# Minimization of Phase Error Dispersion in Closed Type Phase Synchronization Systems in Carrier Frequency Tracking Mode

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**Abstract**

Let's describe overall view of using IoT in education curriculum. Let's assume that there is theoretical educational IoT device The article considers the issues of analysis of phase synchronization systems of radio communication devices. The aim of the article is theoretical research and evaluation of the possibilities of closed-phase phase synchronization systems to ensure high noise immunity, accuracy and speed with simple design. The problem to be solved is to investigate the closed-phase phase synchronization system in terms of the possibilities of increasing the order of astatism and reducing the variance of constant and transient errors in the process of carrier frequency tracking in the presence of noise in the communication channel. The following results are obtained. The analysis of closed type synchronization systems is carried out, their discrepancies in increasing the order of astatism and minimizing the phase error variance during carrier frequency tracking are determined. Conclusions. Taking into account the additive Gaussian noise and instability of the generators, the desire to minimize the variance of the phase error in the class of closed synchronization systems causes a deterioration of the system dynamics and does not increase the order of astatism.

**Keywords** [1]

carrier frequency synchronization, closed phase phase synchronization system, order of astatism, constant error variance, transient error variance Introduction

## 1. Introduction.

Research into the problems of data transmission, finding ways and methods to improve the efficiency of the use of means of communication, are extremely important for solving the challenges facing modern communication and telecommunications systems. The successful solution of the problem of further improving the efficiency of communication systems largely depends on the quality of operation of systems and devices that are part of them. Phase synchronization systems are widely implemented in various radio engineering devices of communication, radar and control technology, as well as in the device of accurate magnetic recording. In particular, in phase-coherent telecommunication and control systems, they are used to restore carrier and clock frequencies and for coherent demodulation of analog and digital signals with angular modulation [1]. The operation of synchronization systems is characterized by the influence of a number of disturbances and noise on their operation. Namely, additive fluctuation noise, perturbation of useful angular modulation (in the case of carrier frequency filtering), phase and frequency jumps and others.

In some cases, it is necessary to ensure high accuracy of the system in steady and transient modes. Thus, in space communication lines the main perturbations are additive Gaussian noise and Doppler frequency shifts. Therefore, synchronization systems operating in such conditions should be characterized by low phase error variance and high speed (system dynamics) [2].

Noise immunity, accuracy and speed of synchronization systems affect the main performance of phase-coherent communication systems. In turn, these system parameters depend on the scheme of its construction.

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From the point of view of simplicity of a design and possibility concerning its improvement in the direction of increase of efficiency of work the most interesting are closed systems of synchronization (CSS). It should be noted that the dynamics of the synchronization system, as an automatic control system, is directly related to the level of its astatism. That is, increasing the level of astatism of the synchronization system to the second and higher orders while ensuring a sufficient level of its speed is one of the ways to ensure the efficient operation of the system as a whole [3].

## 2. Statement of the research problem

Thus, the study of the possibilities of a closed synchronization system to ensure high system dynamics and reduce the phase error dispersion against the background of additive Gaussian noise under the condition of increasing the order of astatism is an urgent and timely scientific task.

## 2.1 Analysis of research and publications.

In scientific works, for example [4, 5, 6, 7], for a class of closed synchronization systems the results of researches directed mainly on optimization of parameters of the filter and system as a whole are given. But the impact of such optimization on the error rate and system dynamics is not fully disclosed.

Improving the dynamics can be done, for example, by recording the signal at the current time and reading at the next clock interval M times, as defined in [8]. However, the processing of information in such systems is not in real time, and in addition, the recording and reproducing devices introduce additional distortions.

A similar effect to improve the dynamics is achieved in comb synchronization systems (SSG). But they require the presence of M branches for parallel processing of information, which complicates the design [8].

