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Code division of signals in a direct chaotic scheme of information transmission

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Abstract. An important direction in the scientific activity of Yu. V. Gulyaev is research and development in the field of nonlinear dynamics and dynamic chaos. As for nonlinear dynamics in general, all the main areas of Yuri Vasilyevich's scientific activity relate to it to one degree or another, starting with classical works in the field of acoustoelectronics. Here, of course, it is necessary to mention research in the field of proper physical fields of biological objects, work in the field of medical electronics, as well as research and development in the field of dynamic chaos and its applications. One such development, which essentially laid the foundation for the development of direct-chaotic transceivers, in the formulation and implementation of which Yuri Vasilyevich played an important role, is described in the introduction to that article. This work was largely a prologue to the development of work on information transmission using dynamic chaos, carried out at IRE RAS since the 90s. The main part of the article proposes and examines a new version of a direct-chaotic information transmission scheme, in which code sequences of chaotic radio pulses are used as an information-carrying signal. *Purpose.* Development of a new method for introducing information into a chaotic signal, providing expanded capabilities for channel separation and multiple access. *Methods.* Computer simulation of the transmission process and theoretical estimates of the noise immunity of the scheme in a channel with white noise. *Results.* A method for modulation/demodulation of code sequences of chaotic radio pulses is proposed and investigated, which provides an increase in the base of the transmitted binary symbol and channel division based on correlation processing of the signal passed through the envelope detector. It is shown that the proposed modulation/demodulation scheme is also effective for organizing multiple access in a network of transceivers that are not synchronized with each other. *Conclusion.* The proposed scheme for inputting information into a direct chaotic signal of the transmitter and its extraction on the receiver side, judging by theoretical calculations and the results of computer simulation, significantly increases the capabilities of direct chaotic communication facilities and expands the areas of their application.

Keywords: direct chaotic information transmission, chaotic radio pulses, code division multiplexing.

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Introduction

In the mid-80s, under the leadership of Vladimir Yakovlevich Kislov, the IRE of the USSR Academy of Sciences actively worked to create sources of dynamic chaos in the radio and microwave ranges. In the style of that time and personally V.Ya. Kislov, there was a practical focus of these studies. The same point of view was shared by the leadership of the institute. After the successful solution of one of the important tasks in this direction by the 16th department, V.A. Kotelnikov, the director of the Institute, suggested focusing his efforts on one of the urgent tasks of electronic countermeasures [1–3]. It was about the AWACS system, created by the Americans, which is engaged in intelligence, essentially a flying locator. And it had to be dealt with somehow. By this time, a counteraction system had been developed in our country, suppressing this system by affecting the side lobes of the directional pattern of the survey locator. But it was a monster that was the size of a railway carriage. And this task required a new solution: compact electronic countermeasures devices were needed.

1. Direct chaotic microwave transmitters. The Prologue

Vladimir Yakovlevich jumped at the idea of creating such devices. And after a while, the laboratory presented a prototype based on a vacuum generator of noise-like chaotic oscillations. But Kotelnikov did not accept it. According to him, first of all, there should be a semiconductor device, not a vacuum device. Secondly, it must be a transceiver antenna array. They left to think. By the summer and autumn of 1986, the appearance of the system began to take shape. And then a landmark event happened.

In the Presidium of the Academy of Sciences, in the dressing room, a meeting was held between Yuri Vasilyevich Gulyaev, then deputy director of the IRE of the USSR Academy of Sciences, director of the specialized scientific research institute «Gradient» in Rostov-on-Don, Yu.M. Perunov, the future general designer of the USSR Radio Industry, V.Ya. Kislov and one of the authors of this article, A.S. Dmitriev. We told Perunov about the task and the state of its development, and he said: «If everything is more or less ready for you and you hand over your sketches of the experimental sample to me in December, then «Gradient» will release its documentation by February. In February, prototypes are produced. In March, we will start joint tests at the «Gradient» Research Institute and in May we will go on field tests».

I sat and thought: the man says that based on experimental layouts, we will make «hardware» in three months. And «hardware» is compact compared to a railway carriage. At that time, such a pace seemed almost unrealistic, and work with industrial enterprises stretched over years. It looks like «whistling». But we broke up, and the work started.

In March, about 20 stations began to come out of production, and we already assembled a team, went to «Gradient» and started setting up these stations. At first, they didn't adjust at all. Then the process passed. We went there in two teams, worked for 12 hours. By the end of March and the beginning of April, everything was ready. Each car, we called them «girls», weighed eighty kilograms, but not tons, like the previous solution. The device has become portable. First, tests were conducted at a base near Rostov-on-Don, in Matveev Kurgan, and in early June, in the Orenburg steppes with real aircraft. That was the level of organization. Sometimes it seemed confusing. But everyone wanted to get the result, and some also knew how to get it on time.

The tests took place in 1987. And in 1989, to a team based on the staff of the IRE of the USSR Academy of Sciences: V.A. Burykin, Yu.V. Gulyaev, A.S. Dmitriev, N.N. Zalogin, V.P. Ivanov, V.Ya. Kislov, V.A. Kotelnikov, M.N. Lebedev, N.A. Maksimov, M.P. Udov, B.A. Hadji, was awarded the prize of the Council of Ministers of the Soviet Union. The award was presented at the Presidium of the Academy of Sciences. The weather was good that day. We were walking along Leninsky Prospekt with a group of 5-6 people with the medals of the laureates we had just received. When the driver of the stopped truck saw us, he opened the door and, pointing at us, said to those around him: «That's who needs to be elected to the Supreme Council, not the clowns who are sitting there». It was our finest hour.

The devices that were created were transceivers with antenna arrays emitting chaotic signals [1–3]. Today, almost forty years later, it can be stated that these were the first transceiver systems with directional emission of chaotic signals, a prologue to future developments in the field of dynamic chaos for information transmission, in which Yu.V. Gulyaev takes an active part [4, 5].

