estimate of the carrier frequency of the main channel signal.

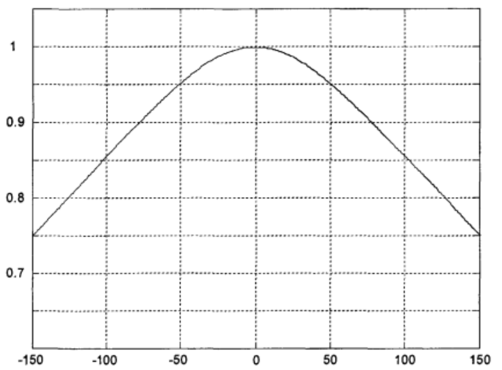


Fig. 3. Normalized convolution of the amplitude spectrum of the signal received from the AFCh MF

But on the dependence presented in Fig. 2, there is a point maximum, at which the first derivative turns into 0 (around $m = 0$). In fact, in the neighborhood $m = 0$, we observe the maximum point of some function, which determines the dependence of the convolution value SW_m on the number of the spectral component m.

Thus, the problem is to find the value of the abscissa of the considered maximum.

The proposed evaluation procedure differs from the above in that the evaluation of the first stage is not sought on the abscissa of the considered convolution maximum, but on the abscissa of the maximum of the considered function, in which the first derivative is converted to 0. The canonical solution of the problem of finding the extrema of a function is reduced to the numerical differentiation of the dependence SW_m as a function of the quantity m.

It is known that the implementation of the operation of numerical differentiation gives significant noise emissions. Therefore, thinning was used to perform this procedure to smooth out noise emissions. Numerical differentiation of dependence SW_m with thinning is realized as follows:

$$SW_m^1 = df_0\left(SW_{m-m_0} - SW_{m+m_0}\right) +$$
$$+df_1\left(SW_{m+m_0/2} - SW_{m-m_0/2}\right),$$

where SW_m^1 – the first derivative of the convolution; $m = -N_{\max} + m_0, -N_{\max} + 2m_0, \ldots, N_{\max} - m_0$, m_0 – even positive number; $N_{\max} = \left[\left(\nu_{\max}/F_d\right)\cdot N_f\right]$, df_0, df_1 – positive constants.

As a result of calculations of the first derivative convolution there is a point K_{loc} which is defined as a point of change of a sign of a derivative from a plus to a minus. Since differentiation was performed with thinning, the value K_{loc} did not directly determine the extremum point.

To find the latter, you need to return to the dependence SW_m and find the corresponding point of the local convolution maximum M_{loc} as follows:

$$M_{loc} = \arg\left\{Max\{SW_m\}/\left(m_0\left(K_{loc}-1\right)\right)\right\}.$$

The value M_{loc} actually determines the amount of offset of the carrier frequency of the main channel. Accordingly, the assessment is rewritten as:

$$\bar{\nu} = M_{loc}\cdot\left(F_d/N_f\right). \tag{2}$$

Based on the assessment of the formulas (2), in turn, an evaluation procedure based on the multiplied phases of the received signal is performed. As a result:

$$\bar{\nu} = \overline{\nu_0^1} + \left(1/M_\phi\right)\cdot f_{M_1}. \tag{3}$$

It should be noted that the increase m_0 leads to the smoothing of noise emissions of the first derivative, but on the other hand leads to a deterioration in the accuracy of the estimate at the calculation stage K_{loc}. It was experimentally established that in the considered conditions for realization of procedure of differentiation it is necessary to stop on $m_0 = 16$. For $m_0 = 16$, $df_0 = 2/3$, $df_0 = 1/12$. The simulation results showed that even under the worst conditions (adjacent channels have the maximum allowable level and is characterized by the minimum allowable frequency offset) in the considered convolution there is a maximum point at which the first derivative is converted to 0.

As an illustration, the result of numerical differentiation of the dependence presented in Fig. 2 for $m_0 = 16$, presented in Fig. 4 [16].