Reduction of constant and transient error components is possible in adaptive synchronization systems (ACS). For example in works [1, 5] the two-channel ACC with channels of rough and exact adjustment is considered. The coarse tuning channel is built on the basis of SSG and is characterized by high speed, and the precision tuning channel is a normal ZSS and is calculated on the condition of ensuring the required accuracy, ie such ACC is two synchronization systems that switch depending on the mode. Since both channels are built on conventional schemes and operate at different intervals, they are characterized by contradictions characteristic of the CSS.

Certain studies in the direction of improving the quality of the SSS due to the change of the implementation scheme in the direction of its combination and reduction of the minimum errors at the stage of phase filtration by various methods were carried out and their results are presented in the following works.

In [9] the peculiarities of the implementation of the carrier frequency recovery system with coherent demodulation of the signal with a continuous phase are shown. The question of practical realization of the system of phase autotuning of frequency on a modern element base is investigated. But research on the possibilities of the scheme of construction of the synchronization system to increase astatism and reduce the variance of the assessment due to this article is missing.

The authors of [10, 11] proposed a method of synchronizing the sequence of signals, which expands in 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 possibility of increasing astatism and ensuring the speed of the system in this work is not considered.

In [12] presents a new direct sequence modulation scheme for distributed spectrum communication systems, defined as delay and addressing modulation (DADS). The scheme proposed by the authors is easy to implement and does not require alignment of the input signal code at its input, which makes it the most optimal for the transmission of short signals. The article does not disclose the type of scheme in relation to which the conclusions were substantiated, and there is no question of increasing the order of astatism in a particular scheme.

## 2.2 Investigation of a closed-phase phase synchronization system.

Studies of the scheme of construction of a closed synchronization system, composed of a combination of logic devices, in the direction of assessing the possibility of increasing the order of astatism of the system, reducing the variance of constant and transient errors in the process of carrier frequency tracking in the presence of noise in the communication channel the problem to which this work is devoted.

In phase-coherent communication systems, it is necessary to distinguish the carrier oscillations from the signal, which can be modeled by a useful message and interference. Inaccuracies in the filtering of the carrier oscillation phase reduce the signal-to-noise ratio at the output of the coherent receiver. Therefore, when filtering the phase, it is necessary to ensure a minimum error, which depends on the law of change of external influence. Usually the laws of change of input influence are unknown. This raises the problem of creating a system that would be insensitive to perturbations of arbitrary form and reproduce without distortion of the input signal of arbitrary form, ie was completely invariant [3].

Due to the fact that it is practically impossible to create an absolutely invariant system, in practice selective absolutely invariant systems are used, which allow to provide zero constant error under certain types of external influences.

In fact, the condition of selective absolute invariance is to require the equality of zero of the first few error rates of the system or, in other words, to require a certain order of astatism of the system [13].

On the other hand, ensuring a minimum phase filtering error is realized by automatically adjusting the specified process due to the presence in the control circuit of the feedback synchronization system. The specified feedback is a proportional controller, the task of which is to increase the accuracy of control commands, ie to increase the astatism of the control system of the carrier frequency synchronization scheme.

A characteristic feature of astatism is the presence of the structural scheme of the system K integrating links [3].

The order of astatism of a closed system in relation to the control effect is equal to the number of integrating links included in the feedback circuit between the points of application of this influence (input) and the error measurement point (output) and does not depend on the number of integrating links included in the direct signal conversion circuit between these points [3].

The block diagram of the closed synchronization system accepted for research is shown in fig.1.

Let us define a mathematical model of the synchronization system on the example of schemes and coherent space communication. The main types of noise on the line artificial satellite of the Earth - Earth Station are the noise of the Galaxy and the noise of discrete radio sources (star radiation). Moreover, the latter are quite small, therefore, in the design of communication systems are taken into account mainly the noise of the Galaxy, which have the character of white Gaussian noise [2].