2. Direct chaotic wireless communication scheme

The next steps towards creating radio systems using dynamic chaos were taken almost 10 years later. These were research and development projects in the field of ultra-wideband (UWB) short-range communication systems, in which chaotic radio pulses were used as an information carrier.

It should be noted that work on the use of dynamic chaos for information transmission, in particular wireless communication, has been carried out all over the world on a broad front since the 90s of the twentieth century. In addition to the general and long-standing interest in communication systems using noise and noise-like signals [6–9], interest in them is related to the simplicity of implementing sources of wideband and ultra-wideband analog noise-like signals, the ability to flexibly control the spectrum by changing system parameters and other properties characteristic of nonlinear dynamic systems with complex dynamics.

It should be noted that the technique of generating chaos in the microwave range, as well as a number of other critical elements necessary for the creation of wireless means of communication in the radio and microwave ranges, were already largely ready for the appearance of practically realizable schemes [10].

This scheme was proposed in 2000 [11–13]. It was a direct chaotic communication scheme (DCCS), using chaotic radio pulses as an information carrier. In the following years, it successfully developed: on its basis, it was possible to create small-sized ultra-wideband transceivers and networks based on them. It has also been adopted as an optional solution in the IEEE 802.15.4a ultra-wideband personal wireless communication standard. To date, DCCS is the only practically implemented and used wireless communication scheme based on dynamic chaos.

At the same time, modern requirements for wireless communications pose new challenges. First of all, this applies to the widespread use of wireless, low-consumption, sufficiently high-speed means of communication for the Internet of Things, for robotics and sensor networks. These tasks stimulate interest in expanding the possibilities of using chaotic signals in the field of wireless data transmission.

In this paper, we propose and analyze a new version of a direct chaotic scheme that uses not single chaotic radio pulses as an information carrier, but code sequences of such pulses. The data entry method used in the new version of the scheme expands the capabilities of the original scheme in terms of channel separation, increased bandwidth, and implementation of multiple access.

3. Information transmission scheme using code sequences from chaotic radio pulses

In the original direct chaotic communication scheme [11–13] chaotic pulses located at certain time positions within bit intervals are used as an information carrier. The presence of a chaotic radio pulse at such a position means the transmission of “1”, and its absence means the transmission of “0”. The remaining part of the bit interval is used as a guard pause, for example, in the presence of multipath propagation.

In the scheme proposed below, a stream of chaotic radio pulses with protective pauses between them is also used to transmit information. However, this uses a different type of pulse modulation by information signals.

Information transmission schemes can be conditionally divided into coherent and incoherent. Theoretically, coherent schemes in a white noise channel are more efficient than incoherent systems and energetically outperform the latter, all other things being equal, by several decibels in signal/noise ratio for the same probability of error per bit (BER—Bit Error Ratio). However, it is required to have a copy of the carrier signal on the receiving side. In the case of a chaotic carrier signal, this is a difficult task to implement, and attempts to create communication systems with chaotic synchronization, in which it is theoretically solved, have shown that such systems are very sensitive to noise and disturbances in the communication channel and are of little use in practice [14–25].

On the other hand, an incoherent communication system based on chaotic radio pulses requires further development in terms of expanding the possibilities of modulation and multiple access methods. To resolve these contradictions, this paper proposes and explores the idea of using coherent reception

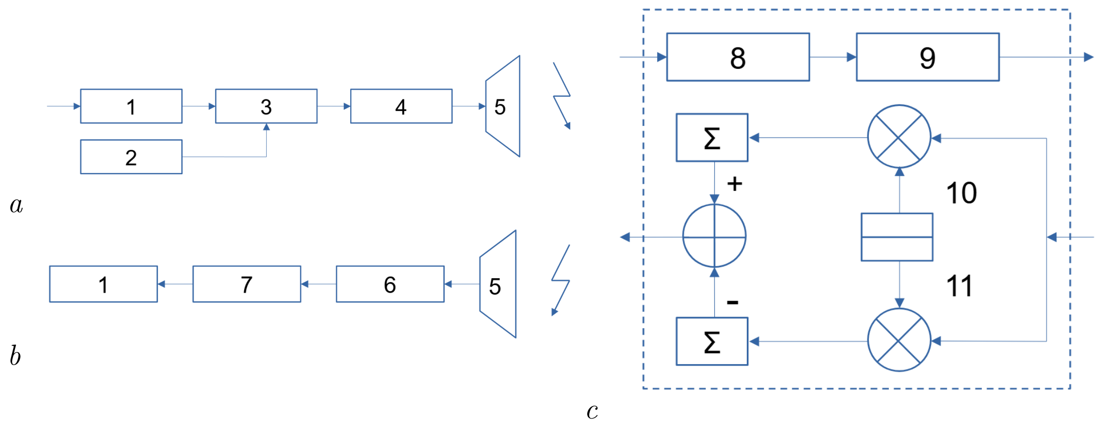

Fig. 1. Structure of the direct chaotic communication system with code division of signals: *a* — transmitter; *b* — receiver; *c* — digital board. 1 — digital board, 2 — chaos source; 3 — modulator; 4 — amplifier; 5 — antenna; 6 — envelope detector; 7 — analog-to-digital converter; 8 — information source encoder; 9 — channel encoder that generates a signal with a spreading code sequence; 10 and 11 — reference code sequences

in relation not to the signals themselves transmitted over the air, but to envelope signals isolated from them on the receiving side, essentially direct analogues of Baseband signals for classical narrowband communications.