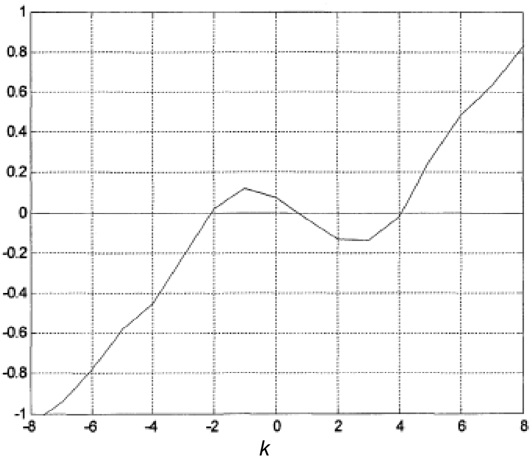


Fig. 4. The results of the calculation of the first derivative convolution

When calculating the derivative k varies from

$$-\left[N_{\max}/m_0\right]-1 \text{ to } \left[N_{\max}/m_0\right]+1 .$$

Thus, the algorithm for estimating the frequency of the carrier oscillation of the FM signal is as follows.

1. Calculate the samples of the amplitude spectrum of the signal received in accordance with (4) and the samples of the convolution of the obtained amplitude spectrum with AFCh MF in accordance with (5) [8]:

$$SR_k = \left\{ \frac{G_{k+\frac{N_f}{2}},\quad k = 0,1,\dots,N_f/2-1}{G_{k+N_f/2}, k = N_f/2, N_f/2+1,\dots,N_f-1} \right\}, \quad (4)$$

$$SW_m = SR_{m+N_f/2} + \\ + \sum_{k=1}^{M_1-1} H_k \left[SR_{m+N_f/2+k} + SR_{m+N_f/2-k} \right]. \quad (5)$$

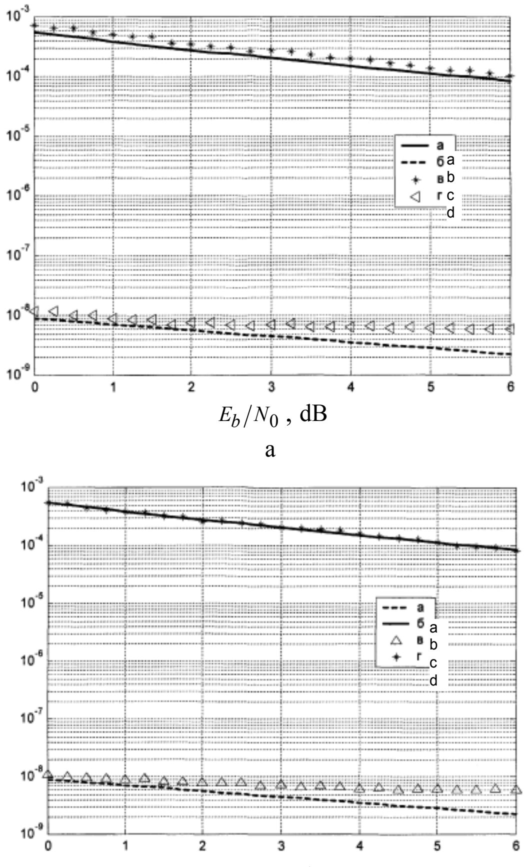
2. Calculate the derivative of the derivative convolution and find the initial estimate of the frequency in accordance with rule (2);

3. On the basis of the received estimation the estimation procedure based on multiplication of a phase of the received signal is carried out and the estimation of a carrier frequency of the signal received according to expression (3) is calculated.

To analyze the effectiveness of the evaluations provided by the proposed evaluation algorithm, computer simulation of the described procedure was performed. Consider the simulation results for FM-2 in the case of the presence of two «neighboring channels». The simulation conditions are set out above.

Fig. 5, a shows the dependences of the normalized variances of estimates $\overline{\sigma_C^2} * T^2$; g – $\overline{\sigma_{\text{v}}^2} * T^2$ from the ratio E_b/N_0 for FM-2 and K = 256. Fig. 5, a also shows the normalized boundaries $\sigma_{\text{v}}^2 * T^2$; $b - \sigma_C^2 * T^2$.