Based on this, in the future we will consider the additive Gaussian noise, taking into account the additional angular modulation due to Doppler waste frequency. [14]:

$$\begin{aligned} x(t) &= \sqrt{2}A_0 \sin\left(\omega_0 t + \varphi_{\text{вх}}(t)\right) + n(t), \\ r(t) &= \sqrt{2}A_1 \cos\left(\omega_0 t + \varphi_{\text{вых}}(t)\right), \end{aligned} \tag{1.1}$$

Where $n(t)$ - additive Gaussian noise in a channel with one-way spectral density $N_0/2$.

We will accept the amplitude of the input signal $\mathrm{A}_0 = \mathrm{const}$ and will consider only the phase of the signal modulated by the useful message and the interference.

Since the input links of the closed control channels are the phase discriminator (PD) and the frequency discriminator, respectively, instead of complete signals (1.1) only their phases can be considered, presenting the PD as a nonlinear link and BH as a differentiating link.

In addition, when moving to a mathematical model, it is necessary to take into account the corresponding phase and frequency transformations due to the action of noise and the reaction of real PD and BH to the sum of signal and noise (1.1).

Thus, when applying to the PD with a sinusoidal characteristic of the signals of the form (1.1), the voltage at its output will be [14]:

$$U_{ФД} = K_{FD(} A_0 \sin\varphi + N_{\varphi}$$

where $K_{FD}$ - FD transfer rate;

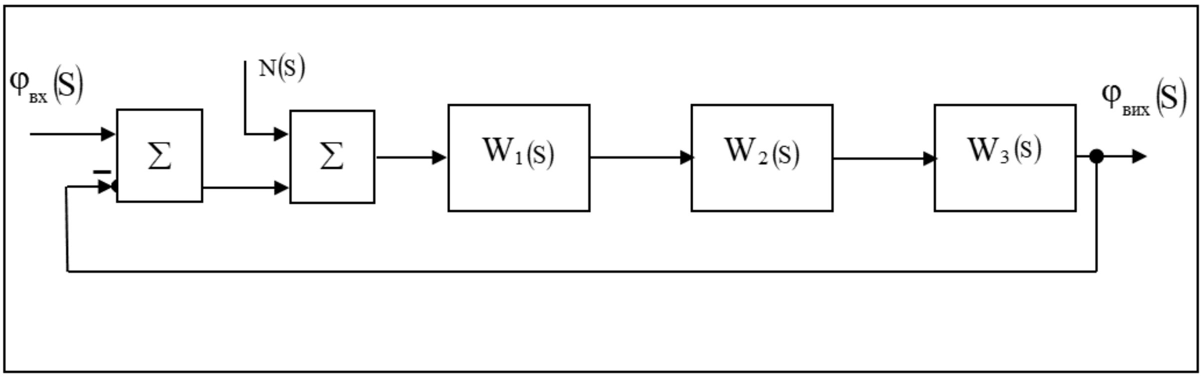

**Figure 1:** The block diagram of the closed synchronization system

The input and output signals of the synchronization system are written, respectively, in the form

$N_\varphi$ - equivalent phase noise, and $N_\varphi = N_C cos\varphi + N_S cos\varphi$

$N_C$ and $N_S$ - cosine and sinusoidal component of the additive white noise $n(t)$ that has passed through the electoral links of the receiver $\varphi = \varphi_{вх}(t) - \varphi_{вих}(t)$/

Since in this paper we consider CSS of high accuracy, we will assume that the magnitude of the phase error (or its variance) satisfies the conditions of smallness [8], which allows us to consider a linear model. If the input noise is white, with a one-way spectral density $N_0/2$, then as shown in [15,16], the equivalent phase noise $N_\varphi$ is also approximately white.

The energy spectrum of the reduced phase noise, listed at the input of the system, will be:

$$G_N(\omega) = N_0/\left(2A_0^2\right) \tag{1.2}$$

Thus, at the input of the closed loop we have the sum of two signals: $\varphi_{вх}(t)$ and $N(t)$ with energy spectra $G_{\varphi_{ВХ}}(\omega)$ and $G_N(\omega)$, accordingly.