The structure of the proposed transmission system is shown in Fig. 1. The system's transmitter (Fig. 1, *a*) consists of: a digital board (1), which receives the initial information; a chaos source (2); modulator (3), controlled by a signal generated in the digital board; an amplifier (4) and a transmitting antenna (5). In the digital board (Fig. 1, *c*) a source encoder (8) is implemented, forming a binary sequence with a bit length of T_b; and a channel encoder (9), forming a code sequence with a chip length of T_b/N, where N is the number of elements in the code sequence. Each sequence chip corresponding to "1", consists of two parts: a chaotic radio pulse and a protective pause, for simplicity equal in duration to each other; the sequence chip responding to "0" consists of an empty position and a protective pause.

The transmission is carried out using binary characters "0" and "1", each of which is represented as «its» binary code sequence of length N, which are orthogonal to each other. First, the binary signal itself $m(t)$ with a length of T_b, is formed, then the binary elements are multiplied each in the channel encoder by their own binary code sequence, increasing the base (processing). After that, the received signal, consisting of short video pulses, is multiplied with a chaotic carrier signal. The sequence of chaotic radio pulses resulting from this operation is amplified and radiated into the air with the help of an antenna.

The receiver of the system (Fig. 1, *b*) consists of an antenna (5), an envelope detector (6) and a digital board (1).

The received signal is processed in two stages. At the first stage, the signal received by the antenna is fed to the envelope detector (6), consisting of the signal detector itself (for example, a quadratic or logarithmic detector) and a low-pass filter, the parameters of which are consistent with the duration of chaotic radio pulses and the intervals between them. As a result, an envelope signal appears at the detector output corresponding to the code sequence of the transmitted symbol ("0" or "1"). This signal enters the digital board (Fig. 1, *c*), where it is multiplied with a copy of each of the two reference code sequences (10 AND 11) generated at the receiver. The multiplication results are summarized to obtain the correlation coefficients between the envelope signal and the reference sequence. The correlation coefficients are compared with each other and the symbol with the higher correlation coefficient is accepted as the transmitted symbol.

Thus, in the proposed modification of the scheme, each bit is represented as one of two sequences of «short» pulses formed using orthogonal sequences (codes) of video pulses with a length of N, one of which corresponds to "0", and the other to "1". Any two sequences orthogonal to each other or close to orthogonal to each other can be used as code sequences of symbols. The broadcast bit is a sequence of chaotic radio pulses with an arrangement along the time axis corresponding to the arrangement of zeros and ones in the code sequence corresponding to this bit.

4. Expanding code sequences

To implement this idea, it is necessary to use code sequences with special correlation and autocorrelation properties. First, we will discuss transmission and reception between two transceivers in the «point–point» mode. When transmitting information using binary signals "0" and "1" on the transmitting side, it is necessary to encode the stream of these signals using two code sequences, and on the receiving side to recognize them with a low (predetermined) error probability. It is known from the theory of coherent reception that codes are best suited for this purpose, in which the ratio N of the main peak of the autocorrelation function (ACF) to the lateral ones is the largest.

Such codes are binary sequences (codes) of Barker [26]. There are only 7 Barker codes. The longest of them consists of 13 characters (for example, "-1" and "$+1$") and has the ratio of the height of the main peak of the ACF to the lateral $N = 13$. This property makes it possible to reliably detect such a signal even when the signal/noise ratio (SNR) < 1.

Below, in the computer simulation, the Barker code of 11 characters is used:

$$+1+1+1-1-1-1+1-1-1+1-1. \quad (1)$$

In the form of binary elements "0" and "1"

$$1\ 1\ 1\ 0\ 0\ 0\ 1\ 0\ 0\ 1\ 0, \quad (2)$$

which does not change its normalized autocovariance function (see, for example, [27]). For transmission "1", the direct code (2) will be used, and for transmission "0", the inverse code will be used, that is

$$0\ 0\ 0\ 1\ 1\ 1\ 0\ 1\ 1\ 0\ 1. \quad (3)$$

5. Simulation

To demonstrate the fundamental possibility of the described modulation scheme, let us consider a simple example of its implementation.

The simulation was carried out using the example of the transmission of information bits "0" and "1". The transmitted bits were encoded with the sequences (2) and (3). Fig. 2 shows the location of the video pulses corresponding to these sequences.

The results of the simulation are presented below using the example of transmitting a single information bit. A sequence of chaotic radio pulses is inserted into the bit position corresponding to the transmission of "1" or "0", formed on the basis of the codes (2) or (3). The base of the «chip» (a short chaotic radio pulse plus a guard interval) in the example is $B_c = 19.2$ ((about 13 dB), the base of the total signal for transmitting a bit is $B_b = 201$ (about 23 dB).

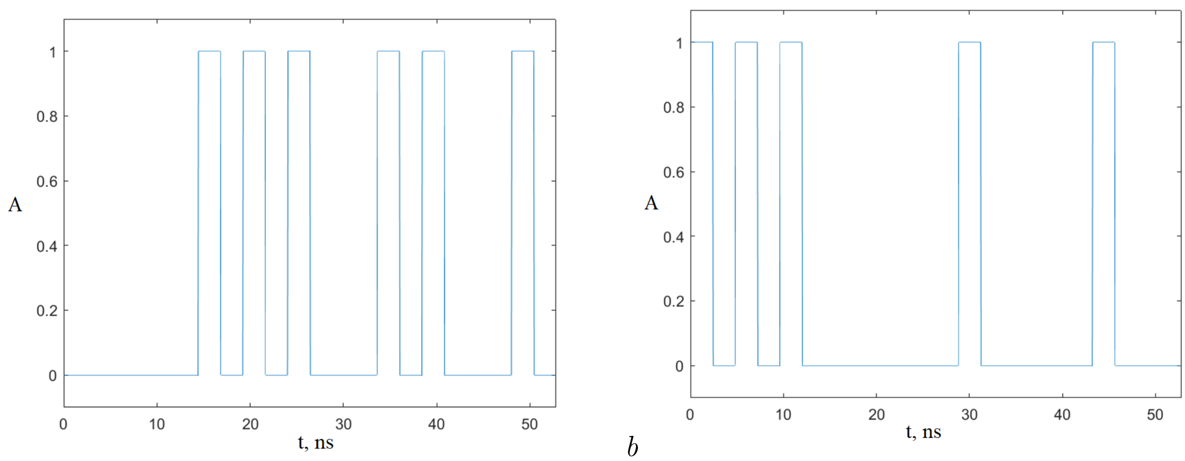

Fig. 2. Coding of "0" and "1" by Barker code sequence: *a* — "0" — inverse sequence; *b* — "1" — direct sequence

