



RESEARCH ARTICLE

Ensuring Thermal Stability of Generators in Information Systems

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ARTICLE INFO	ABSTRACT
Received: Sep 16, 2025	This paper addresses the issue of improving the thermal stability of oscillators, which enables an increase in the efficiency of an information system. This is primarily related to the automation of the process of collecting, processing, and displaying information. The possibility of enhancing the thermal stability of the information system's oscillators is presented, based on the approach of joint processing of the phases of the generated signals used in the work. It is noted that utilizing the capability to improve the oscillators' thermal stability allows for a qualitative enhancement of the information system's characteristics. The foundation for implementing this capability is a more comprehensive use of information links within the system. This makes it possible to compensate for the influence of external factors on the accuracy and stability of the generated signals by simultaneously measuring the phases of the carrier signals.
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INTRODUCTION

In the modern world, where digitalization has permeated all spheres of activity, the reliability and uninterrupted operation of information systems are of critical importance. The effective functioning of such systems directly depends on the stability of the power supply, and generators are a key infrastructure element providing backup power in case of failures in the main grid. However, the operation of generators is associated with the generation of a significant amount of heat, which can negatively impact their performance and service life. Generator overheating not only reduces their efficiency but also poses a serious threat to the stable operation of information systems, potentially leading to failures and significant financial losses. In this regard, ensuring the thermal stability of generators in information systems is a relevant and important task that requires a comprehensive approach and the application of modern technical solutions.

Temperature instability in the oscillators of transmitting and receiving equipment leads to a decrease in the effectiveness of correlation processing of wideband signals in the information system and, as a consequence, to a reduced information transfer probability.

The development of humanity's productive forces at the present stage is linked to the advancement of science-intensive technologies and is characterized by the constant change of technological paradigms. The current stage of development for leading economies can be characterized as the mature state of the sixth technological paradigm.

Studying the main manifestations of technological paradigms, the patterns of their emergence, development, and succession, allows for a more accurate forecasting of the main trends in the development of engineering and technology, as well as the formation of societal needs. It should be noted that each transition to a subsequent technological paradigm is associated with an increasing integration of individual factors in science and engineering into a unified whole, which leads to accelerated development and higher efficiency. Such integration enables an increase in the efficiency of information systems and is characterized by an even greater unification of the various factors that determine societal development. The core of the technological paradigm comprises [1-6]:

- Nanoelectronics;
- Molecular photonics and nanophotonics;
- Nanomaterials and nanostructured coatings;
- Nanosystems engineering;
- Biotechnology;
- Nanobiotechnology;
- Information technology;
- Cognitive sciences;
- Social and humanitarian technologies;
- Convergence of nano-, bio-, info-, and cognitive technologies (the so-called NBIC convergence).

The improvement of information system efficiency is determined, first and foremost, by an increase in the frequency stability of the signals generated within these systems.

1. MATHEMATICAL MODEL AND SOLUTION METHOD

Considering the external factors whose impact leads to a change in the frequency of oscillators and, consequently, to a change in the frequency stability of the generated signals. One of the most significant factors, as noted, is the influence of the ambient temperature at which the oscillator operates. Furthermore, it has been determined that the most technically effective approach to reducing the influence of the operating temperature on the frequency is thermostabilization. In turn, this approach can be implemented either by using temperature-stable components of the oscillator or by thermostabilizing the operating mode of the auto-oscillator's active element [7-10].

Each of these approaches is technically complex to implement. Furthermore, each of them creates conflicting requirements for frequency stability and the energy performance of oscillators. Moreover, the complexity of the technical implementation increases very rapidly as the requirements for frequency stability grow. At the same time, to improve the frequency stability of oscillators, it is possible to use phase processing of the signals from the system of oscillators that are part of the information system.

Let us outline the fundamentals of processing signals generated by a set of oscillators in an information system [11-12]:

- For the signal generated by each oscillator with some deviation from the nominal (required) value f , the signal phase is measured over a certain time interval of duration t (wherein the duration of the measurement time interval is known with some error);
- Based on the measured signal phase value, its deviation from the nominal value is determined (the nominal value of the signal phase is understood as the value corresponding to the oscillator operating at the nominal frequency f_0 over a time interval of nominal duration t_0);
- Based on statistical processing using the maximum likelihood method, an estimate of the true duration of the measurement time interval or its deviation from the nominal duration is determined (wherein the variance of the obtained estimate is significantly less than the instability of the time interval generation);
- The found value of the measurement time interval duration allows for determining the frequency of the oscillator at which the signal is generated, thereby compensating for its deviation from the required value.

