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INFORMATION TRANSMISSION METHODS WITH THROUGH THE USE OF STOCHASTIC SIGNALS

Ruslan M. Didkowsky

Cherkasy State Technological University, Cherkasy, Ukraine

The paper provides an overview of information transmission methods through the use of the noise carrier proposed by researchers from the middle of the last century to the present day. It is shown that the main areas of application of autocorrelation systems with the noise carrier is the confidential communication system construction, where the protection of the transmitted information from intercepting and protection of the channel from the extraneous information injecting are of priority. Methods of information transfer, discussed in the paper, allow solving the problem of sustainable communication in difficult conditions of signal propagation with simple technical means, especially in multipath channels. The paper studies the most urgent theoretical and practical problems relating to communication systems with the noise carrier.

Introduction

It's important to mention that the history of radio engineering started with the ultra wideband communication systems using random form signals. A. Popov and his follower G. Marconi were using damped high frequency electrical oscillations produced by spark discharge (see, example [1]).

But the invention of a vacuum tube-based harmonic signal generator [2] caused supplanting of wideband signals by narrowband signals for more than 40 years.

Harmonic signal as a carrier wave provides a developer with only few parameters to modify: amplitude, phase, frequency. That's why the last half of XX century was all about finding new methods and carriers for information transmission.

In this context we can remember Mortimer Rogoff's (1950) [3] research, who used "noise wheel" for producing a noise-like signal. Also the work of A.A. Kharkevich (1957), who theoretically proved an ability of information transfer based on the modulated noise [4]. This paper has given a description of constructing of communication systems by means of noise-amplitude and noise-frequency modulation.

A lot of attention of engineers and other specialists has been focused on problems of development of effective methods of information transfer by wideband and ultra-wideband signals since that time.

A few main ways in theory and practice of wideband systems construction have been developed.

The most successful one is the use of noise-like signals [5-8]. In this kind of systems complex form signals are formed by spread-spectrum techniques or by using deterministic inharmonious signals [9]. Signal reception is performed through cross correlation methods (stored-reference). The obtained research results have been widely used in commercial and special government communication systems.

Alternative way of modeling signal with a wide frequency spectrum is to use short and ultra short impulses. The idea of usage of short and ultra short impulses in communication systems comes from military departments of USSR and USA 40th – 50th years of XX century.

Development of ultra wideband communication systems and communication in general, and impulse systems in particular is reviewed in details in paper [10]. This way of research is intensively progressing [11].

In the 80th of XX ct. the publications dedicated to methods of communication systems construction based on chaotic dynamics of nonlinear systems appeared, especially A.S. Dmitriev's researches [12]. Those studies were significantly intensified after discovering the phenomenon of synchronization of chaotic self-excited oscillations and chaotic synchronous response [13-14]. Chaotic communication systems have been in focus not only of domestic [15-16], but also foreign [17-18] specialists for a last couple of decades.

For the last decade researches of using truly noise (stochastic) signals as a carrier for information transfer are very active [19-20]. This can be explained by the abilities that can provide noise signal for communication system:

1) Incredibly high signal structural stealth, high cryptosecurity and spoofing resistance;

2) ability of frequency reuse;

3) connection stability in difficult conditions of signal propagation (multipath fading channel, slit penetration of a signal, channel with random or changeable parameters, and other).

4) comparatively simple structure of transmitter and receiver devices.

Let us study the last one more thoroughly. Since the form of a noise signal on each symbol interval is unpredictable, cross-correlation method is impossible for this case.

So systems with noise signals do not require building precision sources of harmonic signal and devices for spreading their spectrum in transmitter also restore reference, channel estimation, phase and frequency synchronization devices in a receiver. That's why it's a lot easier to construct and maintain a transmitter and receiver.

Evolution of electronic components, wide implementation and usage of digital devices of signal formation and signal processing provides an ability to solve the problems in a new way. Previously that was not possible even with strong theoretic researches. However, these conditions caused a lot of new unsolved problems and tasks such as: development of a theory of a system performance for communication systems with a noise signal, developing effective methods of multi-position and multi-channel modulation of a stochastic signal with a maximum usage of signal information capacity, etc.

Using noise signals in the information transmission is considered to be promising in dealing with issues such as the development of new frequency bands (particularly, sub-terahertz frequency range) [21], and the development of environmentally friendly communication systems [22].

So we can conclude that building ultra wideband systems with a noise carrier is an urgent task for developing theory and technology of telecommunication systems. However, since last decade there were no publications which would give a general idea about main achievements and perspective tasks in this direction of researches.

The purpose of this work is to make an overview of existing methods of transmission of digital information with the help of stochastic signals and perspective researches in this direction.

Classification of systems with noise signals

The above mentioned, classic cross-correlation reception techniques cannot be applied in the system due to the stochastic carrier. There are two basic approaches to the solution of the problem of the information entry in the noise signal.

The first approach involves changing the statistical properties of the noise signal by law of informational message. Parameters that may be subject to modulation include: form of the autocorrelation function, mathematical expectation, variance, higher order cumulants, and others.

Signals of this modulation type require nonlinear processing methods. These methods can be characterized as a generalization of the method of energy receiving signals of unknown shape. This notion of the reference signal is not used.

The second approach involves the transfer of the reference signal through a communication channel with the information signal (transmitted-reference). In this case, the signal receiving is usually performed by autocorrelation methods. It should be noted that this system with the autocorrelation technique provides maximum structural stealth of the signal.

Systems with the stochastic signals can be classified according to other factors, such as the type of a source.

Physical sources are based on the phenomenon of stochastic motion of charge carriers and they generate continuous noise signals [23].

Discrete or digital sources form the stochastic numerical sequence. Getting these sequences may be based on analog-to-digital conversion of a continuous noise signal received from the physical source or digital sensors of random numbers [24].

The resulting stochastic sequence (output digital generator) can be recorded in the device memory. Various transformations can be applied to it. It allows application of advanced multi-channel and multiple-access modulation techniques; and stabilizes the statistical parameters of noise fragments corresponding to symbol spacing.

The paper [25] presents that this stabilization can significantly improve the performance of systems with the stochastic carrier.

Systems with combined noise signals

One of the most common approaches to information transmission by means of noise signals is to use implementations of combined random processes. Methods of their formation and reception at the enough high level of generality and mathematical rigor are described in the papers of V.I. Parfenov and A.P. Trifonov [26].

The simplest version of the transmitter systems with combined noise signals can be constructed according to the block-diagram shown in Fig. 1.

The transmitter has two generators of stationary Gaussian Noise NS-0 and NS-1, which are characterized by different correlation functions $K_0(\tau)$ and $K_1(\tau)$ output signals $x_0(t)$ i $x_1(t)$.