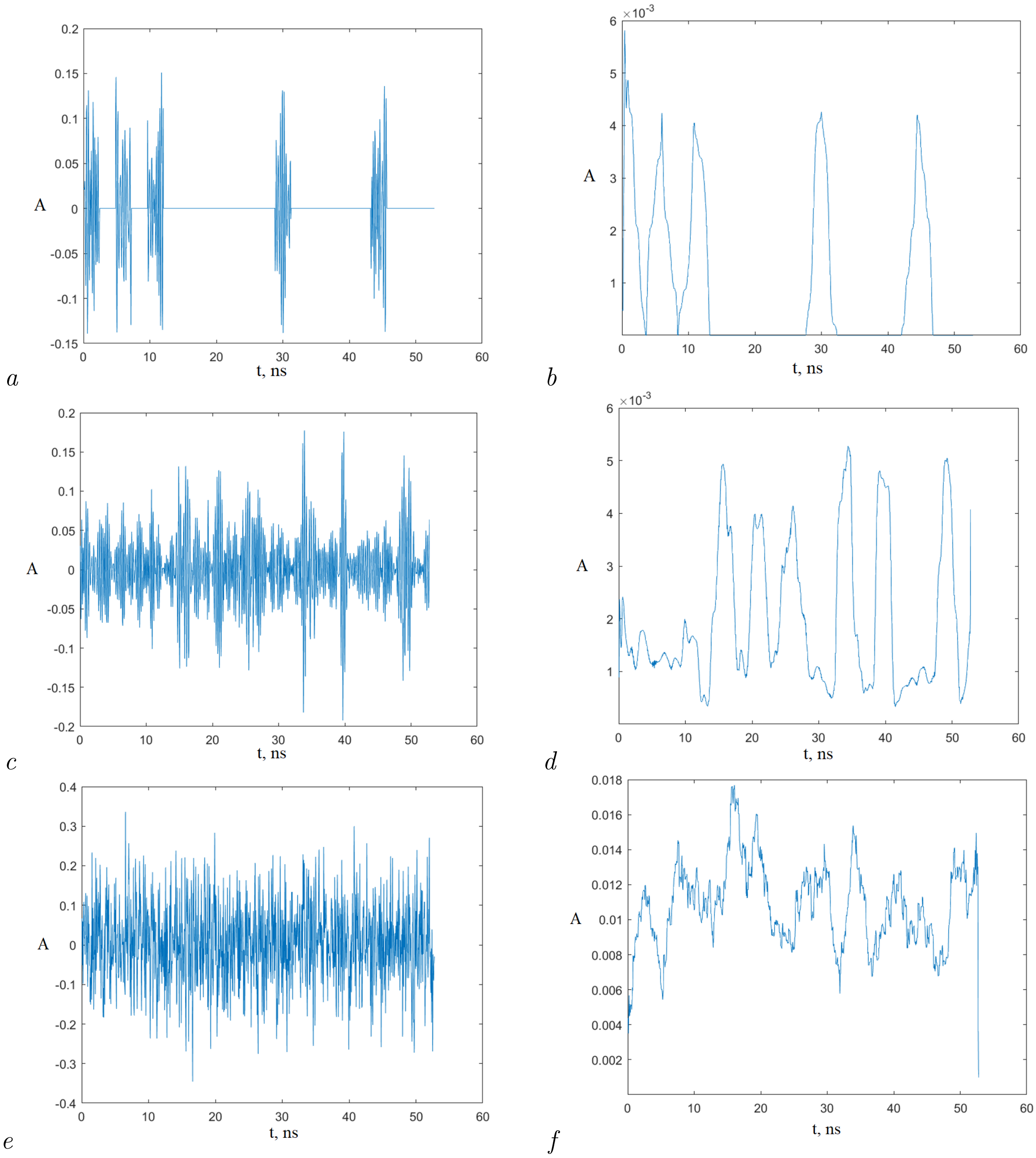

Fig. 3. Examples of signals using the Barker code: *a, b* — transmission of "1", signal in the channel without noise and after the envelope detector; *c, d* — transmission of "0", signal in the channel and after the detector at $E_b/N_0 = 20$ dB (SNR $= -3$ dB); *e, f* — transmission of "0", signal in the channel and after the detector at $E_b/N_0 = 10$ dB (SNR $= -13$ dB)