To evaluate the influence of temperature change on the estimation of the measurement time interval duration and the difference between the actual average and computed nominal values of the oscillator signal frequencies, we will use the fundamental relations from work [13-14]. We will apply this relation in a simplified form:

$$\Delta t = \frac{\sum_{k=1}^K \Delta \varphi_k \sigma_k^{-2} f_{0k}^{-1}}{2\pi \sum_{k=1}^K \sigma_k^{-2}} \quad (1)$$

Let us denote $dt^{(1)}$ as the error in determining the time interval duration, which arises due to the deviation of the oscillator's average frequency from the nominal value under the influence of temperature change. This component of the error in estimating the measurement time interval duration can be expressed as follows:

$$\delta t_k^{(1)} = \frac{\partial(\Delta t)}{\partial f_{0k}} \delta f_{0k} \quad (2)$$

Differentiation in formula (2) with respect to the variables f_{0k} can be easily performed, which makes it possible to write the derivative in explicit form.

$$\delta t_k^{(1)} = -\frac{m_k \Delta \varphi_k \sigma_k^{-2} f_{0k}^{-2}}{2\pi \sum_{k=1}^K m_k \sigma_k^{-2}} \delta f_{0k} \quad (3)$$

Taking into account formula (3), the error component due to the difference between the average frequency over the measurement interval and the nominal value can be expressed as:

$$\delta t^{(1)} = -\frac{\sum_{k=1}^K m_k \Delta \varphi_k \sigma_k^{-2} f_{0k}^{-2} \delta f_{0k}}{2\pi \sum_{k=1}^K m_k \sigma_k^{-2}} \quad (4)$$

The specified component of the deviation in the measurement time interval duration is a random variable, since the change in the temperature of the external environment and the active element, which leads to the frequency change, is random. One of the important characteristics of the random variation of the measurement time interval duration is the standard deviation. Taking into account the independence of the deviations of the mean values of the external influencing factors, the magnitude of the deviation can be expressed as follows:

$$\sigma_{\delta t^{(1)}} = \frac{\sqrt{\sum_{k=1}^K m_k^2 (\Delta \varphi_k)^2 \sigma_k^{-4} f_{0k}^{-4} (\delta f_{0k})^2}}{2\pi \sum_{k=1}^K m_k \sigma_k^{-2}} \quad (5)$$

When analyzing this component of the frequency instability of the generated signals, let us consider a specific but important case. In the practical application of oscillators in an information system, the relationship between the frequency change of a single oscillator and the change in external ambient temperature is determined by the temperature coefficient of frequency. This dependence is expressed as follows:

$$\delta f_{0k} = K_k^{TK\varphi} \cdot f_{0k} \cdot \Delta T, \quad (6)$$

where $K_k^{TK\varphi}$ is the temperature coefficient of frequency; ΔT is the change in the external ambient temperature from the nominal value defining the operating conditions of the information system devices.

This relationship is necessary for developing a method of oscillator frequency thermostabilization aimed at reducing the dependence of the oscillator's frequency on the ambient temperature.

After substituting expression (6), which defines the relationship between the change in ambient temperature and the oscillator frequency, into relation (4), the following formula is obtained for determining the error in estimating the time interval duration due to the change in the average frequency of each oscillator with temperature variation.

$$\delta \alpha^{(1)} = - \frac{\Delta T \left(\sum_{k=1}^K m_k \Delta \varphi_k \sigma_k^{-2} f_{0k}^{-1} K_k^{TK\varphi} \right)}{2\pi \sum_{k=1}^K m_k \sigma_k^{-2}} \quad (7)$$

Relation (7) shows that the deviation in the estimate of the measurement time interval duration is determined by the average value of the phase deviations of the signals generated by the oscillators of the information system. Thus, even under conditions of compact placement with the same temperature change for all oscillators, the joint processing of the phase deviations of their oscillations makes it possible to reduce the error in determining the time interval duration and thereby reduce the error in determining the frequency of the information system's oscillators. This result fundamentally differs from the case of using oscillators with opposite sign values of $K_k^{TK\varphi}$. As formula (7) shows, even with identical $K_k^{TK\varphi}$ values of the information system's oscillators, a reduction in the frequency change of the oscillators is observed with changes in the ambient temperature.