If the input bit λ equals "0", the signal encoder Enc has sustainable value $\alpha_0(t) = 0$. As a result, a managed switch MSw throughout the bit interval $t \in [0; T)$ sends signal $x_0(t)$ to the output of the transmitter.
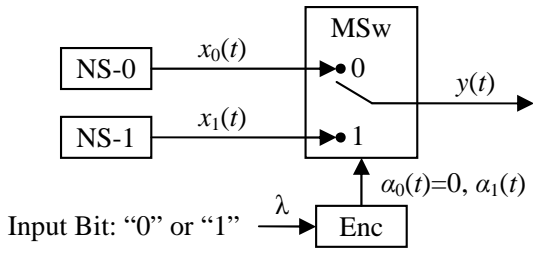
Fig. 1. Block-diagram of the transmitter of communication system with the help of the combined noise signals

When sending "1" during a bit interval signal $\alpha_1(t)$ takes the value 1 or 0 by changing the values in the times $t = \tau_0, \tau_1, ..., \tau_k$. As a result, the output signal $y(t)$ has the form of fragments cortege of a stationary noise.

Depending on the number of generators involved in the formation of the signal, it is called one-, two-, three-component, etc. and indicates the frequency of changes in the properties.

The easiest option is a two-component signal with a single change of the properties. In this case, the signal $\alpha_1(t)$ is as follows:

$$\alpha_1(t) = \begin{cases} 1, & 0 \le t < \tau_0, \\ 0, & \tau_0 \le t < T. \end{cases}$$

Consequently, the output of the transmitter signal has the form

$$y(t) = \begin{bmatrix} x_0(t), \ t \in [0, T), \ \lambda = "0", \\ \begin{cases} x_1(t), \ 0 \le t < \tau_0, \\ x_0(t), \ \tau_0 \le t < T, \end{cases} \lambda = "1". \end{bmatrix}$$

According to the classical model of a communication channel at the receiver input the signal of the following type

$$z(t) = y(t) + n(t), \qquad (1)$$ is observed.

where $n(t)$ is the additive white Gaussian noise.

The optimal system receiver for an ideal observer criterion has the structure shown in Fig. 2.
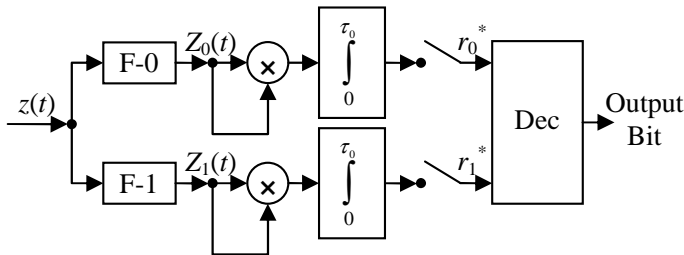

Fig. 2. Block diagram of a receiver for the two-component noise signal with a single change in the properties

A demodulator consists of two energy receivers, which receive signals

$$Z_j(t) = \int_{-\infty}^{\infty} z(\tau) h_j(t - \tau) d\tau, \ j = 0, 1$$

of input filters F-0 and F-1. Impulse characteristics of these filters $h_j(t)$ are defined by the equations

$$h_j(t) = \int_{-\infty}^{\infty} H_j(\omega) \cdot e^{i\omega\tau} d\omega,$$

where

$$H_j(\omega) = \frac{G_i(\omega)}{N_0/2 + G_i(\omega)}, \ G_j(\omega) = \int_{-\infty}^{\infty} K_j(\tau) \cdot e^{-i\omega\tau} d\tau,$$

$j = 0, 1$, N_0 is one-sided noise spectral density of $n(t)$.

At the end of the bit interval ($t = T$) the values

$$r_j^* = \int_0^{\tau_0} Z_j^2(t) \, dt, \ j = 0, 1. \qquad (2)$$

come on decoder Dec.

The decoder decides the value of an output bit by the rule

$$r_1^* \underset{"0"}{\overset{"1"}{\gtrless}} r_0^* + C, \ \ C = \frac{N_0 \tau_0}{4\pi} \int_{-\infty}^{\infty} \ln\left(\frac{1 + 2G_1(\omega)/N_0}{1 + 2G_0(\omega)/N_0}\right) d\omega.$$

According to formula (2), it is clear that the maximum performance of these communication systems is possible at $\tau_0 = T$.

Thus, we come to two important particular cases of a system with the combined noise signals. Let us discuss them below.

System with frequency noise-shift-keying

If the spectral density is $G_0(\omega)$ and $G_1(\omega)$, and $C = 0$ (for example, $G_1(\omega)$ is shifted along the frequency axis copy of $G_0(\omega)$), and $\tau_0 = T$ then the system of this type is called the frequency noise-shift-keying (FNSK) system [27]. That is the system with FNSK is a particular case of a combined noise signal system, provided that the signal spectra differ only in the central frequency and the time property changes coincide with the end of the bit interval.

It should be noted that the energy radiation of the transmitter will be used most effectively if the spectral densities $G_0(\omega)$ and $G_1(\omega)$ are close to rectangular and the relevant frequency ranges do not intersect.

System with amplitude noise-shift-keying

The most simple to implement, and therefore, important for practice, is the amplitude noise-shift-keying (ANSK) [28]. It is a degenerate case of a combined noise signal system provided that $x_0(t)$ is identically zero throughout the range and the bit interval and $\tau_0 = T$.

In this case, both the structure of the transmitter (Fig. 1a), and the receiver structure (Fig. 1b) of the system are simplified.
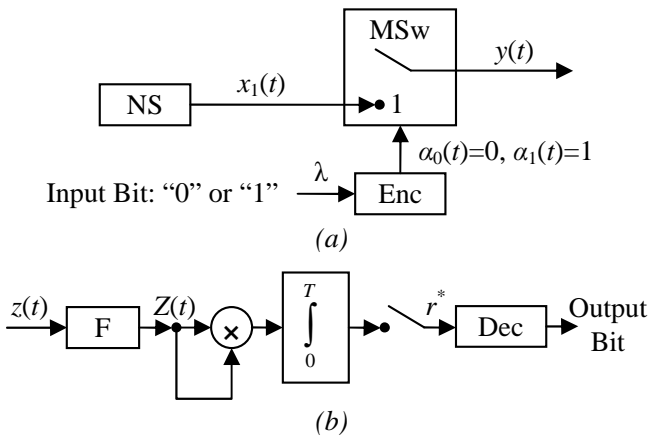

(a)

(b)

Fig. 3. Block diagram of the transmitter *(a)* and of the receiver *(b)* of the ANSK communication system.

The decoder of ANSK system works according to the following rule

$$r^* \underset{"0"}{\overset{"1"}{\gtrless}} \gamma , \qquad (3)$$

where

$$r^* = \int_0^T Z_1^2(t)\, dt \quad \text{and} \quad \gamma = \frac{N_0 T}{4\pi} \int_{-\infty}^{\infty} \ln\left(1 + 2G_1(\omega)/N_0\right) d\omega .$$

Thus, the ANSK system is a particular case of the system with the combined noise signal, using the degenerate single-component signal with the single change of properties when $\tau_0 = T$.