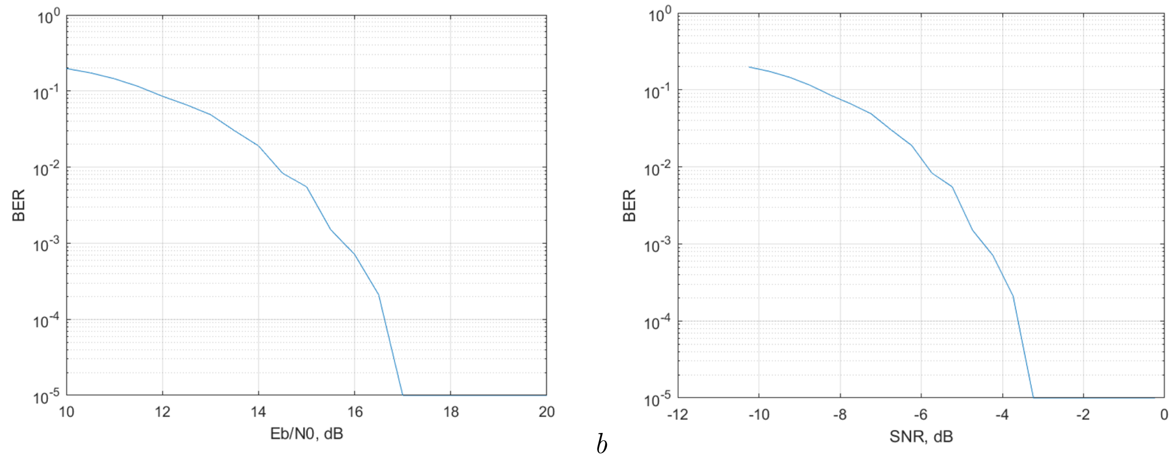

Fig. 4. Probability of errors for representing a bit as a sequence of chaotic pulses in accordance with the Barker code: *a* — from the average energy of a bit per pulse; *b* — from the signal-to-noise ratio

Short chaotic radio pulses in a code sequence are modeled using a random bandpass signal.

In Fig. 3 the results of modeling the transmission of "1" using the Barker code through a communication channel with white noise at different noise levels are presented: *a*, *b* is the transmission of "1", the signal

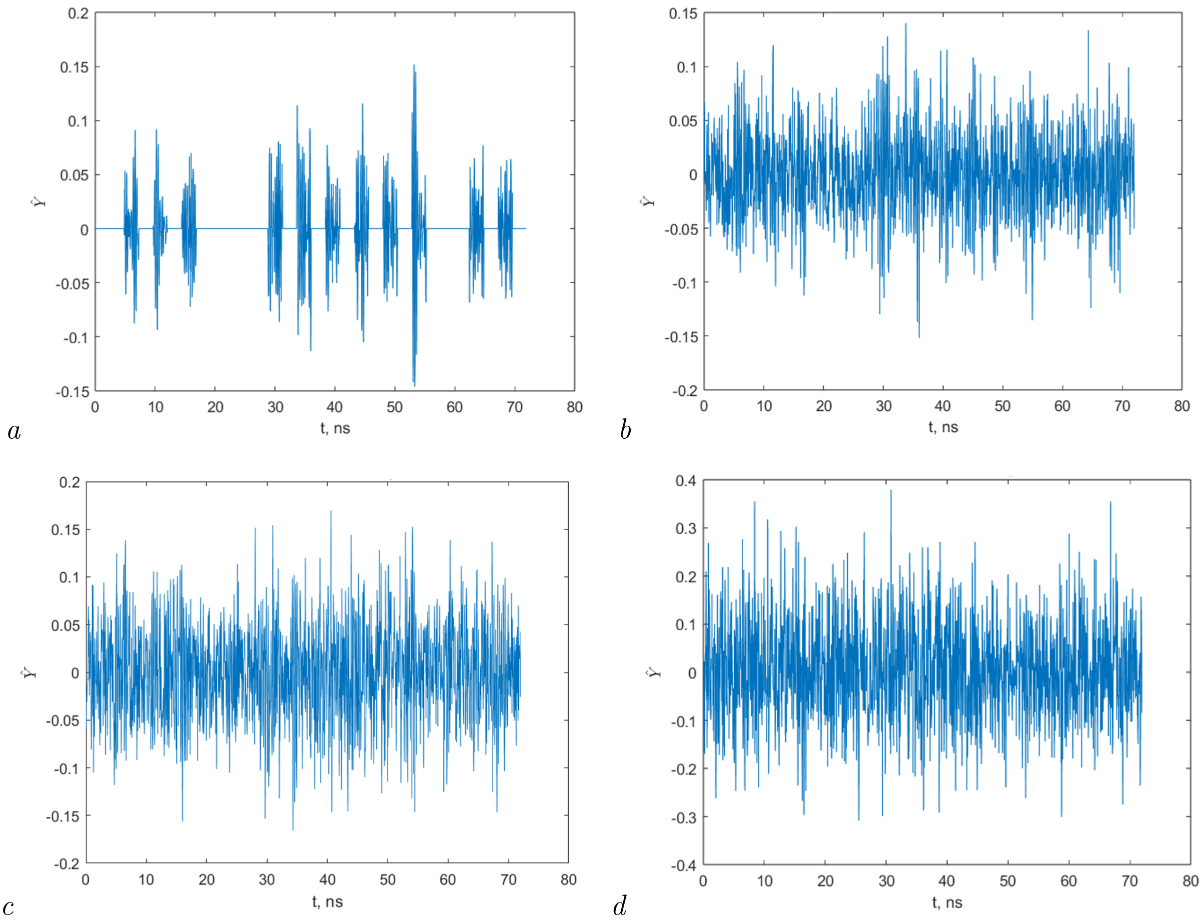

Fig. 5. Total signal of two users in the channel at different levels of white noise: *a* — no noise; *b* — SNR $= -1.5$ dB; *c* — SNR $= -4.5$ dB; *d* — SNR $= -11.5$ dB

in the channel without noise and after the envelope detector; c, d is the transmission of “0”, signal in the channel and after the detector at $E_b/N_0 = 20$ dB (SNR $= -3$ dB); e, f is the transmission of “0”, signal in the channel and after the detector at $E_b/N_0 = 10$ dB (SNR $= -13$ dB).

In the first two shown in Fig. 3 in some cases, information bits are transmitted without errors. However, with a further decrease in the ratio E_b/N_0 the probability of erroneous reception of bits increases. So, Fig. 3 *e, f* shows the transmission of “0” with $E_b/N_0 = 10$ dB. Under these conditions, an error bit was accepted.