Of particular interest is the comparison of the efficiency of the estimates provided by the evaluation procedure proposed in this section and the evaluation procedure based on the calculation of the global maximum convolution of the amplitude spectrum of the signal received from the AFCh MF. To compare the effectiveness of the obtained estimates, we compare the dependences given in Fig. 5. Note that the dependence of the normalized variance of the estimate $\overline{\sigma_C^2} * T^2$ on the ratio E_b/N_0 in Fig. 5, a is almost no different from the corresponding dependence presented in Fig. 5, b.



E_b/N_0 , dB

a

E_b/N_0 , dB

b

Fig. 5. Type of modulation FM-2. K = 256; normalized minimum limiting variance: a – $\sigma_{\text{v}}^2 * T^2$; b – $\sigma_C^2 * T^2$; normalized variances of carrier frequency estimates: c – $\overline{\sigma_C^2} * T^2$; d – $\overline{\sigma_{\text{v}}^2} * T^2$

The refined algorithm proposed in the work allows the pain to accurately estimate the carrier frequency of the received signal and, therefore, in general, significantly improve the operation of the synchronization system. In turn, a promising area for further improvement of this system is the use of combined phase synchronization systems, which have the ability to increase the order of astatism, while monitoring the carrier frequency (pilot signal), the phase of which is modulated by a deterministic Doppler signal [18]. In turn, the further adaptation of the proposed algorithm to estimate the carrier frequency relative to the combined synchronization systems in both continuous and packet modes of signal reception, is a development of the proposed direction to improve the quality of the synchronization system [19].

Conclusions

The paper specifies the algorithm for estimating the carrier frequency of a signal received by a satellite communication system in a continuous mode, taking into account the influence of "neighboring channels" of information transmission. This algorithm allows to estimate 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 continuous mode, taking into account the influence of "neighboring channels" of information with a minimum observation interval.

Achieving the minimum observation interval in the given carrier frequency estimation algorithm is ensured by using the fast Fourier transform function and estimation steps:

- calculating the readings of the amplitude spectrum of the signal received in and the reading of the convolution of the obtained amplitude spectrum with AFCh MF;
- calculation of the reference of the derivative convolution and finding the initial estimate of the frequency;
- based on the obtained evaluation of the evaluation procedure based on the multiplication of the phase of the received signal and the calculation of the estimated carrier frequency of the received signal.

The paper compares the efficiency of the estimates provided by the proposed procedure and the estimates made on the basis of subtraction of the global maximum convolution of the amplitude spectrum of the received signal. A promising direction for further study of the issues raised in the work is the adaptation of this algorithm to the carrier frequency estimation in combined phase synchronization systems that have the ability to increase the order of astatism, monitoring the carrier frequency (pilot signal), the phase of which is modulated by a deterministic Doppler signal.

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Уточнення алгоритму оцінки частоти сигналу, що приймається системою супутникового зв'язку в безперервному режимі при умові впливу «сусідніх каналів»

О. Л. Туровський

Анотація. Супутникові системи зв'язку, які використовують фазову модуляцію сигналу, що призначений для передачі корисної інформації в безперебрвному режимі, при застосуванні за призначенням стикаються з проблемою частотної невизначеності сигналу. Для демодуляторів супутникових модемів таких систем, що працюють з безперервним вхідним сигналом, найбільш значущою є проблема синхронізації по частоті несучого коливання в умовах частотної невизначеності сигналу. Вказане завдання синхронізації фактично зводиться до оцінки істинних параметрів сигналу, а саме оцінки несучої частоти. Складність завдання оцінки несучої частоти в супутниковому каналі з фазовою модуляцією усугубляється наявністю додаткових заважаючих дій «сусідніх каналів» – сигналів з тим же самим типом модуляції і тією ж швидкістю передачі інформації. В роботі уточнено алгоритм оцінки несучої частоти сигналу, що приймається супутниковою системою зв'язку в безперервному режимі з урахуванням впливу «сусідніх каналів» передачі інформації. Вказаний алгоритм дає змогу здійснити оцінку несучої частоти по правилу максимальної правдоподібності з врахуванням умови невизначеності всіх параметрів сигналу, що приймається супутниковою системою зв'язку в безперервному режимі з урахуванням впливу «сусідніх каналів» передачі інформації при мінімальному інтервалі спостереження. Він включає етапи: обчислення відліку амплітудного спектру сигналу, що приймається і відліку згортки отриманого амплітудного спектру з АЧХ УФ; обчислення відліку похідної згортки і знаходження первинної оцінки частоти; на основі отриманої оцінки проведення процедури оцінки, основаної на помноженні фазі сигналу, що приймається і обчислення оцінки несучої частоти сигналу, що приймається. З метою оцінки ефективності вказаного алгоритму в роботі проведено порівняння ефективності оцінок, забезпечених запропонованою процедурою і оцінок, здійснених на основі одрахування глобального максимуму згортки амплітудного спектру сигналу, що приймається. Подані в роботі результати вказаної оцінки показали, залежності нормованої дисперсії від практично не відрізняються. Що підтверджує ефективність та реалізуємість та практичну цінність поданого в роботі алгоритму оцінки несучої частоти з урахуванням впливу «сусідніх каналів» передачі корисного сигналу. Перспективним напрямком подальшого дослідження порушених в роботі питань є адаптація вказаного алгоритму до оцінки несучої частоти в комбінованих систем фазової синхронізації, що мають можливість до підвищення порядку астатизму, при стеженні за несучою частотою (пілот - сигналом), фаза якої модульована детермінованим допплерівським сигналом.