It should be noted that the drawback of the above stated communication systems is a relatively low structural stealth of signal. This is due to the fact that at a rather high signal-to-noise ratio a sensitive narrowband energy receiver can detect modulation characteristics in the input signal.

System with the manipulation of higher order cumulants

Paper [29] studies the use of cumulants of the higher-order of some stochastic process as informative parameters in the transmission of the digital information.

If the information parameter is the variance, the there are Gaussian system signals and there is a second

order polynomial of the input signal in the left of the decision rule, then the given system coincides with the ANSK system. The principal difference appears when manipulating the third order and higher cumulants.

The transmitter structure can be performed according to the diagram of Fig. 1, where $\alpha_1(t) = 1$.

Let the one-dimensional distribution of a stationary ergodic random process, the implementation of which $x_0(t)$, $t \in [0,T)$ is observed at the output of the generator NS-0, characterized by cumulants: $\kappa_1^{x,0} = 0$ (expected value) $\kappa_2^{x,0} = \sigma_x^2$ (variance), $\kappa_3^{x,0}$, ..., $\kappa_{2s}^{x,0}$, where s is some fixed natural number greater than 2. And generator NS-1, respectively, has: $\kappa_1^{x,1} = 0$, $\kappa_2^{x,1} = \sigma_x^2$, $\kappa_3^{x,1}$, ..., $\kappa_{2s}^{x,1}$

In this connection, at least one of the pairs of cumulants is $\kappa_j^{x,0} \neq \kappa_j^{x,1}$, $j = 3,4,...,2s$.

Generation of random sequences with the target values of cumulants can be done, for example, according to the method set out in [30] and [31].

Therefore, the signals corresponding to the symbols "0" and "1" are different only in cumulants with the higher order than the second order. Signal power is the same that is why the receiving energy methods cannot detect the signs of the given modulation. In this way a high level of structural stealth is achieved, the payment for which is the complicating of the receiver structure.

General view of the optimal deciding rule is similar to (3).

But it has

$$r^* = \sum_{j=1}^{s} h_j \int_0^T \left(z^j(t) - \frac{1}{2}(m_j^{z,0} + m_j^{z,1}) \right) dt ,$$

where $z(t)$ is the signal at the receiver input, and $m_j^{z,0}$ and $m_j^{z,1}$ are the raw moments of the conditional distribution of the one-dimensional signal $z(t)$ while transmitting symbol "0" and "1" respectively, h_j are the polynomial coefficients.

Polynomial coefficients h_j are defined as the solution of the system of equations.

$$\sum_{j=1}^{s} h_j F_{ij} = m_i^{z,1} - m_i^{z,0} , \; i = 1,2,...,s ,$$

where $F_{ij} = \frac{1}{2}(m_{i+j}^{z,0} + m_i^{z,0} m_j^{z,0} + m_{i+j}^{z,1} + m_i^{z,1} m_j^{z,1})$.

The right part of the deciding rule (decoder threshold level) equals to

$$\gamma = \frac{T}{2} \sum_{j=1}^{s} h_j (m_j^{z,0} + m_j^{z,1}) .$$

The disadvantage of this system is that the noise power is a complicated part of the equations defining not only the optimum threshold level γ but also functional coefficients r^*. Hence, receiver adaptation to changes in the signal-to-noise ratio results in a cumbersome computational task whose complexity increases rapidly with the growth of the s polynomial degree.

When s grows the receiver structure becomes more complex.

More simple from a technical standpoint decisions which at the same time provide an extremely high level of the signal structural stealth can be obtained by applying the method of transmission of the reference signal together with the autocorrelation receiving of the modulated noise signal.

System with the correlation-delay noise-shift-keying

The transmitter of the correlation-delay noise-shift-keying (CDNSK) system emits the sum of the reference and information signals, information entering the signal occurs by changing the value of the time delay between the reference and information signals according to the law of the input sequence of bits. Fig. 4 shows the block diagram of a CDNSK transmitter.
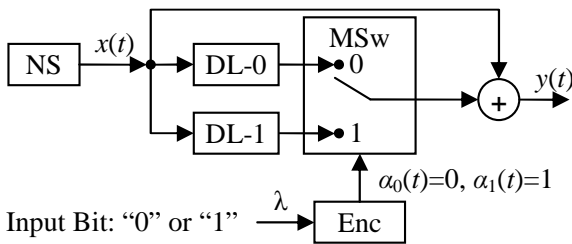

Fig. 4. CDNSK transmitter block diagram

For the first time this system was proposed and tested by German scientists F. Lange and W. Müller [32-33], that is why in many sources (see, e.g. [34-35]) it is called Lange-Muller system.

Mathematical model of the transmitter signal for this system looks as follows

$$y(t) = \begin{bmatrix} x(t) + x(t-\tau_0), & \lambda = "0", \\ x(t) + x(t-\tau_1), & \lambda = "1", \end{bmatrix}, \ t \in [0, T) .$$

Information signals $x(t-\tau_0)$ or $x(t-\tau_1)$ are formed with the help of delay lines DL-0 and DL-1. For defi-

niteness, we assume that $\tau_0 < \tau_1$. Thus, for the delay τ_0 and τ_1 the rules are to be fulfilled

$$\tau_0 >> 1/F , \ \tau_1 - \tau_0 >> 1/F ,$$

where F is a signal bandwidth. That is the least of the time delay and the difference between the time delay should be much bigger than the correlation interval of signal $x(t)$.

The structure of the system signal provides for an additional maximum of the signal autocorrelation function (ACF). Time skew of ACF maximum is the signal information parameter.

The receiver of the Lange-Muller system can be performed according to the diagram, shown in Fig. 5.
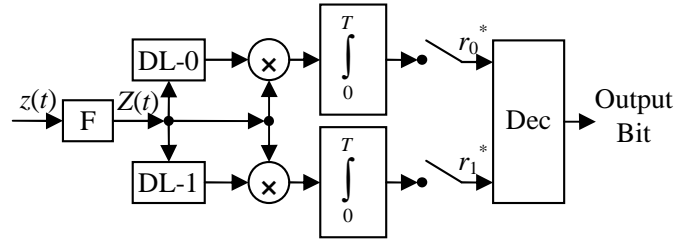

Fig. 5. CDNSK receiver block diagram

The decoder of the correlation-delay noise-shift-keying system works according to the rule

$$r_1^* \overset{"1"}{\underset{"0"}{\gtrless}} r_0^* ,$$

where $r_0^* = \int_0^T Z(t) \cdot Z(t-\tau_0) \, dt$, $r_1^* = \int_0^T Z(t) \cdot Z(t-\tau_1) \, dt$.

