# EVALUATION OF THE VALUE OF EQUIVALENT ENERGY LOSSES DUE TO THE QUALITY OF FREQUENCY SYNTHESIS FUNCTIONING IN DIGITAL COMMUNICATION SYSTEMS WITH QUASI-COHERENT RECEPTION OF SIGNALS WITH QUADRATURE AMPLITUDE KEYPAD

**Vitaly G. Dovbnya,**
*Southwestern State University, Kursk, Russia,* **vit_georg@mail.ru**

**Dmitry S. Koptev,**
*Southwestern State University, Kursk, Russia,*
**d.s.koptev@mail.ru**

**Leon Rea Herman Floresmilo,**
*Southwestern State University, Kursk, Russia,*
**leon.german1987@hotmail.com**

**Georgy I. Podkhaldin,**
*Southwestern State University, Kursk, Russia,*
**www.gog605@yandex.ru**

DOI: 10.36724/2072-8735-2023-17-5-58-63

**Manuscript received** 14 April 2023;
**Accepted** 12 May 2023

**Keywords:** *digital communication systems, quadrature amplitude modulation, integrated relative frequency instability, heterodyne oscillation synthesizers, phase noise power spectral density, potential noise immunity*

**Useful transmitted information when using digital transmission systems with quadrature amplitude shift keying lies in the change in the amplitude and phase of the signal. This circumstance causes significantly higher requirements for the magnitude of destabilizing factors, namely the phase noise of signal packages at the input of the demodulating device of signals with quadrature amplitude keying, which affect the useful signal, resulting in a decrease in the reliability of reception. In this article, we restrict ourselves to considering the requirements for short-term frequency stability of synthesizers of digital transmission lines, which use signals of multi-position quadrature-amplitude keying in conjunction with quasi-coherent reception. The carrier wave is extracted on the receiving side directly with the help of a carrier recovery device from the received QAM signal by demodulating it, followed by narrow-band filtering. The phase-locked loop in this case functions as a narrow-band tunable filter for extracting the carrier wave. An increase in the quality of demodulation and signal filtering processes leads to a decrease in the phase fluctuation of the restored carrier, a decrease in the level of additive noise, and a decrease in the magnitude of energy losses when using quasi-coherent reception compared to the ideal one, which requires the complete absence of a phase error of the selected reference signal. Such an approximation of the noise immunity of real coherent QAM demodulators to the theoretical one limits the phase noise of the signal at the demodulator input, which is associated with the non-ideal operation of frequency synthesizers on the transmitting and receiving sides of digital communication lines. The research methods used in the article are based on the theories of potential noise immunity, demodulator synchronization, and phase locked loop systems. For the carrier recovery device, the noise band value was chosen in the range from to (where T – is the symbol duration), since with the indicated ratios, the distribution law of the phase error can be considered normal. It was assumed in the work that the devices for automatic gain control and clock synchronization in the radio receiving system function ideally, and the frequency response of the channel corresponds to the Nyquist condition.**

**Information about authors:**

***Vitaly G. Dovbnya,*** *Doctor of Technical Sciences, Associate Professor, Professor of the Department of Space Instrumentation and Communication Systems, Southwestern State University, Kursk, Russia*

***Dmitry S. Koptev,*** *Senior Lecturer, Department of Space Instrumentation and Communication Systems, Southwest State University, Kursk, Russia*

***Leon Rea Herman Floresmilo,*** *2nd year master student, Department of Space Instrumentation and Communication Systems, Southwestern State University, Kursk, Russia*

***Georgy I. Podkhaldin,*** *2nd year undergraduate student of the Computer Engineering Department, Southwestern State University, Kursk, Russia*

**Для цитирования:**
*Довбня В.Г., Коптев Д.С., Леон Реа Херман Флоресмило, Подхалдин Г.И.* Оценка величины эквивалентных энергетических потерь, обусловленных качеством функционирования синтезаторов частоты в цифровых системах связи при квазикогерентном приёме сигналов с квадратурной амплитудной манипуляцией // T-Comm: Телекоммуникации и транспорт. 2023. Том 17. №5. С. 58-63.

**For citation:**
Dovbnya V. G., Koptev D.S., Leon Rea Herman Floresmilo, Podkhaldin G.I. Evaluation of the value of equivalent energy losses due to the quality of frequency synthesis functioning in digital communication systems with quasi-coherent reception of signals with quadrature amplitude keypad. *T-Comm*, vol. 17, no.5, pp. 58-63. (*in Russian*)

## Introduction

The presence of phase noise in the input signal of the coherent demodulator requires the bandwidth of the carrier recovery device to be extended to be able to track the phase of the selected carrier behind the fluctuations in the phase of the input signal. Otherwise, a dynamic phase error appears in the scheme of coherent detection of QAM signals, the signal-to-noise ratio at the output of the coherent detector decreases and, as a result, the reliability of information reception.