The voltage at the output of the frequency discriminator (FD) is proportional to the frequency of the total signal at its input and is defined as [15, 23]:

$$U_{FD}(t) = K_{FD}\left[\dot{\varphi}_{inp}(t) + \frac{1}{K_m}\frac{d\theta}{dt}\right] = K_{FD}\dot{\varphi}_{inp}(t) + N_{FD}(t)$$

where $\varphi_{inp}(t)$ is the modulating function,

$K_{FD}$ - transfer rate of frequency discriminator,

$K_m$ - modulation index.

$$N_{FD}(t) = \frac{K_{FD}}{K_m}\frac{d\theta}{dt},\ \theta = arctg\frac{(U_n/U_c)sin\psi}{1+(U_n/U_c)cos\psi},\ \psi = (U_n/U_c)$$

Thus, at the output of the frequency discriminator, when the signal exceeds the interference, we also have the sum of the useful component and the equivalent frequency noise/

If we denote the amplitude of the signal limitation $R_0$, then $R_0 \le A_0 \max$ the energy spectrum of the equivalent frequency noise $G_{NЧД}(\omega)$, as shown in [16, 22], will be:

$$G_{NЧД}(\omega) = C(P_m)\omega^2 G_n(\omega) \tag{1.3}$$

where $C(P_m)$ is a constant that depends on the power of the modeling process;

$G_n(\omega)$ - energy spectrum of input noise.

Note that the differentiating link that multiplies the input spectrum by the value $\omega^2$ can be a mathematical model of FD. If the transmission factor of this link is multiplied by the value

$A_0\sqrt{C(P_m)}$, then as the input noise common to both channels, we can consider the equivalent phase noise $N(t)$, listed at the input of the system, with the energy spectrum (1.2).

In the General case, the phase modulation of the signal contains four components:

$$\varphi_{вх}(t)=d(t)+M(t)+\Delta\psi(t)+N(t) \tag{1.3}$$

Where $d(t)$ - Doppler shift at the input;

$M(t)$ - useful angular modulation;

$\Delta\psi(t)$ - instability of generators.

Depending on the application of the synchronization system, some components in the above expression are useful, others - obstacles.

If the repeater is installed on a satellite with a low orbit, the main error in phase tracking will be due to Doppler frequency deviations. Thus, at an altitude of the satellite orbit of 2000 km, the frequency instability due to Doppler shift is $\nu_Д$ =7×10-5 [1].

If the instability of the generators is of the order of $\nu_G$ = $10^{-6}$ and the carrier frequency is 10 GHz, the frequency deviation due to the Doppler effect and the instabilities of the generator, respectively, will be $\Delta f_D$ = 7 MHz, $\Delta f_D$ = 0.1 MHz [2, 24].

Thus, when transmitting a TV World Cup signal with a bandwidth $\Delta F$ = 60 MHz, the instability of the generators has little effect on noise immunity ( $\Delta f_Г << \Delta F$ ) and they can be ignored [2,5].

Take in expression (1.3) $M(t)=\Delta\Psi(t)=0$ and $\mathrm{d}(t)$ set the function of polynomial type [14, 20]:

$$d(t)=\varphi_0+\sum_{r=0}^{N-1}\left(\Omega_r t^{r+1}\right)\left|(r+1)\right|. \tag{1.4}$$

In Figure 1.2. marked: $\mathrm{W}_1(\mathrm{S})$ - transfer function of the phase discriminator (FD), $\mathrm{W}_2(\mathrm{S})$ - filter (F), $\mathrm{W}_3(\mathrm{S})$ - adjustable generator (AGn), which have the following form:

$$W_4(S)=K_1+\left(D_1(S)\Big/F_1(S)\right) \qquad W_3(S)=K_3\Big/S=D_3(S)/F_3(S)), \tag{1.5}$$

where: $K_1=A_1K_{ФД}$ ;

$K_3$ – AGn gain;

$S$ – Laplace operator.