Simplified Lange-Muller system

Paper [34] deals with the system transmitter which is made according to the scheme of Fig. 4, and the demodulator contains only one autocorrelation filter. The modified diagram of the receiver is shown in Fig. 6.
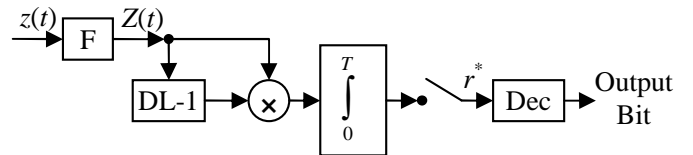

Fig. 6. Block diagram of the transmitter in the simplified Lange-Muller communication system

The decoder of this system works according to the rule of form (3).

The advantage of this system is simplification of the structure of the receiver.

However, this receiver registers only presence or absence of an additional ACF maximum with the time delay τ_1. Thus, this is a system with the passive pause.

The energy expended to form the transmitter ACF maximum with the time delay τ_0 has no useful application. In addition, the decoder comparator has a nonzero threshold level γ. As a result, this system has worse performance.

Autocorrelation system with antipodal signals

A.A. Voronin in paper [36] proposed a system which uses antipodal stochastic signals to encode information. Block diagram of the transmitter is shown in Fig. 7.
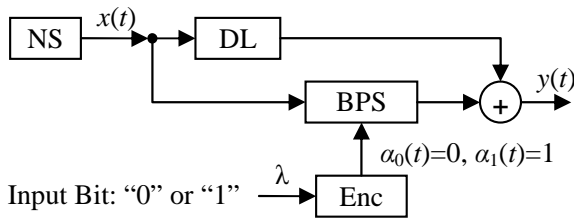

Fig. 7. Block diagram of Voronin system transmitter

The key elements of this device are the delay line DL for time τ and binary phase shifter BPS. If the encoder (Enc) signal, entering the control input phase shifter meets character "1", then the phase slue is 0°, otherwise is 180°.

It should be noted that the broadband phase shifter BPS should provide all-pass phase shift in the frequency range of the signal.

The output signal of the transmitter is of the type

$$y(t) = \begin{bmatrix} -x(t) + x(t-\tau), & \lambda = "0", \\ +x(t) + x(t-\tau), & \lambda = "1", \end{bmatrix}, \ t \in [0, T).$$

The system receiver can be made according to the scheme in Fig. 6, if we set $\tau_1 = \tau$, and the optimal decoder threshold level is $\gamma = 0$. It should be noted that the specified value γ is independent of the noise power.

It is important to note that the system of the antipodal signals has the highest performance of the three types of autocorrelation systems discussed above. However, high levels of intra-system interference significantly affect the properties of such systems. Problem solving is offered while developing the system, which we shall consider next.

System with differential noise-shift-keying

Intra-system interferences occur in Lange-Muller and Voronin systems due to the fact that the signal transmitter is the sum of the reference and information signals. Finite fragments of the restricted by spectrum noise despite having a correlation of zero mathematical expectation, but this correlation in general is nonzero and can vary within wide limits.

Therefore, the problem is to separate the reference and information signal more clearly. One possibility is a complete temporal separation of the signals used in the system with the differential noise-shift-keying (DNSK) [37]. The block diagram of the transmitter is shown in Fig. 8.
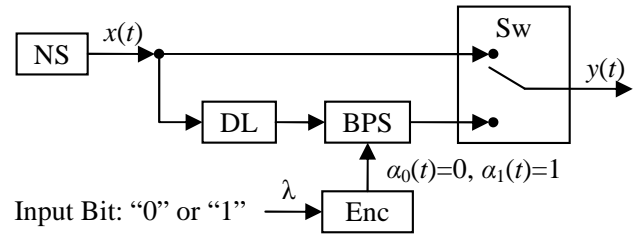

Fig. 8. DNSK transmitter block diagram

Basic principle difference of the transmitter from the circuit of Fig. 7 is the adder substitution (transmitter output) for the switch. As a result, instead of additive mixtures of reference and information signals only reference or information signal enters the channel.

Bit interval T in this system consists of two parts equal in length. During the first half of the bit interval (when $t \in [0, T/2)$) at the output of the transmitter signal $x(t)$ comes directly from the noise source NS. This piece of a bit interval is used as a reference signal.

At the time $t = T/2$ the switch board switches and during next half of a symbol interval (when $t \in [T/2, T)$) at the output either the duplicate reference signal or the signal antipodal to it (depending on the symbol transmitted at this time) come. It should be noted that the delay, made by line DL to the signal, should be equal $T/2$.

Therefore, the system transmitter signal can be given as follows

$$y(t) = \begin{bmatrix} \begin{cases} x(t), & 0 \le t < T/2, \\ -x(t-T/2), & T/2 \le t < T, \end{cases} & \lambda = "0", \\ \begin{cases} x(t), & 0 \le t < T/2, \\ +x(t-T/2), & T/2 \le t < T, \end{cases} & \lambda = "1". \end{bmatrix}$$

Signal reception occurs according to the scheme similar to that one shown in Fig. 6. The particularity of the DNSK system receiver is just that the length of the delay interval is $T/2$ and the range of integration into the integrating device $[T/2, T)$.

Thus, the input of the decoder at the end of a bit interval receives the value of

$$r^* = \int_{T/2}^{T} Z(t) \cdot Z(t - T/2)\, dt \,.$$

As for Voronin system the optimal threshold level of the decoder is $\gamma=0$.

The in-sequence delivery of the reference and information signal in one frequency range makes this system extremely stable to the hard signal propagation conditions set out in the introduction to this article.

It should be noted that the time division of the information and reference signal by far is not the only possible solution. In paper [20] the polarization division of these signals is offered, but still in the mid 80's S.G. Bunin and A.P. Voyter used a combination of frequency and time division of the reference and information noise signal to build multi-channel system "DISPERS".

The "DISPERS" system

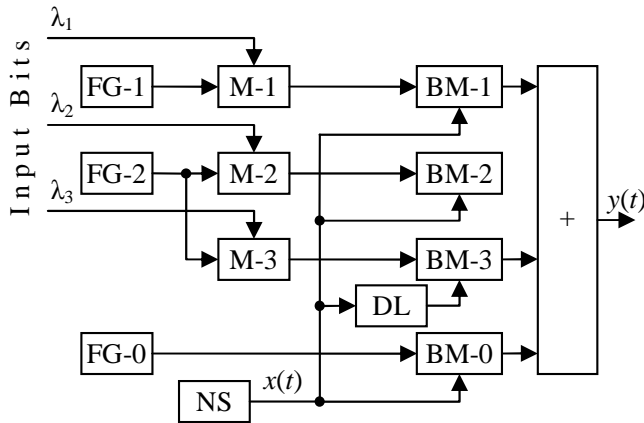According to [38] the structure of the system transmitter corresponds to the diagram in Fig. 9.