The dependences of the probability of errors in transmission represented by a sequence of chaotic radio pulses in accordance with the Barker code from SNR and E_b/N_0 are shown in Fig. 4.

Comparison of the results shown in Fig. 4, with dependencies for the probability of errors with a single pulse and the same signal base, shows that the error probabilities of 10^{-3} and 10^{-5} in both cases are achieved at approximately the same values and E_b/N_0.

At the final stage of processing, the received pulse sequence is correlated with the known sequences for bit “1” and bit “0”. The value for which the correlation is higher is taken as the received information bit.

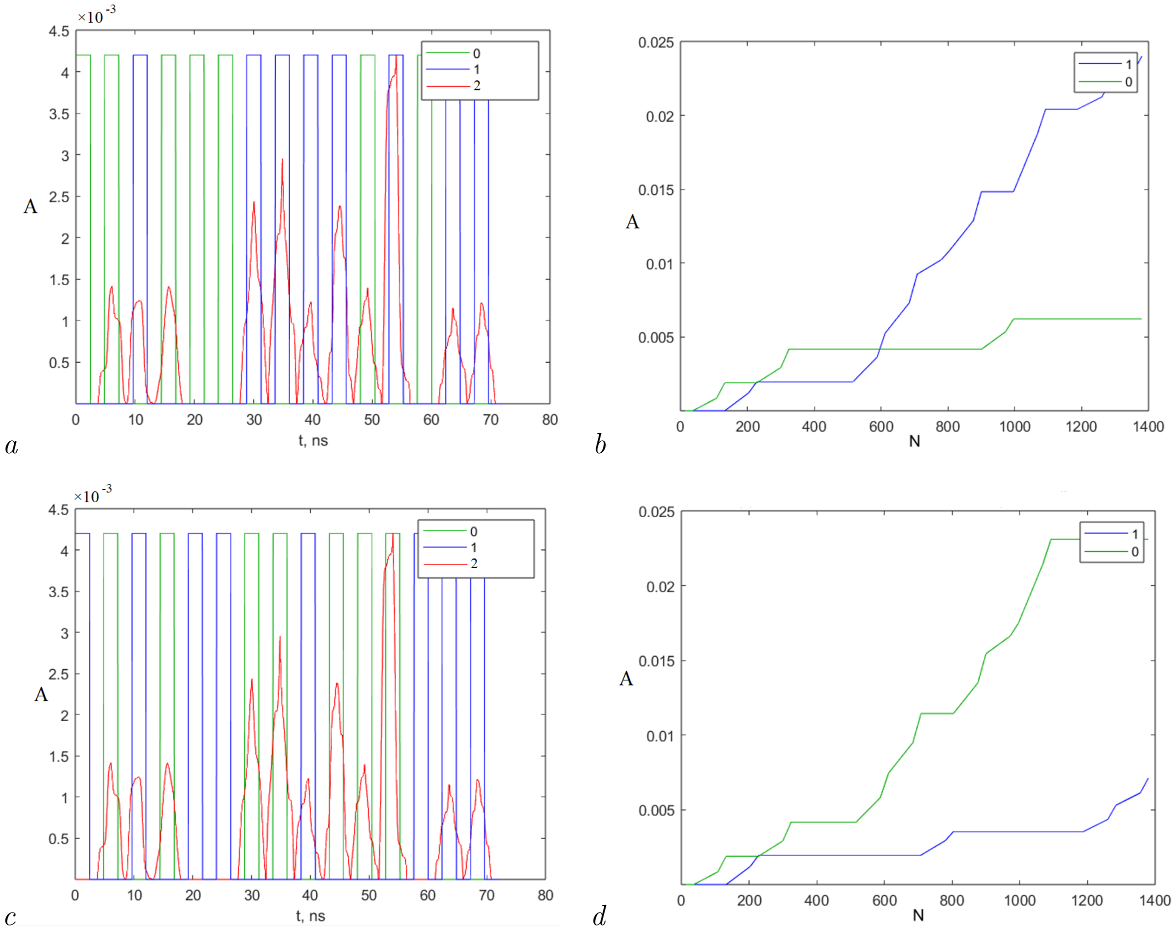

Fig. 6. Separation of signals of two users in the absence of noise: a — received envelope (red) with an ideal pulse sequence for “1” (blue) and for “0” (green) for user 1; b — received envelope (red) with an 15 ideal pulse sequence for “1” (blue) and for “0” (green) for user 2; c — correlation level of the envelope with an ideal sequence for “1” (blue) and for “0” (green) for user 1; d — correlation level of the envelope with an ideal sequence for “1” (blue) and for “0” (green) for user 2 (color online)

6. Multiple access using code sequences

Calculations on the use of code sequences in the scheme of direct chaotic transmission were carried out using Barker codes, which have the best autocorrelation properties for this purpose (side lobes of the autocorrelation function $1/N$). An additional reason for using the Barker code is its «good reputation» due to its use in the IEEE 802.11 standard.

To evaluate the capabilities of this scheme in the interests of multiple access, «mass character» code sequences are more suitable, although with slightly worse characteristics in terms of the level of the side lobes of the autocorrelation functions. The natural candidates here are M-sequences and codes derived from them.

M-sequences or maximum length sequences (MSL) are bit sequences generated using shift registers with maximum linear feedback, and they are so called because they are periodic and reproduce every binary sequence (except the zero vector) that can be represented by shift registers (that is, for registers of length m, they produce a sequence of length $2^m - 1$).