In the following we will consider synchronization systems with a proportional-integrating filter (PIF) in a closed loop with a transfer function of the form [11, 12]:

$$W_2(S)=(T_1S+1)\Big/(T_2S+1) \tag{1.6}$$

If the condition is met $\mathrm{T}_1/\mathrm{T}_2 \leq\leq 1$, then such a filter is close to the ideal integrator (IF) with a transfer function [11, 21]:

$$W_2(S)=\left((T_1S+1)\Big/(T_2S)\right) \tag{1.7}$$

In accordance with the structural scheme (Fig. 1.1) and taking into account the transfer functions of the links (1.5), (1.6), the transfer function for the error of the CSS will be:

$$W(S)=\frac{1}{1+W_1(S)W_2(S)W_3(S)}=\frac{T_2(S+1)S}{a_0S^2+a_1S+a_2}=\frac{D_{\varphi з0}(S)S^{\nu_з}}{F_з(S)}, \tag{1.8}$$

where: $\mathrm{a}_0=\mathrm{T}_2$, $a_1=A_0KT_1+1$, $a_2=A_0K$, $K=K_1\Big/K_3$, $D_{\varphi з0}(S)=T_2(S+1)$

From expression (1.8) it is seen that the achievement of invariance in the CSS is impossible, because equality must be observed $\mathrm{D}_{\varphi}{}^{3}0(\mathrm{S})=0$.

To determine the error of the SSS in the steady state, we decompose the transfer function $W_\varphi(S)$ around the point S = 0 into the Taylor series.

Then:

$$\varphi(t)=W_{\varphi}(p)\varphi_{вх}(t)=\sum_{k=0}^{m}(C_k/k)p^k\varphi_{вх}(t)\ , \tag{1.9}$$

where: $W_{\varphi}(p)=W_{\varphi}(S)\Big|_{s=p}$, $p={}^{d}\!/_{dt}$, $C_k=\left[Д^k W_{\varphi}(p)/Д\,P^k\right]_{P=0}$, $k=1,2,...,m$

Substituting the expression (1.4), (1.8) in equation (1.9) we find a constant error in the CSS.

In the case r = 1 in (1.4) we have $\varphi_{13}=\Omega_0/K$

At r = 2 $\varphi_{23}=\Omega_0 C_1+2\Omega_1 C_2+2\Omega_1 C_1 t$

Where: $C_1=1/R_0K$ , $C_2=\left[2A_0KT_2-(A_0KK_3+1)\right]/A_0K$

That is, the CSS with PIF the mutual fund in this case is inoperable.

To eliminate this shortcoming, it is necessary to increase the order of astatism of the CSS, in the first case to = 2, in the second, to = 3.

In this case, the PIF (1.6) is replaced by IF (1.7) or two series-connected IF.

To switch from the link with the transfer function (1.6) to (1.7), the parameter $T_1$ must be reduced and $T_2$ increased.

Since both of these parameters are included in the characteristic equation of the CSS $F_3(S)=0$, their change will affect the quality of the transition process.

Let's evaluate this influence. The characteristic equation of CSS has two roots $S_{1,2}=\left(-a_1\pm\sqrt{a_1^2-4a_0a_2}\right)\Big/2a_0$, and the coefficient $a_0$ depends on the parameter $T_2$, and $a_1$ on $T_1$. Therefore, $a_1$ it decreases and $a_0$ increases, which causes a decrease in the absolute value of the roots (or their real parts), the imaginary parts of the roots increase, the transition process becomes oscillating and weakly attenuating.

In this case, as shown in [20, 22], the choice of system parameters must be made under the condition of compromise adjustment.

A similar situation arises in the SSS of a higher order, the approach of the filter in a closed loop to the integrating second order also worsens the transition process [13,17].

In addition, as follows from the relations and conclusions given in [15,17], for CSS, by switching from PIF to IF it is possible to reduce the permanent error, but it is not possible to eliminate it completely, and at r = 2 in (1.4) the system remains inoperable .