Fig. 9. "DISPERS" transmitter block diagram

This shows an example of a three-channel transmitter system in which information channel number 1 is separated from the channels number 2 and 3 due to different frequency of the harmonic signal generator FG-1 and FG-2 (Frequency Division). Information channels No. 2 and 3 are separated by a time delay of the spreading signal $x(t)$ (time division).

Channel number 0 is used to transmit the reference signal. It is separated from the information channels due to differences in the frequency of the generator FG-0 in comparison with FG-1 and FG-2.

Information enters the signal with the help of modulators M-1, M-2 and M-3 and balanced modulators BM-1, BM-2 and BM-3 are used to spread the spectrum of the signal.

The transmission of the reference signal allowed developers to get rid of the necessity of the phase and frequency synchronization in the receiver. However, the problem of the symbol timing synchronization is quite important for the systems of this type.

Signal reception of the given system can be achieved according to the scheme in Fig. 10. This figure is marked as Det-n narrowband detector channel No. n.

Frequency shifts between the generators of the reference and information channels must be chosen so that after mixing using a band-pass filter F-n it could be possible to allocate frequency $|f_n - f_0|$, which is a useful signal of channel number n. These combination frequencies should not fall to a filter band-pass for this purpose. The choice of such a frequency grid for a large number of channels is a challenging task.

Furthermore, in case of the frequency-selective fading the correspondence between the reference and information signals can be broken.
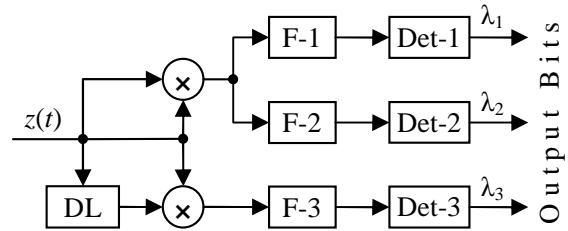

Fig. 10. "DISPERS" receiver block diagram

The "DISPERS" system is an important example of the realized multi-channel system of data transfer (up to 8 parallel channels), based on the principles of the transmitted reference signal and use of stochastic signal for spectrum spreading.

The above stated material provides an overview of the main results in the development of communication systems with the noise carrier received from the middle of the last century to the early 2000-s.

Let us consider promising research areas of recent years and the main problems arising in the development of the theory and technology due to the noise carrier.

Studies of the performance of the basic noise signal modulation techniques

During the development of a communication system it is often necessary to compromise between the complexity of certain methods of generating and processing of the signal and potential noise immunity of these methods.

Let the known dependence $P_b = P_b(h^2)$ between the bit error probability P_b and normalized per bit signal-to-noise ratio h^2 (this dependence is determined by the manipulation and signal processing).

Signal bandwidth F and the signal power at the receiver input P_y are usually limited due to some technical or regulatory reasons. The noise spectral density N_0 depends on the particularities of the selected frequency range, the quality of electronic components accessible to build a system and operating conditions of the system. Then the requirements for the reliability of data transfer set by the inequality $P_b \le p_e$, where p_e is some constant, are easily converted into requirements on the channel energy parameter $h^2 = (P_y / N_0) \cdot T$ in the form of inequality $h^2 \ge h_e^2$, where h_e^2 is the solution of equation $P_b(h^2) = p_e$. Hence, we have restrictions on one of the key performance indicators of the system that is data bit rate:

$$R = \frac{1}{T} \le \frac{P_y}{N_0 \cdot h_e^2} \; .$$

Thus, it is clear how important for the selection and optimization of methods for the noise signal manipulation is the problem of obtaining of theoretical estimates of system performance for these methods.

Paper [39] offers a method of calculation of the bit error probability in systems with a noise carrier based on finding of the distribution densities of random variables observed at the output of the system demodulator. Here the transition to the discrete time and the method of characteristic functions are used.

It became possible to obtain unbiased theoretical estimates of system performance for the basic system types.

It is well known that to study performance of classical communication systems it is enough to study the dependence of the type $P_b = P_b(h^2)$. However, the analysis of the obtained results shows that for systems with the noise signals it is not true. Cross-section for surface $P_b = P_b(h^2, B)$ at a fixed signal bandwidth-delay product $B = F \cdot T$ has a traditional form of a "waterfall", but the shape of the corresponding curves in the transition from one value of B to another is changing.

Notwithstanding, the most unusual result will be obtained if cross-section for surface $P_b = P_b(h^2, B)$ are explored at a fixed value h^2. For classical systems such cross-sections are horizontally straight. For systems with the noise signals, these are curves with the complex shape with a single minimum and a horizontal asymptote at $B \to +\infty$.

Hence it is clear that each fixed value of signal-to-noise ratio h^2 has an optimal bandwidth-delay product value B_{opt}, at which the minimum probability of error P_b is achieved. The dependence B_{opt} on h^2 can be found in the following way. On the plane (h^2, B), we construct a set of level curves for the surface $P_b = P_b(h^2, B)$. Then we draw a straight line $h^2 = c$ on this plane, where $c = const$ is the set value. This line is tangent to one of the level lines. We mark on the plane the corresponding point of contact. Now, changing the value of the constant c, we follow the trajectory of the contact point (Fig. 11). The resulting curve gives the sought dependence.
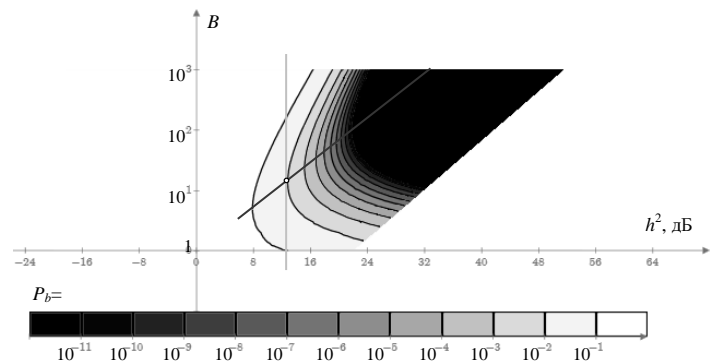

Fig. 11. Determining dependence B_{opt} on h^2 for the DNSK

Let us discuss the essence of the concept of optimal bandwidth-delay product from a different perspective. From the research we know that the B_{opt} is connected to the signal-to-noise ratio per bit h^2 with equality $B_{opt} = k \cdot h^2$.

