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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences was held on 24 December 1997 at the P L Kapitza Institute for Physical Problems, RAS. The following reports were presented at the session:

(1) **Reznikov A E** (Institute of Terrestrial Magnetism, the Ionosphere, and Radio Wave Propagation, RAS, Moscow) "Superwideband communication systems: characteristics and applications";

(2) **Gaponov S V, Salashchenko N N** (Institute for Physics of Microstructures, RAS, N. Novgorod) "Creation and application of multilayer X-ray optics on a base of nanometer and subnanometer periodical structures";

(3) **Vinogradov A V** (P N Lebedev Physics Institute, RAS, Moscow) "Successes in X-ray microscopy in the soft and hard wave' ranges".

A summary of the first report is published below.

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Superwideband communication systems: characteristics and applications

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The subject matter of this article is one direction of the development of radio physics and radio engineering, which has grown especially fast during recent years. All of us live in a world, where all types of communication (including wireless) will become digital by the end of the century. After that, the transition to a digital broadcasting in all ranges will follow. Digital systems of communication guarantee high quality, they effectively use frequencies and power, and ensure multiple access to network information resources.

In 1948, the intuitive idea that noise can limit the exactness of message broadcasting was disavowed in the pioneering work by C Shannon. The result of Shannon's work was that noise could determine channel capacity instead of the information exactness. This is one of the cornerstones of radio physics and radio-engineering science devoted to the research of spread spectrum signals. Therefore, it is possible to receive indefinitely high error-free transmission applying encoding by rather long blocks of signals. Thus, the receiver detects a mixture of signals and noise and compares them with a code pattern stored in the receiver.

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Let S be the power of the signal and the jam be white noise with power N in a band W. According to Shannon's theorem, there is such an encoding system, which allows the transmission of binary digits with the velocity

$$C = W \log\left(1 + \frac{S}{N}\right)$$

and infinitely low error possibility. There is no method of errorless transmission with a higher velocity.

The following theoretical scheme of transmission may realize this channel capacity. On the transmitting side, a long sequence of binary digits is sent out, each represented by a complicated signal of appropriate duration.

The receiver registers these signals and additive jam (band-limited white Gaussian noise) and, by correlating with known code pattern, makes a decision on the most probable transferred message. Then the final device reproduces the corresponding binary sequence. Approaching the velocity limit the decision delay will increase because the infinitesimal error should be ensured by increasingly longer blocks representing binary information. The form of desirable signals becomes clear during a proof of the theorem. The best result is reached (following Shannon) when different realizations of band-limited white noise are used as the representing signals.

Certainly, the described scheme has only a theoretical character because the number of signals in the ensemble grows as 2^M, where M is the number of binary digits in the chosen block, and is not practical at large M.

Let us define the specific energy per bit of transmitted information at a constant spectral noise density N_0. If the expression for the energy per bit ($E = S/C$) is

$$\frac{E}{N_0} = \frac{S}{WN_0} \log^{-1}\left(1 + \frac{S}{WN_0}\right),$$

we obtain that the energy expenditure per bit reaches a minimum value N_0 using all the bandwidth W. Thus, the ratio of spectral signal density S/W to spectral noise density N_0 becomes small.

However, there is no saving of power in a simple transmission because in this case the error probability depends only on the full signal energy and not on the internal modulation of pulses. It is possible to reach some diminution of energy per bit using block coding, for example, when every M bits are transmitted by one of mutually orthogonal 2^M pseudonoise signals (PNS). When the transmission velocity is fixed, the necessary bandwidth for the M-valued alphabet is extended M times, and the required energy (bit value) decreases $\log M$ times.

If the transmitters' powers are equal and the channel capacity is determined only by mutual jam, the maximum number of users n is given by

$$C = W \log\left(1 + \frac{1}{n-1}\right).$$

A PNS realizing a band-limited white noise contains both random phase and amplitude modulation. These two types of modulation also enable the arrangement of a high channel capacity in a specific frequency band. Rejecting amplitude modulation (as a rule because of technical difficulties) we lose the channel capacity for a specific band and retire from the theoretical limit. Today's PNS systems reproduce the phase structure of band-limited noise quite satisfactorily but they use only one level of signal amplitude.

In the modern statistical theory of communication the signals are considered as non-random functions of an ensemble forming a stochastic process of information transmission and the jam is regarded as a stochastic process. According to this theory jams and signals have no principal differences.