The obtained result shows that the use of joint phase processing of oscillator signals makes it possible to correct the frequency change of each oscillator and thereby increase the frequency stability of each signal generated in the information system. Consequently, this method allows for reducing the temperature-induced frequency instability of the oscillators. Formula (7) provides a quantitative characteristic of the improvement in the thermal stability of the oscillators in the information system, achieved through the joint processing of oscillator signals based on a statistical approach using the likelihood function.

Analysis of the obtained results shows that the use of joint frequency processing of oscillators can lead to both a decrease and, in some cases, an increase in the temperature coefficient of frequency. However, the number of oscillators from the considered set for which $K^{TK\varphi}$ decreased constitutes a significant portion (about 80%) of the entire set of oscillators. Furthermore, the average value of $K^{TK\varphi}$, taken over the entire set of oscillators, decreases when using the considered frequency stabilization method.

The most comprehensive analysis of the relationship between the parameters of each oscillator (frequency, relative instability, $K_0^{TK\varphi}$) and the number of oscillators with achievable $K^{TK\varphi}/K_0^{TK\varphi}$ reduction can only be performed by investigating the change in $K^{TK\varphi}/K_0^{TK\varphi}$ averaged over the set of oscillators and the change in $K^{TK\varphi}/K_0^{TK\varphi}$ for each oscillator across realizations.

Taking into account the above, for a more complete representation of the obtained research results, Figures 3-6 show the graphs of the dependence of $K^{TK\varphi}/K_0^{TK\varphi}$ for various realizations and

parameter combinations. The parameters of the oscillators for which the dependencies shown in Figures 1-4 were obtained correspond to the initial data used in constructing Tables 1-4.

Values of $K^{TCF}/K_0^{TCF} < 1$ correspond to an improvement in the thermal stability of the oscillators when they are combined into a system and the approach proposed in [15] is used. Values of $K^{TCF}/K_0^{TCF} = 1$ correspond to the preservation of the oscillators' thermal stability unchanged when they are combined into a system. Values of $K^{TCF}/K_0^{TCF} > 1$ correspond to a degradation of the oscillators' thermal stability after their integration into the system.

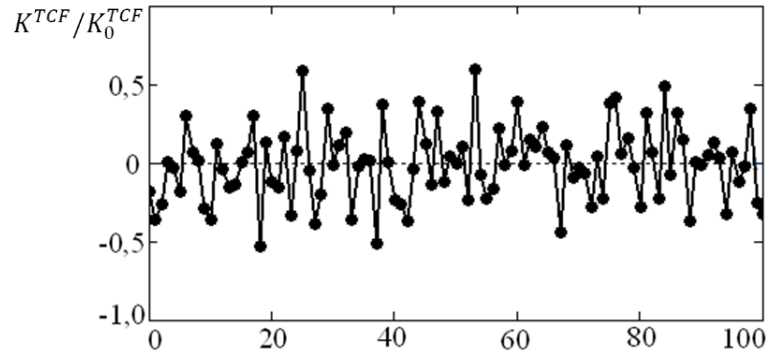


Figure 1 – Statistical distribution of the error in determining the deviation of the duration of the time interval, normalized to the deviation value, in the case of different frequencies and instabilities of the stabilized generators

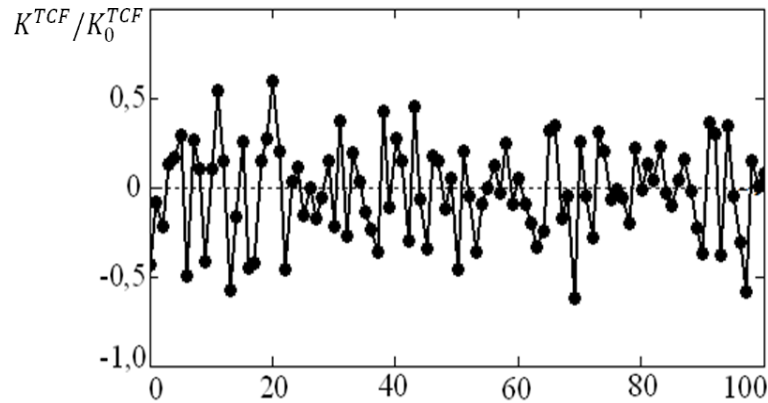


Figure 2 – Statistical distribution of the error in determining the deviation of the duration of the time interval, normalized to the deviation value, in the case of different frequencies and instabilities of the stabilized generators