Along with the external influence on the quality of the phase synchronization system can cause internal disturbances, the main of which in phase-coherent synchronization systems are the instability of the adjustable generator [2, 20]. The task of assessing the impact of instability of generators in the communication channel on the efficiency of a closed synchronization system under the influence of external additive Gaussian noise and Doppler frequency shift is an urgent scientific problem that must be solved in improving the structure of phase synchronization of different types.

Coherent reception requires accurate knowledge of the current phase of the carrier oscillation. When using the synchronization system as a phase filter, the input signal is, in accordance with expression (1.3) the sum $d(t)+\Delta\psi(t)$, where $\Delta\Psi(t)=\Psi 1(t)-\Psi 2(t)$, $\Psi 2(t)$ is the instability of the adjustable generator. Processes $M(t)$ and $N(t)$ in this case are an obstacle.

The phase error variance consists, thus, of four components [13,21]:

$$\sigma_{\varphi}^2=\sigma_{d}^2+\sigma_{\Delta\varphi}^2+\sigma_{M}^2+\sigma_{N}^2, \tag{1.10}$$

each of which according to spectral theory is defined as follows:

$$\sigma_1^2=\sigma_d^2+\sigma_{\Delta\varphi}^2=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_{\varphi}(j\omega)\right|^2 G_S(\omega)d\omega\,, \tag{1.11}$$

$$\sigma_2^2=\sigma_M^2+\sigma_N^2=\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|W_{\varphi}(j\omega)\right|^2 G_n(\omega)d\omega\,, \tag{1.12}$$

where $W\ (S)=1-W_{\varphi}(S)$.

For this case:

$$G_S(\omega)=G_d(\omega)+G_{\Delta к}(\omega),\ G_n(\omega)=G_M(\omega)+G_N(\omega).$$

The transfer function by error of a closed synchronization system is defined by expression (1.8) [4,14], where is $W_3(S)$ the adjustable transfer function of the generator.

The transfer function $W_3(S)$ will be defined by the following expression:

$$W_3(S)=\left[W_1(S)W_2(S)W_3(S)\right]/\left[1+W_1(S)W_2(S)(S)W_3(S)\right] \qquad (1.13)$$

From expressions (1.8), (1.13) it is seen that the value $\sigma_\varphi^2$ can be minimized only by appropriate selection of parameters of links $W_1(S)$ and $W_3(S)$. Since these parameters are included in the characteristic equation of a closed synchronization system $F_3(S)$ = 0, changing them to reduce the phase error variance will worsen the quality of the transient in a closed synchronization system [3, 22]. That is, it is not possible to completely reduce the effect of phase instability of generators in a closed synchronization system. Possibilities for minimizing the phase error variance in combined synchronization systems and development of a method for the synthesis of open communication under the condition min $\sigma_\varphi^2$ need further research.Obviously, the further development of the process of minimizing the phase error requires solving problems to change the scheme of construction of the synchronization system. One of the ways to solve this is the synthesis of combined synchronization systems in the direction of the introduction of open communication. This issue is sufficiently covered in the works [18, 19]. The purpose of such research is to solve the problem of synthesis of more complex connections in combined synchronization systems with variable structure and with logical devices that increase the order of astatism of the system, reduce the variance of constant and transient errors in the carrier frequency tracking in the presence of noise in the communication channel. languages, which are currently unsolved and is an urgent scientific problem, the solution of which is devoted to this work [23, 24, 25]. The block diagram of one of the variants of the combined synchronization system is shown in Fig. 2. The final stage of the synthesis of more complex connections in combined synchronization systems is the solution of a number of problems, namely:

- development of scientifically substantiated schemes of synchronization of communication systems in the direction of minimizing the variance of the phase error while ensuring high system speed.
- assessment of the marginal capabilities of the proposed schemes to increase the order of astatism of the synchronization system.

In turn, the development of various variants of such schemes of open communication of carrier frequency synchronization systems and evaluation of their capabilities to increase the order of astatism is a separate scientific problem, the solution of which determines the relevance of the proposed research in the following works.