Substituting B_{opt} in the equality that defines the signal-to-noise ratio $h^2 = \rho^2 \cdot B$, where $\rho^2 = P_y / (N_0 \cdot F)$ we obtain

$$h^2 = \rho^2 \cdot B_{opt} = \rho^2 \cdot k \cdot h^2 \Rightarrow \rho^2 = \frac{1}{k} \; .$$

This value $\rho^2 = 1/k$ will be called the optimal signal-to-noise ratio on power and will be denoted by ρ_{opt}^2.

It is important to note in case the system gets the optimum value ρ^2, any selected value of B is optimal. It is also important that the coefficient k of these equalities is an invariable depending on the system type.

Thus, the procedure for setting of optimal parameters in the communication system with the noise signals involves the following steps: 1) to measure the noise power in the working frequency range $P_n = N_0 \cdot F$,

2) to set the optimal level ρ^2, by adjusting the signal transmitter power, 3) selection of the B required to achieve the given value h^2, and hence the probability of error P_b.

Thus, it is relevant to compare performance of the systems under the conditions of optimal control of the parameters in each one. In this case B and h^2 are bound variables, that is why each system is characterized by a single curve $P_b = P_b(h^2)$. Moreover, the shape of these curves has a classic form. This allows us to estimate the ratio between the performance of the systems under consideration by means of one number [40]. The results of these studies are summarized in Table. 1.

Table 1.

Value ρ^2_{opt} and loss of systems in their performance

System type	ρ^2_{opt}	Versus BPSK, coherent rec.		Versus DNSK	
		times	dB	times	dB
ANSK	3,556	12,8	11,072	1,893	2,773
FNSK	3,2	6,76	8,299	1	0
Lange-Muller	0,943	32	15,051	4,734	6,752
Simpl. Lange-Muller	0,978	64	18,062	9,467	9,762
Voronin	0,894	16	12,041	2,367	3,742
DNSK	1,456	6,76	8,299	1	0

The analysis of the obtained results leads to the following conclusion. Combining the highest performance in this class of systems, of a high signal structural stealth and an acceptable level of energy stealth makes DNSK method the best choice to build communication systems with a noise carrier on its base.

Performance increasing for communication systems with the noise carrier

One of the main factors impinging the performance of system with the noise carrier is fluctuations in the signal capacity on the symbolic interval.

To solve this problem two ways are possible. The first method proposed in [41], focuses on the use of systems with the analog noise signal generator. It uses the noise generator with non-Gaussian distribution. Moreover, this distribution should have the least possible cumulant coefficient of the 4th order γ4 (kurtosis coefficient).

Using a binary distribution effectively increases the system performance (Fig. 12, lines B) compared

with the Gaussian reference signal generator (Fig. 12, lines A). The figure shows the graphs based on these fixed values of the signal bandwidth-delay product:

$B = 16$ ——; $B = 32$ ------; $B = 64$ — —.

However, the use of binary distribution in the noise signal generator leads to the presence of a clear-cut amplitude in the signal oscillograph chart, which is a significant enabling factor in the background of the Gaussian noise.

In [41] symmetrization methods of β-distribution, allowing building a noise generator with the high stealth of the signal and small value of the coefficient of kurtosis are offered.
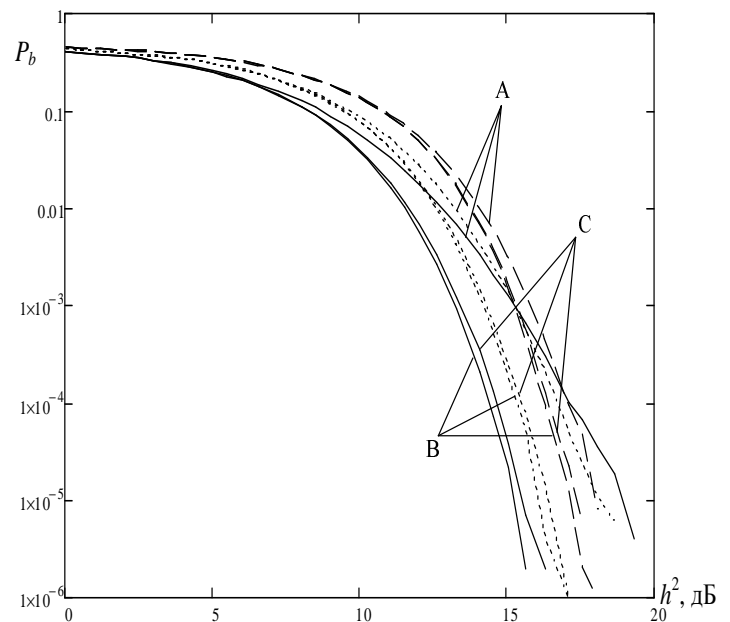

Fig. 12. The dependence of the bit error probability P_b versus the signal-to-noise ratio h^2: A — Gaussian distribution of useful signal; B – the binary distribution, C – symmetrized beta distribution

The application in the transmitter of noise generator with symmetrized β-distribution with $\gamma_4 = -1.8$ instead of binary distribution with $\gamma_4 = -2$ leads to a slight loss of performance (compare lines B and C in Fig. 12).

Another way to improve system performance is the power normalization of the noise signal generator on the symbolic interval [25].

The average power of the some finite fragment of random process with Gaussian distribution ($\gamma4 = 0$) realization is a random variable. It is possible to artificially deprive the realization of a stochastic process from such fluctuations. To do this the normalization procedure is needed, which is the transition from signal to signal $x(t)$, $t \in [0,T)$ to the signal

$$\breve{x}(t) = \frac{x(t) - m_{1\,въб}^{(x)}}{\sigma_{x\,въб}},$$

where

$$m_{k\,въб}^{(x)} = \frac{1}{T}\int_0^T x^k(t)\,dt,\ k=1,2\ ,\ \sigma_{x\,въб} = \sqrt{m_{2\,въб}^{(x)} - \left(m_{1\,въб}^{(x)}\right)^2}\ .$$

In the discrete time this procedure is as follows

$$\breve{x} = \frac{\overline{x} - m_{1\,въб}^{(x)}}{\sigma_{x\,въб}},$$

where $\overline{x} = (x_0, x_1, ..., x_{N_x-1})$, $m_{k\,въб}^{(x)} = \frac{1}{N_x}\sum_{i=0}^{N_x-1} x_i^k$.

Studies show that the regulation of the output signal of the noise generator provides the same effect as applying in the generator of the binary distribution to the system performance.

Analogue implementation of the normalization procedure is a rather complicated task. Therefore, this approach to improve the performance of systems with the noise carrier is focused on the digital methods of signal forming and signal processing.

Symbol timing synchronization in systems with noise signals

Providing of the accurate symbol timing synchronization is an important task for systems with noise signals. As a form of the noise signal is not known on the receiving side, the classical methods of synchronization cannot be used. There are two solutions to this problem: 1) the use of external sources of the timing signal (e.g., GPS signal); 2) development of specific methods of synchronization.