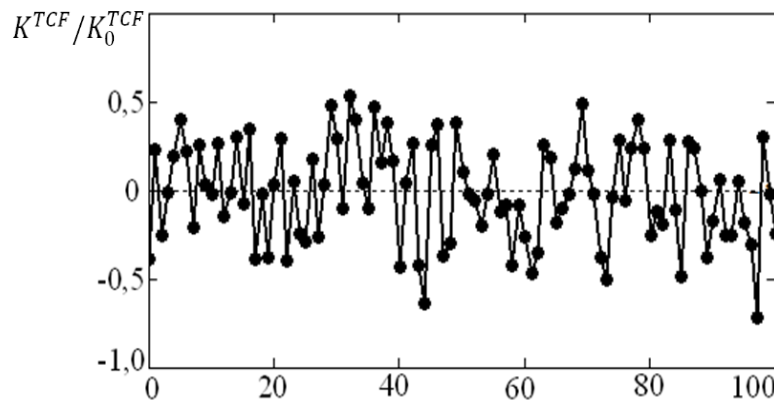


Figure 3 – Statistical distribution of the error in determining the deviation of the duration of the time interval, normalized to the deviation value, in the case of different frequencies and instabilities of the stabilized generators

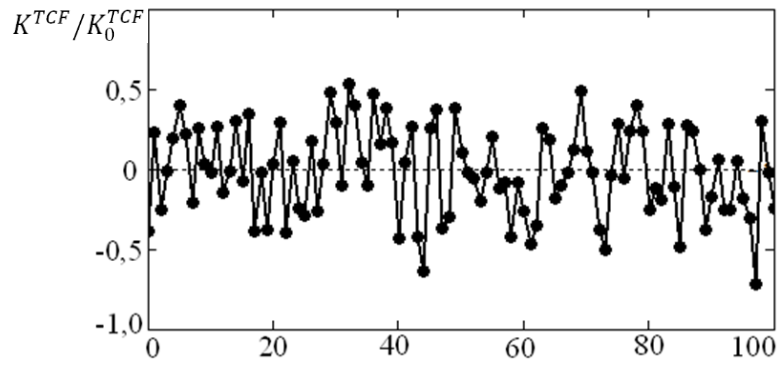


Figure 4 – Statistical distribution of the error in determining the deviation of the duration of the time interval, normalized to the deviation value, in the case of different frequencies and instabilities of the stabilized generators

From the results presented in Figures 3-6, it follows that in all realizations and for any combinations of nominal frequency and relative instability values, the result $K^{TCF}/K_0^{TCF} < 1$ is achieved. This shows that when using the method developed in [16], the thermal stability of the oscillators improves, i.e., when the ambient temperature changes, the change in the frequency of the oscillators will be smaller.

Thus, the statistical processing of oscillator signal phases proposed in [17] makes it possible to reduce the temperature coefficient of frequency and diminish the influence of temperature changes on the frequency variation of the oscillators and the frequency of the generated signals.

The use of the method of joint statistical processing of the phases of signals generated by the information system's oscillators, based on achieving the maximum of the likelihood function, generally reduces the influence of temperature changes on the frequency variation of the oscillator. This means that for the same change (both increase and decrease) in ambient temperature, the frequency change of oscillators integrated into a system will be less than that of a single oscillator.

The application of this method in each specific case can lead to either a decrease or an increase in the temperature dependence of the oscillator frequency. However, the number of oscillators for which a decrease in K^{TCF}/K_0^{TCF} is achieved will be greater than the number of oscillators for which this value increases. The average value of K^{TCF}/K_0^{TCF} across the set of oscillators decreases, meaning the collective stability of the oscillator system is higher than that of a single oscillator.

The use of the statistical stabilization method makes it possible to reduce the average value of K^{TCF}/K_0^{TCF} across the set of possible changes in external factors. However, in some realizations, an increase in the temperature dependence of the frequency of individual oscillators may be observed. Overall, the thermal stability of the oscillator system is higher than that of a single independent oscillator.