The research methods used in the article are based on the theories of potential noise immunity, demodulator synchronization, phase-locked frequency systems.

The article presents the developed analytical model, on the basis of which, by an iterative method in the *MathCAD 11* environment, graphs of the equivalent energy losses are plotted, respectively, on the integral relative frequency instability and the power spectral density of the phase noise of the heterodyne oscillations, normalized when detuned from the carrier by 10 kHz. The calculation was carried out for a local oscillator frequency of 10 GHz and a typical distribution profile of the power spectral density of its phase noise.

From the obtained results, it would be fair to say that the permissible level of equivalent energy losses (from 0,2 to 0,3 dB) is ensured at values of the integral relative frequency instability of $3\cdot10^{-7}$; $1,5\cdot10^{-7}$; $7\cdot10^{-8}$; $3\cdot10^{-8}$ and the power spectral density of phase noise is not more than minus 85, 91, 97 and 103 dBW / Hz for signals with modulation types QAM-16, QAM-64, QAM-256 and QAM-1024, respectively. When calculating, it was assumed that the integral relative frequency instability and the spectral power density of the phase noise of the received signal and the reference generator of the carrier recovery device are significantly lower than that of the oscillation synthesizer of heterodynes. If we assume that the parameters under consideration for the master oscillator of the carrier oscillation and the synthesizer of the local oscillator are comparable, then the requirements should be doubled (for the power spectral density of phase noise – by 3 dB) [1-4].

Thus, the analytical model developed in the article and the obtained graphical dependences allow us to assess the degree of influence of the integral relative instability of frequency and spectral power density of phase noise of oscillation of heterodynes on the noise immunity of receiving multi-position signals with quadrature amplitude modulation, as well as theoretically substantiate the requirements for the quality of functioning of oscillator synthesizers of heterodynes of radio receiving systems of digital communication lines [5-6].

## Materials and methods of research

An integral indicator of the quality of functioning of oscillation synthesizers of heterodynes, which have the most significant impact on the noise immunity of radio receiving systems, is the integral relative instability of frequency and spectral power density of phase noise (fluctuations) of the generated oscillations.

The main requirements for a heterodyne are the following: generation of the required frequency and tuning it in a given range, high stability of the generator oscillation frequency, ensuring the necessary amplitude of the output voltage, constancy of the amplitude of the generated oscillations, the minimum level of higher harmonics in the output voltage, minimizing the level of intrinsic noise, eliminating the microphone effect associated with a change in the frequency of the output signal due to vibrations.

With coherent reception, the frequency drift and partially phase fluctuations of the oscillation of the heterodynes are monitored, and, consequently, compensated by the carrier recovery device (CRD) in the signal demodulator.

In the works [7, 8], the requirements for the quality of oscillations of heterodynes, taking into account the functioning of the CRD, are considered in relation to simple types of modulation – two-position phase manipulation, and for signals with quadrature amplitude modulation – without such consideration. The purpose of the article is to evaluate the influence of the quality of functioning of synthesizers of heterodyne oscillations on the noise immunity of signal reception systems with high positional quadrature amplitude modulation.

To assess the influence of the quality of heterodyning, taking into account the functioning of the CRD, we use expression 1 [6]

$$P_b(h) = \int_{-\psi_L}^{\psi_L} P_b(h,\varphi)\, w(\varphi)\, d\varphi, \qquad (1)$$

where $P_b(h,\varphi)$ – conditional probability of a bit error;

$w(\varphi)$ – density function of phase difference distribution;

$\psi_L = \mathrm{arcctg}(L-1)$;

$L$ – the number of amplitude levels of the quadrature components of the M-positional QAM signal, equal $\sqrt{M}$, if the multiplicity of the signal is $\log_2 M$ – even, and $\sqrt{1{,}125M}$, if it is odd [9].

To calculate the conditional probability of a bit error, we use the expression 2 [10]

$$P_b(h,\varphi) = \frac{1}{L^2 \log_2 L} \sum_r \sum_l \mathrm{erfc} \times$$
$$\times \left\{ \sqrt{\frac{1{,}5h^2}{M-1}} \left[ 1 + (l-1)(1-\cos\varphi) + r \sin\varphi \right] \right\}, \qquad (2)$$

where $\mathrm{erfc}(y) = \frac{2}{\sqrt{\pi}} \cdot \int_y^{\infty} \exp(-x^2)\,dx$ – additional error function;

$h^2 = \frac{\bar{E}}{N_0}$ – signal-to-noise ratio (the ratio of the average energy of the symbol $\bar{E}$ to the one-way spectral power density of Gaussian noise $N_0$);

$$r = -(L-1), -(L-3), \ldots, (L-1);\ l = -(L-2), -(L-4), \ldots, (L-2).$$

Let us determine the statistical parameters of the tracking error of the carrier phase of the input signal. To do this, we present the block diagram of the CRD (Fig. 1).