Since the use of external synchronization signal requires additional receiving equipment and significantly reduces the security of data in the system, it makes the sense to study specific methods of communication systems synchronization with the noise carrier.

The first method proposed in [42], are mainly oriented for use in systems with analog noise source.

According to this method each information packet must begin with the determined sequence of bits. Because of the optimal auto- and cross- correlation properties Barker codes of length 11 or (preferably) 13 can be used as sequences. At the receiving side the output of the autocorrelation device is fed to the filter the impulse response of which looks like a triangle wave, the polarity of the peaks of which corresponds to the selected Barker sequence.

If synchro-sequence found, then the filter responds with the high narrow emission of the output signal, enabling the receiver synchronization.

The study of empirical distributions of synchronization error obtained by computer simulation of the system with various signal parameters suggests that under conditions of sufficient bandwidth-delay product of signal this method is acceptable for practical use. The advantage of this method is the invariance of the structure and properties of the signal and the clock signal processing in the low-frequency area.

The disadvantage is the large number of proprietary information in the information package, which reduces the data rate.

Another solution to the problem of synchronization proposed in [43], involves the use of digital generator of stochastic sequences. The method involves the application to the signal of a specially designed linear transformation A to the information part.

The correspondence between reference and information signal can be renewed in the transmitter by using direct conversion to the reference signal or the inverse transformation to the information one.

Conversion A must satisfy the following requirements: 1) maintaining of the basic statistical characteristics of a signal $x(t)$; 2) signals $x(t)$ and $A(x(t))$, $t \in [0, T)$ must have good mutual correlation characteristics; 3) function $r(t)$ observed at the output of the demodulator (in the recovery of the conformity) must have a sharp extremum at the end of the symbol interval.

For finite-dimensional space vectors the transformations satisfying the specified conditions can be set by the system of optimal code sequences (OCS). For each positive integer $n = p - 1$, where p is a prime number, the OCS system is defined by a matrix A with elements $a_{ij} = i \cdot j \bmod(n+1)$, $i = 1, 2, ..., n$, $j = 1, 2, ..., n$.

Matrix A is symmetric, its lines will be marked as A_i and $i = 0, 1, ..., n-1$. These lines form a system of code sequences, optimal in the sense that any two sequences A_i and A_j, $i \ne j$ at the arbitrary aperiodic displacements with respect to each other have no more than one match.

Each code sequence will be interpreted as a transformation of the n-dimensional Euclidean space, which is the appropriate permutation of coordinate vectors. It should be noted that the sequence A_0 is always a natural permutation, and hence determines the identity transformation. Therefore, to build a synchronization system a sequence of numbers from 1 to $n-1$ is used.

We obtain estimates of the system performance of the method of synchronization and the optimum threshold values of the detector of synchronization signals are defined (Fig. 13).
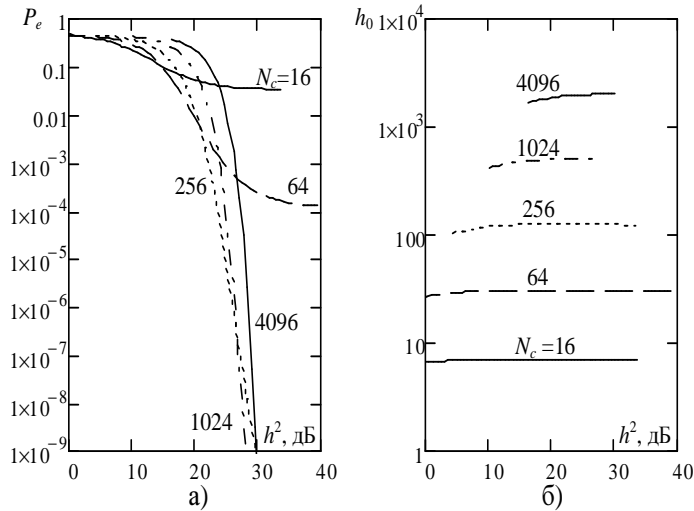

Fig. 13. The probability of synchronization errors (a) and optimal detector threshold level (b)

The figure contains the information about the vector length near the curves, which is a discrete representation of the reference signal.

An important side effect of this method of symbol timing synchronization is a significant increase in the signal structural stealth as unauthorized observer who does not know the type of transformation applied in the system can correctly identify information from the intercepted signal.

Development of the multiple access systems with the noise signals

The limited frequency resource encourages researchers to develop communication systems in which several stations simultaneously use a common frequency band to transmit information. Such communication systems are called multiple access systems.

Thus, each receiving station must be able to find in the mixture of channel signals its "own" signal according to some targeted basis.

The classical approach to solving the problem of constructing a system of multiple accesses involves the use of orthogonal or quasi-orthogonal signal ensembles. Then the waveform selected from the group for a particular channel serves as a basis for the targeted channel separation and the orthogonality of signals minimizes the inter-channel interference.

Using the stochastic signal in the system raises two issues: 1) the waveform cannot be the basis of a targeted channel, because it is unknown to the receiving party, and 2) the problem of construction of large ensembles of stochastic orthogonal signals was not previously addressed.

The approach is proposed in paper [44]. The idea is as follows. Let us assume that there exists a system of linear transformations, the use of which for any fixed stochastic vector gives a vector orthogonal ensemble.

Targeted feature of the communication channel is the kind of transformation that is used in the transmitter to the information signal. The receiver of this channel uses identical transformation to the reference signal. The correspondence between the reference and the information signals is restored. Paper [44] shows the possibility of use of this method of channels separation in ad-hoc peer systems.

Paper [45] shows that the best effect can be achieved when using this method of separation of channels in a multiple access system with the centralized control. In this case, signals of the forward link (base station — subscriber terminals) can be fully synchronized and reference signal can be shared by all channels.

Currently the methods of quasi-synchronized organization of the feedback channel are known. Under these conditions, the orthogonality of the ensemble of the information signals allows to minimize inter-channel interference.

The task of constructing of maximum volume of linear transformations, on which the method of channel separation is based, is solved in paper [46].

Formal mathematical formulation of the problem is as follows. Assume R^n to be n-dimensional real Euclidean space, and $\bar{x}$ is a fixed nonzero vector of this space, given by its coordinates in the standard basis. It is necessary to construct a maximal system of linear transformations (operators) $A_1, A_2, \ldots, A_q$, for which the following conditions are performed:

1) $\langle A_i \bar{x}, \bar{x} \rangle = 0, \ i = 1,2,..,q,$

2) $\langle A_i \bar{x}, A_j \bar{x} \rangle = |\bar{x}|^2 \cdot \delta_{ij}, \ i = 1,2,..,q, \ j = 1,2,...,q,$

where δ_{ij} is Kronecker symbol,

3) $|A_i \bar{x}| = |\bar{x}|, \ i = 1,2,...,q$.