In a work by V Kotelnikov, who laid the foundation of the theory of optimal reception, the main problems of optimal reception in presence of white noise jam were first posed and solved. He also introduced the concept of an ideal receiver which distinguishes messages with minimum error in the case of discrete signals or provides the best similarity between the received and transmitted messages in a general case. The noise immunity exhibited by an ideal receiver is called the potential noise immunity.

Which processing of an incoming signal $x(t)$ will be optimum? In a classical formulation the ratio of the output signal power to the noise power is to be maximized. For linear processing $\int_0^T x(t)\,h(t)\,\mathrm{d}t$ of the signal contaminated with an arbitrary noise the optimum function $h(t)$ may be obtained as a solution to the Fredholm integral equation

$$\int_0^T R(t-u)\,h(u)\,\mathrm{d}t = S(t)\,,$$

where the kernel is just the noise correlation function and $S(t)$ is the desired output signal. This equation can be only solved for few types of jams. For an uncorrelated white noise the function $h(t)$ should coincide with the signal.

A model of the optimum receiving system, which normally can not be realized in practice, should reveal the best possible quality of communication and trace the structure of a real device. In general the optimum parameters of a system are not unique: different optimum criterions lead to different results. Therefore, one should make a correct choice of an optimization criterion in agreement with the main tasks which the communication system must solve.

Transmission of discrete information is based on control of the amplitude, phase and frequency of a high-frequency carrier. In this case the modulated parameter is changed discretely, and modulation is called manipulation. The frequency band of the carrier is proportional to the manipulation rate. For spreading the spectrum additional manipulation at high rate is necessary, and normally one uses manipulation with pseudorandom sequences (PRS). To realize this additional modulation the original binary information stream is superimposed on a stream of characters from the extended alphabet of the PRS which are transmitted at a much higher rate. In order to encode a binary character of the original message all bits in the corresponding block of the PRS representing this character are inverted if this character is 1, and left unchanged if this character is 0. At the first glance the binary sequence which is superimposed on the information stream looks like a random sequence of units and zeros, although it is generated by regular digital methods. Modulation of the information stream by the spectrum spreading stream of additional bits is the base of the PNS method. The number of bits per character of the extended alphabet is the measure of spectrum spreading, and it can be very high. This modulated stream in a double-balanced mixer manipulates the carrier phase and is transmitted into space.

In the framework of the PNS method it is necessary to make an additional demodulation of the extended code in order to retrieve the original information. The received signal is multiplied by a replica of the PRS which must be available at the receiving point. Tuning mainly consists of adjusting the PRS parameters used for extending the original signal with its replica in the receiver. In an ideal case of full synchronization the spectrum extension is completely removed and after performing correlation it is possible to observe a usual sequence of information premises as if after a synchronous detector in a narrow-band communication system.

This reception method determines the main advantages of using PNS systems. Multiplication of the received signal by the extension code replica turns all other signals modulated via different (even in one parameter, say bit frequency, bits mutual disposition, shift of the code first character) codes into a chaotic sequence of short pulses with wide spectrum. Therefore only a tiny fraction of their power passes the narrowband filter. This is the mechanism of code separation. Similarly, a narrowband jam is also turned into a random sequence of short pulses and is damped by the filter.

Thus, a unique device provides code separation and noise immunity with respect to a big variety of different types of noise. However this implies that we are faced with new problems, namely with synchronization of the code generator and the incoming signal in the receiver, and with several other related to detection of PNS and establishing connection. Nevertheless all these problems might be overcome and PNS systems may be created providing all their advantages.

According to fundamental results of the potential noise immunity theory the error probability in performing signal separation in presence of such jam only depends on the signal energy. What is the origin of the great activity in developing actual PNS systems? The answer is that the PNS method accepted the ideas of the optimal reception theory in the most complete manner, mainly because all of them were developed with respect to white noise.

The main advantages of PNS systems are the following.

(1) The receiver becomes resistant against a big variety of jam, although special adjustment may increase resistivity against a given jam.

(2) There is an opportunity to arrange asynchronous code separation. (For synchronous separation of signals it is enough to choose them mutually orthogonal.) Utilizing the PNS code structure it is possible to make signals mutually quasiorthogonal at any temporal shifts, and increasing the code length leads to improvement of this property.

(3) There is an opportunity to use internal modulation of PNS pulses for measuring distances in navigation systems.