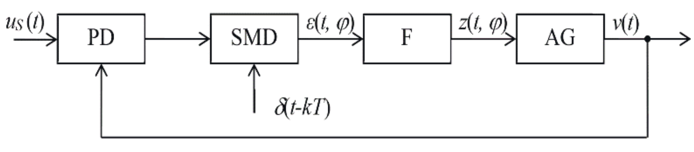



**Fig. 1.** Structural diagram of a carrier recovery device: PD – phase discriminator; SMD – sampling-memorizing device; F – filter; AG – adjustable generator

Let us write the output signal of the SMD device $\varepsilon(t, \varphi)$ in the form

$$\varepsilon(t,\varphi) = \bar{A}S_g[g_n(\varphi) + \xi(t,\varphi)] \quad (3)$$

Where $\bar{A}$ – the average value of the amplitude of the input signal at the time of the decision;

$S_g = \lim\limits_{h\to\infty} \left.\dfrac{dg(\varphi)}{d\varphi}\right|_{\phi=0}$ – PD transmission coefficient at signal-to-noise ratio $h \to \infty$;

$g(\varphi)$ – discriminatory characteristics of the PD;

$g_n(\varphi) = g(\varphi)/S_g$ – normalized discriminatory characteristic of the PD;

$\xi(t,\varphi)$ – equivalent additive Gaussian interference with power spectral density

$$S_\xi(\Omega) = h_\xi(\phi)\left[\sin(\Omega T/2)/\Omega T/2\right]^2; \quad (4)$$

$h_\xi(\varphi)$ – fluctuation characteristic of PD [11].

Then the signal at the filter output $z(t,\varphi)$ and the instantaneous frequency of the adjustable generator $\omega_V$ in the operator form, respectively, will have the following form:

$$z(t,\varphi) = \bar{A}S_g K(p)\left[g_n(\varphi) + \xi(t,\varphi)\right]; \quad (5)$$

$$z(t,\varphi) = \bar{A}S_g K(p)\left[g_n(\varphi) + \xi(t,\varphi)\right] \quad (6)$$

where $K(p)$ – transmission coefficient of the CRD filter;

$p = \dfrac{d}{dt}$ – differentiation operator;

$\omega_{V0}, \delta\omega_V$ – respectively median value of the frequency of free oscillations and the integral frequency instability of the adjustable CRD generator;

$\varphi_V$ – phase fluctuations of the adjustable CRD generator;

$S = S_g S_V$ – transmission coefficient CRD with open feedback at $h \to \infty$;

$S_V$ – the transmission coefficient of the adjustable generator.

Considering that the instantaneous frequency difference of the input and output CRD signal is the derivative of their phase difference, i.e. $\omega_S - \omega_V = p\varphi$, we write the basic CRD equation in the form [12]

$$\varphi = \varphi_S - \varphi_V - \frac{\bar{A}S}{p}\left\{K(p)\left[g_n(\varphi) + \xi(t,\varphi)\right] - \gamma_0\right\}, \quad (7)$$

where $\omega_S = \omega_T - \omega_R$ – instantaneous CRD input frequency;

$\omega_T, \omega_R$ – instantaneous frequencies of the respectively received signal and the oscillation synthesizer of the heterodyne;

$\varphi_S = \varphi_T - \varphi_R$ – phase fluctuations of the CRD input signal;

$\varphi_T, \varphi_R$ – phase fluctuations of the respectively received signal and oscillation of the heterodyne.

The normalized initial frequency detuning is determined by the expression 8

$$\gamma_0 = \Omega_0 / \bar{A}S \quad (8)$$

where $\Omega_0 = \omega_{T0}(1+\delta\omega_T) - \omega_{R0}(1+\delta\omega_R) - \omega_{V0}(1+\delta\omega_V)$ – initial frequency detuning – initial frequency detuning;

$\omega_{T0}, \omega_{R0}$ – median values of frequencies of the respectively received signal and the oscillation synthesizer of the heterodyne;

$\delta\omega_T, \delta\omega_R$ – integral relative frequency instabilities of the respectively received signal and the oscillation synthesizer of the heterodyne.

The functional scheme of the CRD described by equation (7), is shown in Figure 2.