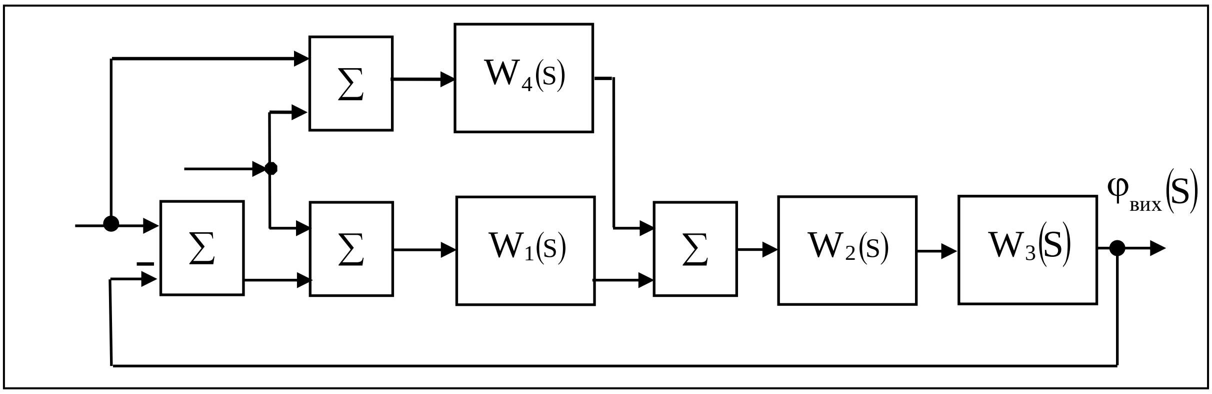

**Figure 2:** Block diagram of a linear model of a combined synchronization system with an additional link

It should be noted that in general, when receiving the input signal by the synchronization system, the actual problem is to reduce the effect of noise interference in order to increase the signal-to-noise ratio (SNR). This problem is also relevant for other technical systems operating under various influencing factors. One of the methods of reducing the impact of noise interference at the input of the synchronization system is quite illustratively presented in [20,22]. The scientific article [25] is devoted to orthogonal Lager filtering of noise processes, which are described by linear random processes. The proposed filtration method makes it possible to reduce the influence of noise interference, which is described by stationary linear random processes, during the operation of correlation systems. The idea of this method is to use orthogonal Lagerr filters as input links of the correlation system. This method can be used in further studies to improve the efficiency of the process of minimizing the variance of the phase error in the process of monitoring the carrier frequency.

It should be noted that the quality of the carrier frequency estimate is significantly affected by the parameters of the noise environment, which can be formed by various environmental factors, among which are both external and internal noise. Among the list of internal noises of some interest in the process of frequency estimation may take into account the internal noise associated with changes in nonlinear properties of composite materials of the synchronization system under the influence of increasing number of additional tracks of charge carriers due to decay in the material structure of radioisotope inclusions [26]. This can affect the growth of the internal noise of the synchronization system and requires its consideration in the development of advanced systems.

## 3. Conclusions

The paper presents the results of theoretical research and evaluation of the capabilities of closed-phase phase synchronization systems to ensure high noise immunity, accuracy and speed with simple design. The research was carried out in relation to the variant of the scheme of construction of the system of phase synchronization of the closed type at tracking of the carrier frequency in the conditions of presence of noise in the communication channel offered in article.

It is shown that taking into account the additive Gaussian noise and instability of generators, the desire to minimize the phase error variance in the class of closed synchronization systems causes a deterioration of the system dynamics and does not increase the order of astatism.

The paper considers the influence of phase instability of generators in communication channels on minimizing the phase error variance in a closed synchronization system against the background of additive Gaussian noise and Doppler frequency shift. It is shown that for a closed system, minimizing the variance of the phase error by reducing the parameters of the transfer functions of the components of the system in the phase instability of the generators will worsen the quality of the transient process

A further direction of research is to work on the synthesis of broken communication in combined synchronization systems against the background of additive Gaussian noise, taking into account the phase instability of the generators.

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