M-sequences are characterized by a rather low level of the lobes of the autocovariance function, decreasing according to the law $1/\sqrt{N}$, where N is the length of the sequence. Therefore, they are often used as the basis for obtaining pseudorandom sequences in digital communication systems with

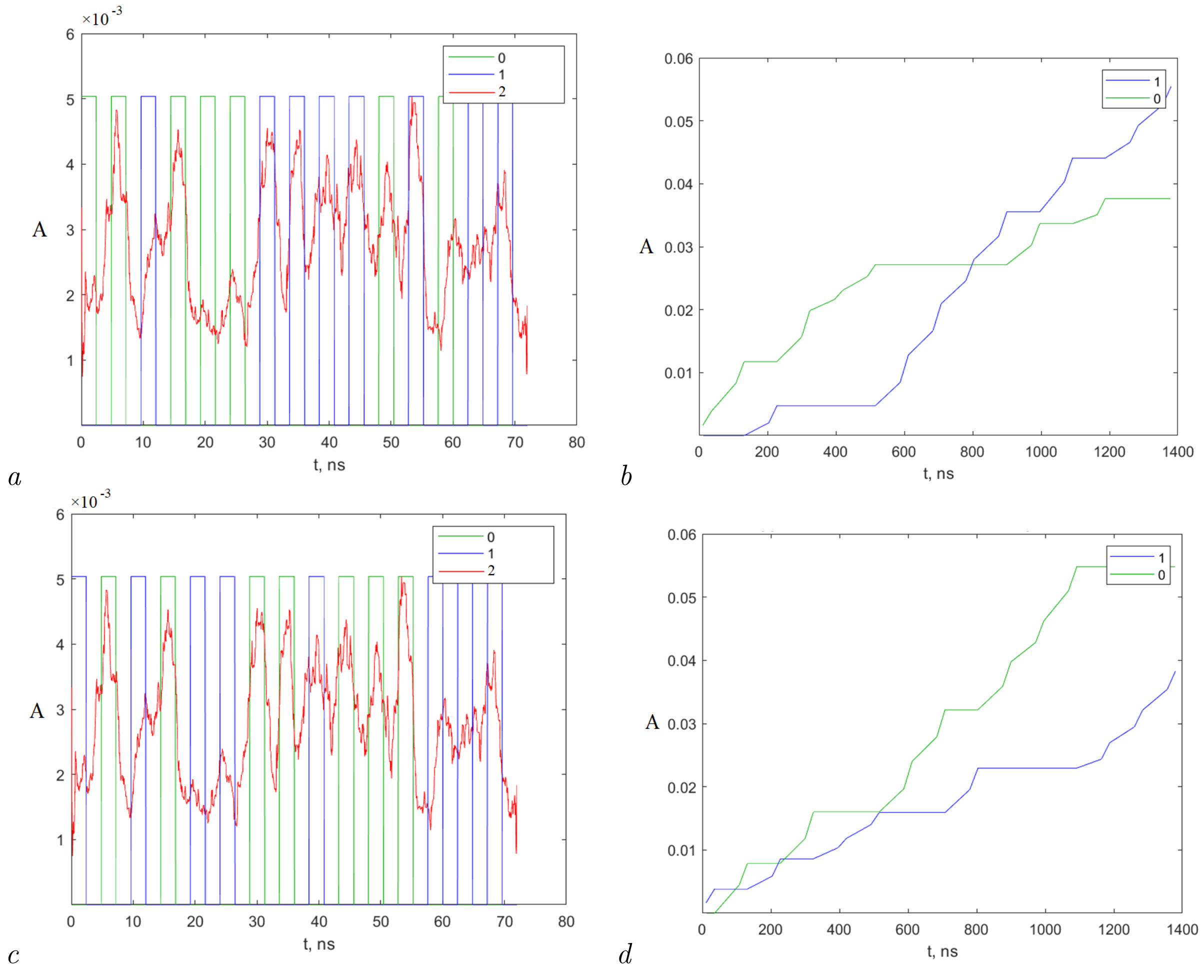

Fig. 7. Separation of signals of two users at SNR = −4.5 dB: *a* — received envelope (red) with a noisy pulse sequence for “1” (blue) and for “0” (green) for user 1; *b* — received envelope (red) with a noisy pulse sequence for “1” (blue) and for “0” (green) for user 2; *c* — correlation level of the envelope with a noisy sequence for "1"(blue) and for “0” (green) for user 1; *d* — correlation level of the envelope with a noisy sequence for “1” (blue) and for “0” (green) for user 2 (color online)

an extended spectrum of direct sequence and an extended spectrum transmission system with frequency hopping.

For a communication system with two users, transmission characteristics were studied depending on the noise level. During the simulation, the sequence $b_1^1 = 001000111101011$ (corresponds to the logical "1") was transmitted for the first user and the sequence $b_0^2 = 010100110111000$ (corresponds to the logical "0") for the second user. Fig. 5 shows the view of the total signal in the channel at different levels of external noise, assuming that: 1) the signals from two users have the same amplitude; 2) the generating M-sequences in the simulation start simultaneously; 3) the observation point is equidistant from the users.

In Fig. 6–8 the results on the separation of signals from two users with an increase in the level of external noise are presented.

In Fig. 6 the results for the case of no noise in the channel are given: *a* is the received envelope (red) with an ideal pulse sequence for "1" (blue) and for "0" (green) for user 1; *b* is the received envelope (red) with an ideal pulse sequence for "1" (blue) and for "0" (green) for user 2; *c* is the correlation level of the envelope with the ideal sequence for "1" (blue) and for "0" (green) for user 1; *d* is the correlation level of the envelope with the ideal sequence for "1" (blue) and for "0" (green) for user 2.

From the analysis of the figure, it follows that the logical "1" will be accepted by the first user, and "0" by the second. The difference in the correlation level between the correct accepted symbol and the incorrect one for each user is more than an order of magnitude.