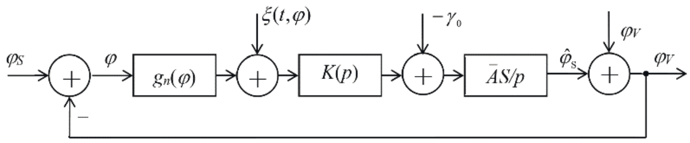



**Fig. 2.** Functional diagram of a carrier recovery device

Ideally, CRD can be represented as a linear phase synchronization system (PSS) of the second order, for which the discriminative, fluctuation, and transfer characteristics are described respectively by the following expressions:

$$g(\varphi) = S_g\varphi; \quad (9)$$

$$h_\xi(\varphi) = N_0 / S_g^2\bar{A}^2 = T / S_g^2 h^2; \quad (10)$$

$$H_\varphi(p) = \frac{\bar{A}SK(p)}{p + \bar{A}SK(p)}. \quad (11)$$

For such a CRD, the solution of equation (7) in operator form will have the form

$$\varphi = \frac{p}{p + \bar{A}SK(p)}\left(\varphi_S - \varphi_V + \frac{\bar{A}S\gamma_0}{p}\right) - \frac{\bar{A}SK(p)}{p + \bar{A}SK(p)}\xi(t,\varphi) \quad (12)$$

or

$$\varphi = \left[1 - H_\varphi(p)\right]\left(\varphi_S - \varphi_V + \frac{\bar{A}S\gamma_0}{p}\right) - H_\varphi(p)\xi(t,\varphi) \quad (13)$$

and a steady-state phase error in the absence of noise [13] –

$$m_\varphi = \gamma_0 = \Omega_0 / \bar{A}S. \quad (14)$$

The analysis of the expression (13) shows that the resulting phase error consists of the following components:

– phase fluctuations of the received signal, the oscillation synthesizer of the heterodynes and the tuned CRD generator, the spectrum of which is beyond the CRD bandwidth;

– initial frequency detuning;

– component, caused by additive noise in the CRD bandwidth.

As a result, the variance of the CRD phase error can be determined by the expression 15

$$\sigma_\varphi^2 = \frac{1}{2\pi}\int_0^{T/2}\left|1 - \dot{H}_\varphi(\Omega)\right|^2 S_T(\Omega)d\Omega + \frac{1}{2\pi}\int_0^{T/2}\left|1 - \dot{H}_\varphi(\Omega)\right|^2 S_R(\Omega)d\Omega +$$

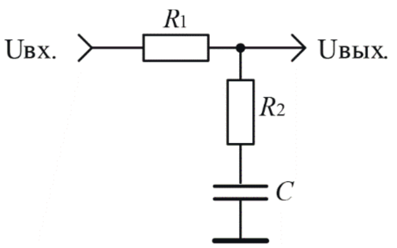
$$+\frac{1}{2\pi}\int_{0}^{T/2}\left|1-\dot{H}_{\varphi}(\Omega)\right|^{2}S_{V}(\Omega)d\Omega+\frac{TB_{l}}{h^{2}} \quad (15)$$

where $S_T(\Omega), S_R(\Omega), S_V(\Omega)$ – spectral power densities of phase noise of the master generator of the carrier of the transmitting path of the digital communication line (DCL), the oscillation synthesizer of hetero-dynes and the adjustable CRD generator;

$\dot{H}_{\varphi}(\Omega)$ – complex transfer characteristic of CRD;

$B_l = \frac{1}{2\pi}\int_{0}^{T/2}\left|\dot{H}_{\varphi}(\Omega)\right|^{2}d\Omega$ – one-way noise band of CRD.

In CRD, a proportionally integrating filter (PIF) is most often used as a filter, the scheme of which is shown in Figure 3 [14, 15].




$$\tau_1 = (R_1 + R_2)C$$
$$\tau_2 = R_2 C$$

Fig. 3. Scheme of proportionally integrating filter

Such PIF has a transfer characteristic of the form

$$K(p)=\frac{1+\tau_2 p}{1+\tau_1 p}, \quad (16)$$

where $\tau_1$, $\tau_2$ – filter time constants.
The coefficient of proportionality of the PIF $F_0 = \tau_2/\tau_1 << 1$.

Transfer characteristic for CRD with PIF for the case when $\tau_2\bar{A}S >> 1$, what takes place in real communication systems, will have the form [16]

$$H_{\varphi}(p)=\frac{1+\frac{r+1}{4B_l}p}{1+\frac{r+1}{4B_l}p+\frac{1}{r}\left(\frac{r+1}{4B_l}\right)^{2}p^{2}}, \quad (17)$$

where

$$r = 4\zeta^2 = \tau_2 F_0 \bar{A}S; \quad (18)$$

$$B_l \approx \frac{r+1}{4\tau_2}; \quad (19)$$

$\zeta^2$ – damping (attenuation) coefficient.