It is proved in the paper that the system operators $A_1, A_2, \ldots, A_q$ can be regarded as the basic elements of the Clifford algebra $Cl(p, q)$ with the positive signature p and negative signature q.

To solve the problem we will be interested only in maximal Clifford algebras, which are at the fixed $n = 2^m$ have the largest negative signature (Table 2).

Table 2. Maximal Clifford algebras with the largest negative signatures for the given n

m	1	2	3	4	5	6	7	…
n	2	4	8	16	32	64	128	…
Signat.	(0,1)	(0,3)	(0,7)	(1,8)	(0,9)	(0,11)	(0,15)	…

In general, the maximum number q of non-identical changes in the system depends on the dimension $n = 2^m$ of vector $\bar{x}$ and is defined by equation

$$q = \left[\frac{\log_2 n - 1}{4}\right] \cdot 8 + \begin{cases} 1, & (\log_2 n - 1) \bmod 4 = 0, \\ 3, & (\log_2 n - 1) \bmod 4 = 1, \\ 7, & (\log_2 n - 1) \bmod 4 = 2, \\ 8, & (\log_2 n - 1) \bmod 4 = 3, \end{cases}$$

where the square brackets denote the operation of taking the integer part, and the equation of the form $a \bmod b$ means the remainder of the number division a by a number b.

Based on the results presented in [47], in [46] the obtained recurrent relations, that allow to find a real matrix representation of all the basic elements of the Clifford algebra, were included in table 2. It is shown that for practical application the entry of system operators in the form of formulas of the vector coordinate transformation is optimal. They are called alternating permutations. Examples of alternating permutations are given in Table 3.

Table 3. Presentation of operators with the coordinate transformation formulae

n	i	$A_{(p,q),i}$
2	1	$(x_2, -x_1)$
4	1	$(x_4, \ x_3, \ -x_2, \ -x_1)$
	2	$(x_3, \ -x_4, \ -x_1, \ x_2)$
	3	$(x_2, \ -x_1, \ x_4, \ -x_3)$
8	1	$(x_7, \ x_8, \ x_5, \ x_6, \ -x_3, \ -x_4, \ -x_1, \ -x_2)$
	2	$(x_5, \ x_6, \ -x_7, \ -x_8, \ -x_1, \ -x_2, \ x_3, \ x_4)$
	3	$(x_4, \ x_3, \ -x_2, \ -x_1, \ x_8, \ x_7, \ -x_6, \ -x_5)$
	4	$(x_3, \ -x_4, \ -x_1, \ x_2, \ x_7, \ -x_8, \ -x_5, \ x_6)$
	5	$(x_6, \ -x_5, \ x_8, \ -x_7, \ x_2, \ -x_1, \ x_4, \ -x_3)$
	6	$(x_2, \ -x_1, \ x_4, \ -x_3, \ -x_6, \ x_5, \ -x_8, \ x_7)$
	7	$(x_8, \ -x_7, \ -x_6, \ x_5, \ -x_4, \ x_3, \ x_2, \ -x_1)$

The offered the structure of multiple access signal that provides a gain in the probability of an error in terms of bits of information transmitted by increasing the number of active channels. This benefit comes at the cost and complexity of algorithms of signal forming and signal processing and due to more optimal use of the information capacity of the noise signal. It should be noted that there is no additional extension of the signal compared to the binary system with DNSK.

Construction of sub-terahertz range systems with noise signals

Advantages of communication systems with noise carriers are fully manifested only when there exists a sufficient width of the signal (at least several hundred MHz, ideally several GHz).

One of the solutions to the problem is to go into the sub-terahertz frequency range (D-band).

The development of sub-terahertz range itself causes considerable interest in connection with the following:

1. Weak occupancy of the given range compared to the centimeter range.

2. Ability to the selection of wide frequency bands (5 GHz).

3. A simplified procedure for the allocation of frequencies in many countries.

4. Significant reduction in size of antenna systems that provide forming of a narrow directivity pattern.

5. The rapid attenuation of radio waves in combination with narrow channeled antennas eliminates the problem of interference of multiple signal sources thus simplifying the frequency planning problem.

6. Environmental safety.

These circumstances make this range unique to the construction of personal, local and urban transport wireless networks and channels "point to point" (radio relay lines).

A simple structure of receiving and transmitting devices for communication systems with noise signals makes them well suited for the implementation in the sub-terahertz frequency range. Thus, the noise autocorrelation of this range acquires a set of properties very attractive for the development of effective systems of confidential communication.

Let us consider the basic approaches to the communication system building with the noise carrier in the sub-terahertz range [48].

The greatest interest in terms of simplicity and efficiency of the structure is caused by the construction of a system with the direct generation and signal processing in the sub-terahertz frequency range.

This approach allows us to fully realize all of the above benefits.

The main problem of the system development with PNSM is the development of the broadband phase switcher with constant (frequency independent) phase shift of 180°, which operates within the range of 130-134 GHz and a long delay line (half of the bit interval). Critically important point is also a quick switch.

To implement systems with noise signals other options are also possible. In particular, the formation and modulation signal at the intermediate frequency with further frequencies in the sub-terahertz range. This approach is intensively studied by the group of scientists led by M. Il'chenko [49].

Modern means of digital signal development and processing make the implementation of the system with

the help of the random digital sequence rather perspective.

Modern DAC and ADC can generate and process signals with a bandwidth of a few GHz, and the digital signal presentation allows for complex modulation techniques of the stochastic signal.

Thus, the design and construction of communications of the sub-terahertz range of signal-noise carrier offers a number of interesting scientific and engineering problems whose solution opens new prospects in the environmentally friendly telecommunication systems providing a high level of information security.

Conclusion

This review shows that the history of theoretical and experimental research in the field of communication systems with the noise signal dates back to the mid-twentieth of the XX century.

During this time a considerable arsenal of methods to make the information noise signal and reception of such signals has been gathered. Among the methods for manipulating of binary noise one of the most promising is the phase shift keying perceived noise signal.

The main areas of application of the autocorrelation of the noise carrier is the construction of confidential communication, which is the priority objectives of protection of transmitted data from being intercepted and protect the channel from the extraneous information injecting.

In addition, methods of information transmission, discussed in the paper, allow solving the problem of sustainable communication in difficult conditions of signal propagation, especially in multipath channels by means of simple technical resources.

The paper is devoted to the most urgent theoretical and practical problems relating to the communication systems with the noise carrier:

1) the development of the general theory of potential noise immunity with the stochastic signals;

2) finding ways to improve the reliability of data signals in Gaussian noise channel and non-classical channels (multipath channel, with quasi-harmonic noise, channels with impulse noise);

3) improve methods of clock synchronization systems with the noise carrier;

4) development of formation methods of a complete orthogonal basis on the basis of a stochastic vector;

5) development of the high-speed broadband electronic components of the sub-terahertz frequency range.

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