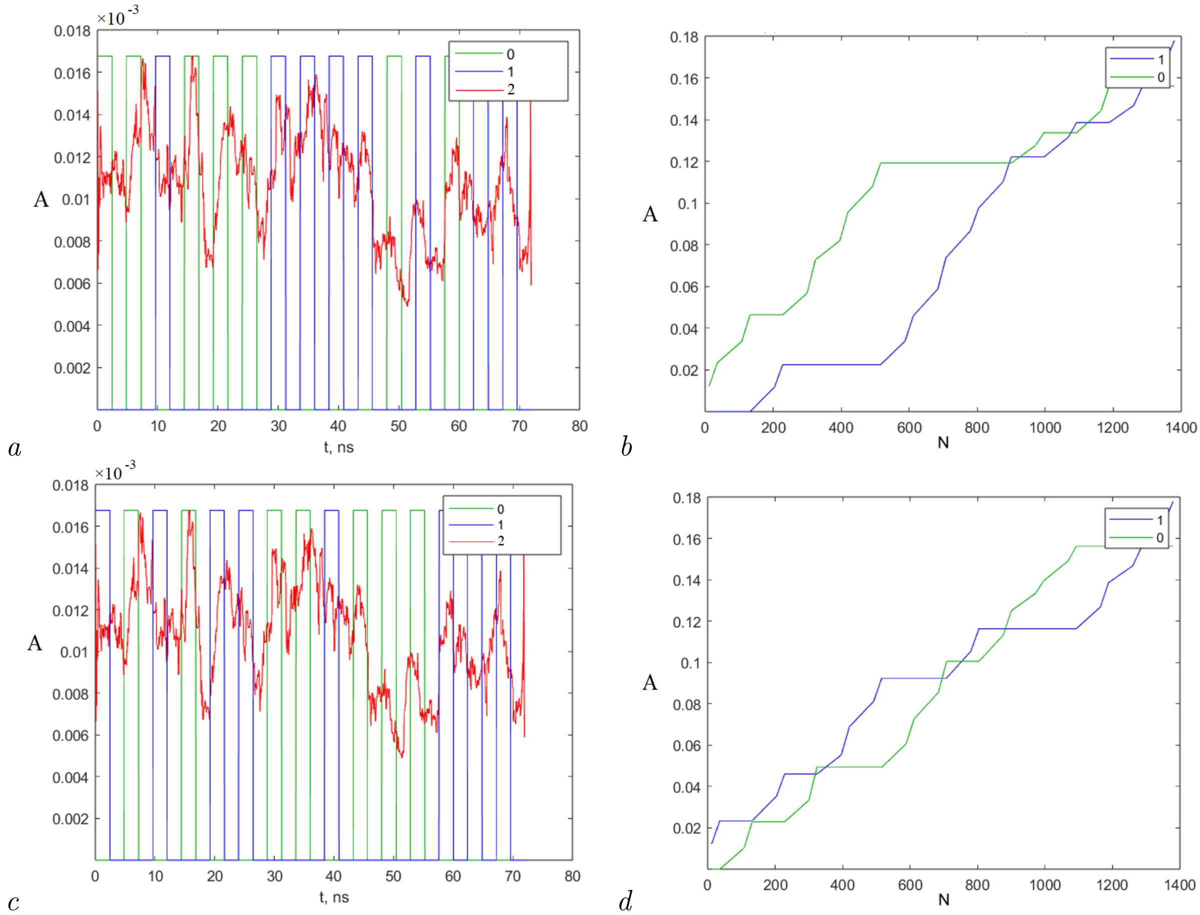

Fig. 8. Separation of signals of two users at SNR = −11.5 dB: *a* — received envelope (red) with a noisy pulse sequence for "1" (blue) and for "0" (green) for user 1; *b* — received envelope (red) with a noisy pulse sequence for "1" (blue) and for "0" (green) for user 2; *c* — correlation level of the envelope with a noisy sequence for "1"(blue) and for "0" (green) for user 1; *d* — correlation level of the envelope with a noisy sequence for "1" (blue) and for "0" (green) for user 2 (color online)

Now let us consider the case with the noise level SNR $= -4.5$ dB (Fig. 7). In this case, the received signal is significantly distorted, but still, correlation processing makes it possible to correctly identify the transmitted binary characters for both user pairs.

Finally, consider the case with a noise level of SNR $= -11.5$ dB (Fig. 8). In this case, the received signal is distorted so much that correlation processing does not allow the transmitted binary characters to be correctly and reliably distinguished for users.

Detailed calculations show that the noise level limit at which it is possible to correctly identify binary characters with BER $= 10^{-3}$ is approximately -5 dB in this case.

It should be noted that for both the first and second user, an additional user in the channel plays the role of additional noise. A rough estimate, which does not take into account the degree of synchronicity of the channels and the degree of their orthogonality, assuming the same signal power in the channel and continuous signal transmission by each user, suggests that in the absence of external noise, adding a second user reduces the signal/noise ratio from SNR $= \infty$ to SNR $= 0$. With 4 users, the additional noise will be already 5 dB. Since the simulation showed that a system with two users remains operational with an external additional noise of 5 dB, in the absence of external noise in the channel, the system in our example provides simultaneous operation of up to 5 users. A further increase in the number of users can be achieved by further increasing the signal base.

Conclusion

The information transmission scheme proposed in this article, which uses sequences of chaotic radio pulses as an information carrier, belongs to the class of direct chaotic systems. In comparison with the basic direct chaotic communication scheme (DCCS), the proposed DCCS variant using sequences of chaotic radio pulses to represent binary symbols allows using not only their temporal separation, but also code separation for multichannel multi-channel transmission. In this case, the idea of coherent demodulation of the signal in the receiver is partially realized.

An important property of the scheme is also the zero decision threshold at the final stage of signal processing.

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