The expression (14) for the static phase error taking into account (18) and (19) can be written as follows

$$m_{\varphi} = \frac{\Omega_0 F_0}{4B_l}\left(1+\frac{1}{r}\right). \quad (20)$$

For CRD, the value of the noise band $B_l$ is selected, as a rule, in the range from $0{,}001/T$ to $0{,}02/T$, the PIF proportionality coefficient $F_0$ – from 0,02 to 0,1, and the optimal value $r_{opt}$ is approximately equal to 7 (ζ=1,32) [11, 16]. With the specified ratios between the noise band $B_l$ and the signal band $B_s = 1/T$, the phase error distribution law can be assumed to be Gaussian with a distribution density function of the form

$$w(\varphi)=\frac{1}{\sigma_{\varphi}\sqrt{2\pi}}\cdot\exp\left[-\frac{(\varphi-m_{\varphi})^{2}}{2\sigma_{\varphi}^{2}}\right]. \quad (21)$$

## Results and discussions

Figures 4 and 5 show the dependences of equivalent energy losses, respectively, on the integral relative instability of the frequency and spectral power density of phase noise oscillations of heterodynes, normalized during detuning from the carrier at 10 kHz, obtained by iterative method in *MathCAD 11* using the expressions (1), (2), (15), (20), (21). The calculation was carried out for the clock frequency of the 1 MHz signal, typical values of the CRD ($B_l = 0{,}01/T$, $F_0 = 0{,}05$) parameters, the oscillation frequency of the 10 GHz heterodyne and the typical distribution profile of the spectral power density of its phase noise with the following slope characteristics in the tuning range: from 1 to 10 kHz – 5 dB/decade; from 1 to 100 kHz – 10 dB/decade; from 100 kHz to 1 MHz – 20 dB/decade; more than 1 MHz – 0 dB/decade (Fig. 6).

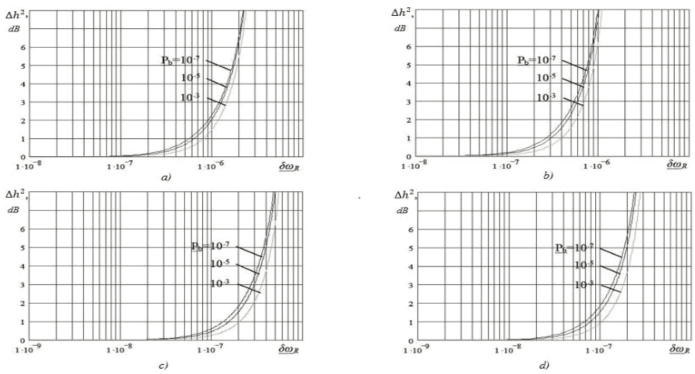


**Fig. 4.** Dependence of equivalent energy losses upon reception on the integrated instability of the oscillation frequency of the local oscillators for signals: a – QAM-16; b – QAM-64; c – QAM-256; d – QAM-1024

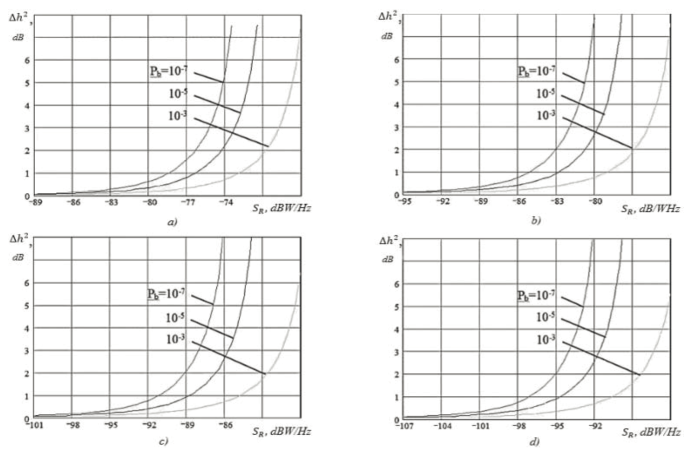


**Fig. 5.** Dependence of equivalent energy losses upon reception on the spectral power density of the phase noise of local oscillations for signals: a – QAM-16; b – QAM-64; c – QAM-256; d – QAM-1024

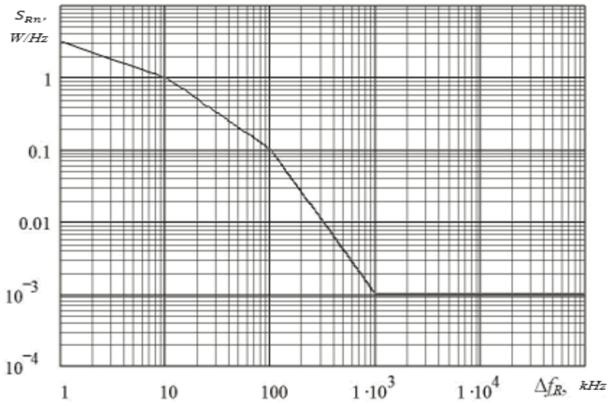



**Fig. 6.** Typical profile of the distribution of the spectral power density of phase noise, normalized to the value at the offset from the carrier at 10 kHz

In the calculation, it was assumed that the integral relative frequency instability and the spectral power density of the phase noise of the received signal and the CRD reference oscillator are significantly lower than those of the heterodyne oscillation synthesizer. If we assume that the parameters under consideration for the master oscillator of the carrier wave and the synthesizer of heterodyne oscillations are commensurate, then the requirements should be doubled (for the spectral power density of phase noise – by 3 dB).