2. RESULTS

Research on improving the efficiency of an information system through enhanced thermal stability of oscillators shows that joint phase processing of signals generated within the information system makes it possible to increase the thermal stability of the oscillators without the use of additional technical and technological solutions. The results demonstrated that the achieved improvement in oscillator thermal stability enables:

- reducing the frequency mismatch between the received and reference signals, thereby increasing the output level during correlation processing of wideband signals;
- decreasing the bit error rate as the level of the received signal increases, and consequently improving the reliability of digital information stream transmission.

- At the final stage, studies were conducted to determine the improvement in the efficiency of digital systems during the transmission of digital information streams. The efficiency of the system during information transmission is defined as the product of the bit error probability and the number of transmitted information bits.

Increasing the efficiency of an information system in transmitting information is determined by the formula:

$$E = (P_{sh})^{-m} \quad (8)$$

where m is the ratio of the volume of transmitted information to the unit of measurement 100 MB.

The results of the studies are presented in Tables 1-4.

Table 1 Increasing the efficiency of the information system with increasing thermal stability of generators (K_0^{TCF} values for generators with the same nominal frequency and relative instability)

K_0^{TCF} \ K^{TCF}	0,88	0,83	0,41	0,81	0,66	0,72	0,79	0,36	0,83	0,73
$m = 1$	1,14	1,20	2,44	1,23	1,51	1,39	1,27	1,31	1,20	1,37
$m = 2$	1,29	1,45	5,94	1,52	2,31	1,93	1,66	1,73	1,45	1,88
$m = 5$	1,89	2,54	8,63	2,87	7,98	5,17	3,25	3,94	2,54	4,82
$m = 10$	3,59	6,44	7,45	8,22	16,7	26,7	9,57	15,6	6,44	23,3
$m = 20$	12,9	41,5	55,4	13,1	41,3	7,13	6,43	24,1	41,5	36,7

The presented results show that improving the thermal stability of the oscillators in the receiving and transmitting equipment of an information system makes it possible to increase the system's efficiency by reducing the bit error probability during the transmission of digital information streams. This is manifested in an increase in the information transmission rate while maintaining the operating temperature range of the equipment. However, the improvement of the equipment's thermal stability can also be considered from another perspective. In particular, expanding the operating temperature range within which the bit error probability does not exceed a specified value allows for a reduction in the requirements for thermal regulation devices. This makes it possible to simplify these devices or even eliminate them, which in turn reduces the cost, weight, size, and power consumption of the information system equipment.

Table 2. Increasing the efficiency of the information system with increasing thermal stability of generators (K_0^{TCF} values for generators with the same nominal frequency and different relative instability)

K_0^{TCF} \ K^{TCF}	0,74	0,78	0,76	0,83	0,72	0,72	0,74	0,72	0,83	0,86
$m = 1$	1,35	1,28	1,32	1,20	1,39	1,39	1,35	1,39	1,20	1,16
$m = 2$	1,83	1,64	1,73	1,45	1,92	1,92	1,83	1,92	1,45	1,35
$m = 5$	4,51	3,46	3,94	2,54	5,17	5,17	4,51	5,17	2,54	2,13
$m = 10$	20,3	12,1	15,6	6,44	26,7	26,7	20,3	26,7	6,44	4,52
$m = 20$	41,2	14,3	24,1	17,6	71,3	71,3	41,2	71,3	41,5	20,4

The research results show that in the case of oscillators with the same relative instability and different nominal frequencies of the generated signals, the improvement in efficiency is more significant. Moreover, as in the first case, the efficiency increases with the number of bits transmitted in the stream.

Table 3 Increasing the efficiency of the information system with increasing thermal stability of generators (values of K_0^{TCF} for generators with different nominal frequencies and the same relative instability)

$K_0^{TCF} \backslash K^{TCF}$	0,79	0,96	0,89	0,94	0,94	0,81	0,92	0,81	0,91	0,68
$m = 1$	1,27	1,04	1,12	1,06	1,06	1,23	1,09	1,23	1,10	1,47
$m = 2$	1,60	1,09	1,26	1,13	1,13	1,52	1,18	1,52	1,21	2,16
$m = 5$	3,25	1,23	1,79	1,36	1,36	2,87	1,52	2,87	1,60	6,88
$m = 10$	10,56	1,50	3,21	1,86	1,86	8,23	2,30	8,23	2,57	27,3
$m = 20$	21,5	2,26	10,28	3,44	3,44	19,8	5,30	19,8	6,59	43,1

The results presented in Table 3, like the previously provided data, show that improving thermal stability makes it possible to reduce the bit error probability during the transmission of digital information streams and, consequently, decrease the number of incorrectly transmitted bits. As a result, an increase in the information transmission rate is achieved.