(4) The low spectral density of PNS ensures their ideal electromagnetic compatibility with all communication systems. The spectrum spreading results in reduction of the

signal level at the input of the receiver, and makes detection, recognition and acquisition difficult or even impossible (Fig. 1).

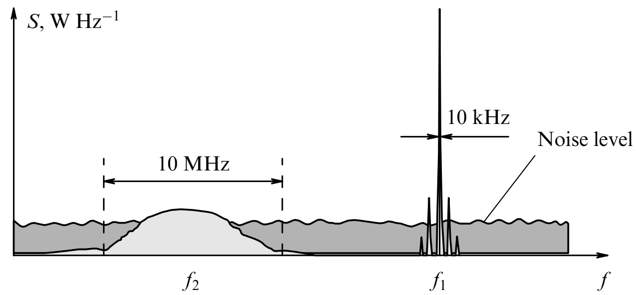

Fig. 1. The signal spectral density of a narrow and wideband communication systems of equal power.

The area of commercial applications of PNS systems includes local wireless computer networks, cellular mobile communication systems (up to global networks), and personal communication systems, providing informational community with talking facilities, data transfer, electronic mail, and video information.

The most important feature of PNS systems, determining their priority in commercial applications, is providing multiplexing on the grounds of code separation. The advanced ideology of increasing channels capacity enables to increase capacity of networks, quality and coverage of information.

So far the communication channels were separated either in the frequency range, time domain, or both methods were used simultaneously. Modern analog systems were developed on the base of frequency division multiple access (FDMA). Next step, which permits an increase in capacity and quality of networks, was development of the hybrid scheme (GSM) on the base of time and frequency separation (TDMA). Each user got his own temporal-frequency slot on the carrier which could not be used by anybody else up to termination of the connection. The efficiency of this separation system essentially depends on organization of the scheme of the frequency slot reuse in the neighboring cells of the network and mutual jam. At present the major part of GSM users are mobile and this perspective will not change.

Intensive development of communication systems resulted in overloading of all ranges with electromagnetic waves. The actual network capacity and error probability is completely determined by mutual jam.

From the standpoint of mutual jam the principal difference between the narrowband signals and PNS is that although the mean spectral density under a given loading appears to be the same, it is distributed more even in the case of PNS systems. Variations of the spectral density for narrowband systems are very high (about the signal/noise ratio), whereas for PNS systems they are essentially less.

Therefore, a heavy loading of a range with a guaranteed probability of a satisfactory communication quality is possible. In other words, a PNS system on the average ensures the required quality of communication with small fluctuations of error. Narrowband communication systems provide this average quality of communication at the expense of excellent quality in some cases and poor quality or absence of communication in other.

With full transition to PNS communication systems the distribution of mutual jam will tend to the uncorrelated normal. Therefore the optimum methods of jam processing will be reduced to those which are based on white noise. For this jam type the internal modulation of pulses has no influence on the reception reliability which is only determined by the net energy of the signal. Then, why do we need to spread the spectrum? Only to make it possible and pass to white noise.

We may presume that with the complete transition to PNS systems we shall return to the potential noise immunity which is determined by white noise. It will not be necessary to optimize receivers with respect to mutual jam, but only to white noise.

The radio physical problems arising in developing PNS communication systems are mainly determined by the basic difference of PNS from ordinary quasimonochromatic signals, i.e. a wide relative frequency band. Although PNS can be used practically in all ranges of radio frequencies, each range has its specific features. Common problems for all ranges are the following.

(1) The problem of transmitting and receiving antennas, which should provide undisturbed transmission and reception of signals in a wide frequency range. In certain cases it is necessary to design special antennas (say, consider resistive loaded dipoles whose resonance properties become worse due to absorbtion).

(2) The multipath problem. In contrast to narrowband systems, where the multipath arrival resulted in interference amplification or attenuation of a signal, the PNS method allows temporal separation of rays after the correlation processing. Not only this enables to avoid interference disturbances, but also to use the energy of spurious rays for increasing reliability of communication. The most serious problems arise in the case of mobile communication systems. For their solution it is necessary to develop radiophysical models of wave propagation under the condition of multiple reflections and of signal processing algorithms.

For the ultra-high and lower frequencies the basic problem is in signals distortions caused by dispersion due to interaction of waves with the ambient media. The dispersion sets limits to spectral width of a signal, which results in a reduction of the channel capacity. The dispersion influence may be reduced via compensation of phase and amplitude disturbances accumulated by the signal on its way. To do so it is necessary to develop models of signal propagation in dispersive media.