## Conclusion

From the analysis of the obtained dependencies, it follows that the permissible level of equivalent energy losses (from 0,2 to 0,3 dB) is provided for the values of the integral relative frequency instability $3 \cdot 10^{-7}$; $1{,}5 \cdot 10^{-7}$; $7 \cdot 10^{-8}$; $3 \cdot 10^{-8}$ and the spectral power density of phase noise is no more than minus 85, 91, 97 and 103 dBW/Hz for signals with modulation types QAM-16, QAM-64, QAM-256 and QAM-1024, respectively.

The developed analytical model and the obtained graphical dependences make it possible to assess the degree of influence of the integral relative frequency instability and the spectral power density of the phase noise of heterodyne oscillations on the noise immunity of receiving multi-position QAM-signals, as well as theoretically substantiate the requirements for the quality of functioning of oscillation synthesizers of heterodynes of radio receiving systems of digital communication lines.

## References

1. Dovbnya V.G., Asiatsev V.E., Mikhailov S.N. Noise immunity of radio receiving systems of digital communication lines: monograph. Southwest. state un-t. Kursk, 2017. 175 p.

2. Tikhonov V.I., Kulman N.K. Nonlinear filtering and quasi-coherent signal reception. Moscow: Sov. radio, 1975. 704 p.

3. Safaryan O.A., Sakharo I.A. v, Boldyrikhin N.V., Yengibaryan I.A. Method of Reducing Phase Noise in the System Simultaneously and Independently Operating the High-Frequency Signal Generators. *Engineering Computations*. Emerald Group Publishing Ltd. 2017 Vol. 34, no. 8, pp. 2586-2594.

4. Sklyar B. Digital communication. Theoretical foundations and practical application. 2nd, rev. Moscow: Publishing house Williams, 2003. 1104 p.

5. Framing structure, channel coding and modulation for second generation digital terrestrial television broadcasting system (DVB-T2) [El. resource] // DVB. URL: https://dvb.org/? standard=frame-structure-channel-coding-and-modulation (Accessed 01.24.2023).

6. Sidelnikov G.M. Noise immunity of signal demodulators with phase and relative phase modulation in channels with multipath. *Omsk Scientific Bulletin*. 2017. No. 5 (155), pp. 146-151.

7. Sidelnikov G.M. Comparative analysis of the efficiency of diversity reception of signals with quadrature amplitude and phase modulation in a channel with discrete multipath. *Vestnik PSTU. Series Radio engineering and information systems*. 2020. No. 2 (46), pp. 18-30. DOI: https://doi.org/10.25686/2306-2819.2020.2.18

8. Glushkov A.N., Litvinenko V.P., Matveev B.V., Chernoyarov O.V., Salnikova A.V. Basic Algorithm for the Coherent Digital Processing of the Radio Signals. *Proceeding of the 2015 International Conference on Space Science & Communication*. Malaysia, Langkawi, 2015. 5 p.

9. Gerasimenko E.S. Algorithm for digital coherent demodulation of phase shift keying signals and its characteristics. *Bulletin of the Voronezh Institute of the Ministry of Internal Affairs of Russia*. 2017. No. 1, pp. 137-143.

10. Sergienko A.B. Digital signal processing. Textbook. St. Petersburg: Peter, 2002. 608 p.

11. Dvornikov S.V. et al. Improving the noise immunity of KAM-16 signals with transformed constellations. *Questions of radio electronics. Series: TV Technique*. 2014. No. 2, pp. 51-56.

12. Dovbnya V.G., Koptev D.S. Influence of the quality of functioning of local oscillators on the noise immunity of receiving signals with quadrature amplitude modulation. *Radiotekhnika*. 2020. Vol. 84. No. 9 (17), pp. 40-48.

13. Dvornikov S.V., Pshenichnikov A.V., Burykin D.A. Structural and functional model of a signal constellation with increased noise immunity. *Information and space*. 2015. No. 2, pp. 4-7.

14. Zheng B., Dan L., Sawahashi M., Kamiya N. Characteristics of phase noise estimation and compensation using pilot symbols and PLL for high-order cyclic QAM [Electronic resource]. URL: https://ieeexplore.ieee.org/document/8303987 (accessed 08.19.2022).