Ключові слова: оцінка несучої частоти сигналу; мінімально гранична дисперсія оцінки несучої частоти; вплив «сусідніх каналів» передачі інформації; функція швидкого перетворення Фур'є; алгоритм оцінки частоти сигналу.

Уточнение алгоритма оценки частоты сигнала системой спутниковой связи в непрерывном режиме при условии влияния «соседних каналов»

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Аннотация. Спутниковые системы связи, использующие фазовую модуляцию сигнала, который предназначен для передачи полезной информации в безперебрвному режиме, при применении по назначению сталкиваются с проблемой частотной неопределенности сигнала. Для демодуляторов спутниковых модемов таких систем, работающих с непрерывным входным сигналом, наиболее значимой является проблема синхронизации по частоте несущего колебания в условиях частотной неопределенности сигнала. Указанное задача синхронизации фактически сводится к оценке истинных параметров сигнала, а именно оценки несущей частоты. Сложность задачи оценки несущей частоты в спутниковом канале с фазовой модуляцией усугубляется наличием дополнительных мешающих действий «соседних каналов» - сигналов с тем же типом модуляции и той же скоростью передачи информации. В работе уточнен алгоритм оценки несущей частоты сигнала спутниковой системой связи в непрерывном режиме с учетом влияния «соседних каналов» передачи информации. Указанный алгоритм позволяет осуществить оценку несущей частоты по правилу максимального правдоподобия при условии неопределенности всех параметров сигнала спутниковой системой связи в непрерывном режиме с учетом влияния «соседних каналов» передачи информации при минимальном интервале наблюдения. Он включает этапы: вычисление отсчета амплитудного спектра сигнала и отсчета свертки полученного амплитудного спектра с АЧХ УФ; вычисления отсчета производной свертки и нахождения первичной оценки частоты; на основе полученной оценки проведения процедуры оценки, основанной на умножение фазе сигнала и вычисления оценки несущей частоты сигнала. С целью оценки эффективности указанного алгоритма в работе проведено сравнение эффективности оценок, обеспеченных предложенной процедурой и оценок, сделанных на основе расчетов глобального максимума свертки амплитудного спектра сигнала. Представленные в работе результаты указанной оценки показали, зависимости нормированной дисперсии от практически не отличаются. Что подтверждает эффективность и реализуемость и практическую ценность представленного в работе алгоритма оценки несущей частоты с учетом влияния «соседних каналов» передачи полезного сигнала. Перспективным направлением дальнейшего исследования затронутых в работе вопросов является адаптация указанного алгоритма к оценке несущей частоты в комбинированных систем фазовой синхронизации, имеют возможность к повышению порядке астатизма, при слежке за несущей частотой (пилот - сигналом), фаза которой модулирована детерминированным допплеровским сигналом.

Ключевые слова: оценка несущей частоты сигнала; минимально предельная дисперсия оценки несущей частоты; влияние «соседних каналов» передачи информации; функция быстрого преобразования Фурье; алгоритм оценки частоты сигнала.