The results of the final analysis case are presented in Table 4.

Table 4 Increasing the efficiency of the information system with increasing thermal stability of generators (K_0^{TCF} values for generators with different nominal frequencies and different relative instability)

$K_0^{TCF} \backslash K^{TCF}$	0,83	0,71	0,65	0,73	0,79	0,86	0,92	0,88	0,94	0,78
$m = 1$	1,09	1,13	1,26	1,26	1,20	1,16	1,09	1,13	1,06	1,28
$m = 2$	1,18	1,29	1,64	1,44	1,39	1,35	1,18	1,29	1,13	1,64
$m = 5$	1,51	1,89	3,46	2,11	1,95	2,13	1,52	1,89	1,36	3,64
$m = 10$	2,30	3,60	12,0	4,83	3,91	4,52	2,30	3,59	1,86	4,12
$m = 20$	5,30	12,9	21,1	15,7	12,1	11,6	4,29	6,91	3,44	21,2

The results presented for the most general case of oscillators with different nominal frequency values and relative instabilities confirm the previously made conclusion about improving the efficiency of the information system based on enhancing the thermal stability of the oscillators in the receiving and transmitting equipment. Furthermore, the growth in the information system's efficiency increases with the volume of transmitted digital streams.

Thus, the conducted research shows that:

- the use of joint processing of signals generated by the information system's oscillators makes it possible to reduce the temperature coefficient of frequency instability and thereby ensure higher stability and accuracy of signal generation in information systems;
- the improvement in the stability and accuracy of signal generation in information systems ensures a reduction in the bit error probability during the transmission of digital streams in the information system channels;
- the reduction in bit error probability achieved through the improvement of the oscillators' thermal stability leads to an increase in the efficiency of the information system. Moreover, the achieved improvement in efficiency during the transmission of digital streams at a rate of 100 Mbps ranges from 10% to 30%.

CONCLUSION

Existing technical solutions for improving the thermal stability of generators in receiving and transmitting equipment in information systems do not fully utilize all the potential for improving thermal stability. A well-known method for processing signals from simultaneously and

independently operating generators in information systems allows for improving the thermal stability of generators in receiving and transmitting systems. Overall, the results of the justification for using this method can be summarized as follows:- The use of the method of joint statistical processing of the phases of signals generated by the oscillators of the information system, based on achieving the maximum of the likelihood function, generally reduces the influence of temperature changes on the frequency variation of the oscillator. This means that for the same change (both increase and decrease) in ambient temperature, the frequency change of oscillators integrated into a system will be less than that of a single oscillator:

- The use of a method of joint statistical processing of phases generated by generators of an information signal system, based on achieving the maximum likelihood function, makes it possible to generally reduce the influence of temperature changes on changes in generator frequency;
- The application of this method in each specific case can lead to either a decrease in the temperature dependence of the generator frequency or an increase in it. In this case, the number of generators for which a decrease in K^{TCF}/K_0^{TCF} is achieved will be greater than the number of generators for which this value increases. The average value of K^{TCF}/K_0^{TCF} for the set of generators decreases, i.e., the overall stability of the generator system is higher than that of a single generator;
- Using the statistical stabilization method makes it possible to reduce the average value of K^{TCF}/K_0^{TCF} over a set of possible changes in external factors. However, in some implementations, an increase in the temperature dependence of the frequency of individual generators may be observed.
- Research into applicability in information systems has shown that:
- Joint processing of signals from information system generators significantly reduces the impact of temperature on frequency stability, thereby increasing the accuracy of signal generation.
- Improved signal stability and accuracy leads to a reduced probability of errors during data transmission over information system channels.
- The reduced probability of bit errors, achieved by improving the temperature stability of generators, increases the efficiency of the information system. In particular, when transmitting digital streams at a rate of 100 Mbps, the efficiency gain ranges from 10% to 30%.

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