15. Grishin I.V., Kalinkina A.A. Review of methods of multifrequency signal modulation in modern wireless communication networks. *Information technologies and telecommunications*. 2020. Vol. 8. No. 2, pp. 55-66. DOI 10.31854/2307-1303-2020-8-2-55-66.

16. Pechnikov S.S., Shersyukov S.A. Analysis of methods and devices for optimizing the structure of spectrally efficient radio signals with vector modulation. *Security, safety, communications* – 2020. 2021. No. 6-1, pp. 185-191.

17. Lukyanov A.S., Pechnikov S.S., Popov A.V. Optimization of the signal-to-noise ratio for colored noise. *Bulletin of the Voronezh Institute of High Technologies*. 2019. No. 1 (28), pp. 4-7.

# ОЦЕНКА ВЕЛИЧИНЫ ЭКВИВАЛЕНТНЫХ ЭНЕРГЕТИЧЕСКИХ ПОТЕРЬ, ОБУСЛОВЛЕННЫХ КАЧЕСТВОМ ФУНКЦИОНИРОВАНИЯ СИНТЕЗАТОРОВ ЧАСТОТЫ В ЦИФРОВЫХ СИСТЕМАХ СВЯЗИ ПРИ КВАЗИКОГЕРЕНТНОМ ПРИЁМЕ СИГНАЛОВ С КВАДРАТУРНОЙ АМПЛИТУДНОЙ МАНИПУЛЯЦИЕЙ

**Довбня Виталий Георгиевич,** *Юго-Западный государственный университет, г. Курск, Россия,* ***vit_georg@mail.ru***
**Коптев Дмитрий Сергеевич,** *Юго-Западный государственный университет, г. Курск, Россия,* ***d.s.koptev@mail.ru***
**Леон Реа Херман Флоресмило,** *Юго-Западный государственный университет, г. Курск, Россия,* ***leon.german1987@hotmail.com***
**Подхалдин Георгий Игоревич,** *Юго-Западный государственный университет, г. Курск, Россия,* ***www.gog605@yandex.ru***

## Аннотация
Полезная передаваемая информация при использовании цифровых систем передачи с квадратурной амплитудной манипуляцией кроется в изменении амплитудных и фазовых посылок сигнала. Данное обстоятельство обуславливает существенно более высокие требования к величине дестабилизирующих факторов, а именно фазовых шумов сигнальных посылок на входе демодулирующего устройства сигналов с квадратурной амплитудной манипуляцией, влияющих на полезный сигнал, результатом чего является снижение достоверности приёма. В данной статье ограничимся рассмотрением требований к кратковременной стабильности частоты синтезаторов цифровых линий передачи, в которых используются сигналы многопозиционной квадратурно-амплитудной манипуляции в совокупности с квазикогерентным приемом. Несущее колебание выделяется на приемной стороне непосредственно с помощью устройства восстановления несущей из принимаемого КАМ-сигнала путем его демодуляции, с последующей узкополосной фильтрацией. Система фазовой автоподстройки частоты в данном случае функционирует как узкополосный перестраиваемый фильтр выделения несущего колебания. Рост качества процессов демодуляции и фильтрации сигнала приводит к уменьшению флуктуации фазы восстановленной несущей, снижению уровня аддитивного шума, уменьшению величины энергетических потерь при использовании квазикогерентного приёма по сравнению с идеальным, требующим полного отсутствия фазовой ошибки выделенного опорного сигнала. Подобное приближение помехоустойчивости реальных когерентных демодуляторов КАМ-сигналов к теоретической ограничивает фазовый шум сигнала на входе демодулятора, связанный с неидеальностью работы синтезаторов частоты на передающей и приемной сторонах цифровых линий связи. Методы исследования, используемые в статье, базируются на основах теорий потенциальной помехоустойчивости, синхронизации демодуляторов, систем фазовой автоподстройки частоты. Для устройства восстановления несущей значение шумовой полосы выбиралось в диапазоне от 0,001/Тдо 0,02/Т (где Т - длительность символа), так как при указанных соотношениях закон распределения фазовой ошибки можно считать нормальным. В работе полагалось, что устройства автоматической регулировки усиления и тактовой синхронизации в радиоприемной системе функционируют идеально, а частотная характеристика канала соответствует условию Найквиста.

***Ключевые слова:*** *цифровые системы связи, квадратурная амплитудная модуляция, интегральная относительная нестабильность частоты, синтезаторы колебаний гетеродинов, спектральная плотность мощности фазовых шумов, потенциальная помехоустойчивость.*

## Литература

1. *Довбня В.Г., Азиатцев В.Е., Михайлов С.Н.* Помехоустойчивость радиоприёмных систем цифровых линий связи: монография. Юго-Зап. гос. ун-т. Курск, 2017. 175 с.
2. *Тихонов В.И., Кульман Н.К.* Нелинейная фильтрация и квазикогерентный прием сигналов. М.: Сов. радио, 1975. 704 с.
3. *Safaryan O.A.* Method of Reducing Phase Noise in the System Simultaneously and Independently Operating the High-Frequency Signal Generators / I.A. Sakharov, N.V. Boldyrikhin, I.A. Yengibaryan // Engineering Computations. Emerald Group Publishing Ltd. 2017. Vol. 34, no. 8. Pp. 2586-2594.
4. *Скляр Б.* Цифровая связь. Теоретические основы и практическое применение: пер. с анг. Изд. 2-е, испр. М.: Издат. дом "Вильямс", 2003. 1104 с.
5. Framing structure, channel coding and modulation for second generation digital terrestrial television broadcasting system (DVB-T2) [Эл. ресурс] // DVB. URL: https://dvb.org/? standard=frame-structure-channel-coding-and-modulation (дата обращения 24.01.2023).
6. *Сидельников Г.М.* Помехоустойчивость демодуляторов сигналов с фазовой и относительной фазовой модуляцией в каналах с многолучевостью // Омский научный вестник. 2017. №5 (155). С.146-151.
7. *Сидельников Г.М.* Сравнительный анализ эффективности разнесенного приема сигналов с квадратурной амплитудной и с фазовой модуляцией в канале с дискретной многолучевостью // Вестник ПГТУ. Серия Радиотехнические и информационные системы. 2020. №2 (46). С.18-30. DOI: https://doi.org/10.25686/2306-2819.2020.2.18
8. Basic Algorithm for the Coherent Digital Processing of the Radio Signals/ A.N. Glushkov, V.P. Litvinenko, B.V. Matveev, O.V. Chernoyarov, A.V. Salnikova // Proceeding of the 2015 International Conference on Space Science & Communication. Malaysia, Langkawi, 2015. 5 p.
9. *Герасименко Е.С.* Алгоритм цифровой когерентной демодуляции фазоманипулированных сигналов и его характеристики // Вестник Воронежского института МВД России. 2017. №1. С. 137-143.
10. *Сергиенко А.Б.* Цифровая обработка сигналов. Учебник. СПБ: Питер, 2002. 608 с.
11. Дворников С.В. и др. Повышение помехоустойчивости сигналов КАМ-16 с трансформированными созвездиями // Вопросы радиоэлектроники. Серия: Техника телевидения. 2014. № 2. С. 51-56
12. *Довбня В.Г., Коптев Д.С.* Влияние качества функционирования гетеродинов на помехоустойчивость приема сигналов с квадратурной амплитудной модуляцией // Радиотехника. 2020. Т. 84. № 9 (17). С. 40-48.
13. *Дворников С.В., Пшеничников А.В., Бурыкин Д.А.* Структурно-функциональная модель сигнального созвездия с повышенной помехоустойчивостью // Информация и космос. 2015. № 2. С. 4-7.
14. *Чжэн Б., Дэн Л., Савахаши М., Камия Н.* Характеристики оценки и компенсации фазового шума с помощью пилот-символов и ФАПЧ для циклической QAM высокого порядка [Электронный ресурс]. URL: https://ieeexplore.ieee.org/document/8303987 (дата обращения: 29.05.2021).
15. *Гришин И.В., Калинкина А.А.* Обзор методов многочастотной модуляции сигналов в современных сетях беспроводной связи // Информационные технологии и телекоммуникации. 2020. Том 8. № 2. С. 55-66. DOI 10.31854/2307-1303-2020-8-2-55-66.
16. *Печников С.С., Шерсюков С.А.* Анализ способов и устройств оптимизации структуры спектрально-эффективных радиосигналов с векторной модуляцией // Охрана, безопасность, связь – 2020. 2021. № 6-1. С. 185-191.
17. *Лукьянов А.С., Печников С.С., Попов А.В.* Оптимизация отношения сигнал/шум при цветных шумах // Вестник Воронежского института высоких технологий. 2019. №1 (28). С. 4-7.

**Информация об авторах:**
***Довбня Виталий Георгиевич,*** *д.т.н., доцент, профессор кафедры космического приборостроения и систем связи, Юго-Западный государственный университет, г. Курск, Россия*
***Коптев Дмитрий Сергеевич,*** *старший преподаватель кафедры космического приборостроения и систем связи, Юго-Западный государственный университет, г. Курск, Россия*
***Леон Реа Херман Флоресмило,*** *магистрант 2-го курса кафедры космического приборостроения и систем связи, Юго-Западный государственный университет, г. Курск, Россия*
***Подхалдин Георгий Игоревич,*** *магистрант 2-го курса кафедры вычислительной техники, Юго-Западный государственный университет, г. Курск, Россия*