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Basic Principles of Direct Chaotic Communications

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Basics of the theory of direct chaotic communications is presented. We introduce the notion of chaotic radio pulse and consider signal structures and modulation methods applicable in direct chaotic schemes. Signal processing in noncoherent and coherent receivers is discussed. The efficiency of direct chaotic communications is investigated by means of numerical simulation. Potential application areas are analyzed, including multiple access systems.

Key words: dynamic chaos, chaotic radio pulse, communication system

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1 Introduction

Direct chaotic communication (DCC) systems are systems in which the information-carrying chaotic signal is generated directly in RF or microwave band [1–9]. Information is put into the chaotic signal by means of modulating either the chaotic source parameters or the chaotic signal after it is generated by the source. Consequently, information is retrieved from the chaotic signal without intermediate heterodyning.

The idea of direct chaotic systems and results of experiments with a wideband communication system operating in 900–1000 MHz band and providing transmission rates 10 to 100 Mbps were presented in Refs. [2–6]. The results of experiments with ultra-wideband direct chaotic circuit operating in 500–3500 MHz band with up to 200 Mbps rate are given in Refs. [6–9]. The limit transmission rate in that system is estimated as 500–1000 Mbps. These experiments verified practical applicability of DCC and estimates of its performance.

A key notion of direct chaotic systems is the notion of chaotic radio pulse, which is a signal fragment whose duration is longer than the quasiperiod of chaotic oscillations. The frequency bandwidth of the chaotic radio pulse is determined by the bandwidth of the original chaotic source signal and is independent of the pulse duration in a wide range of duration variation. This makes the chaotic radio pulse essentially different of the classical radio pulse filled with a fragment of periodic carrier, whose frequency bandwidth Δf is determined by its duration τ

$$\Delta f \sim \frac{1}{\tau} \qquad (1)$$

In this paper, the basics of the theory of direct chaotic transmission of information are given.

The paper layout is as follows.

In the first section, the scheme of direct chaotic communications is described. In the second, we consider the signal structure and modulation methods. In the third section, receiver models are described and their effectiveness is discussed. The system performance with noncoherent and coherent receivers is investigated in the fourth section. Then, we analyze in brief organization of multiple access, electromagnetic compatibility and ecological aspects.

2 Scheme of information transmission using chaotic radio pulses

Three main ideas constitute the basis of direct chaotic communication circuits [2–9]: (1) chaotic source generates oscillations directly in the prescribed microwave band; (2) information is put into the chaotic signal by means of forming the corresponding sequence of chaotic radio pulses; (3) information is retrieved from the microwave signal without intermediate heterodyning.

Block diagram of direct chaotic communication system in the cases of external and internal modulation is shown in Fig. 1.

The transmitter of the system is composed of a unit of oscillator control; a chaotic source that generates the signal directly in the frequency band of information transmission, i.e., in RF or microwave band; a keying-type modulator; an amplifier; an antenna; an information source; a message source encoder, and a channel encoder.

Chaotic source provides generation of the signal with the frequency bandwidth

$$\Delta F = F_u - F_l \qquad (2)$$

where F_l andF_u are the lower and upper boundaries of the chaotic oscillation band. The chaotic signal frequency bandwidth is the frequency range, at which boundaries the power spectral density is –20 dB of the maximum within the range.

The central frequency

$$F_0 = (F_u + F_l)/2 \qquad (3)$$

and the bandwidth ΔF of the generated signal may be adjusted by control unit. Modulator forms chaotic radio pulses and intervals between them.

Information that comes from an information source is transformed by the message source encoder into a signal that is fed to the channel encoder, which in turn transforms it into a modulating signal that controls the modulator. Modulator forms chaotic radio pulses either by means of multiplying chaotic signal and modulating pulses (the case of external modulation, Fig. 1, a), or by means of modulating the oscillator parameters (the case of internal modulation, Fig. 1, b). The duration of the formed chaotic pulses may be varied in the range $\tau \sim 1/\Delta F$ to $\tau \to \infty$.

The formed signal is put through amplifier and is emitted to free space with wideband antenna. Information stream can be formed by means of changing the intervals between the pulses, the pulse duration, the mean square amplitude of the pulses, or by means of combining these parameters.

For example, the stream can be formed so as to have constant rate of pulse positions and fixed duration of the pulses. In this case, the presence of a pulse at a certain prescribed position in the stream corresponds to transmission of symbol “1”, and the absence of the pulse in the stream corresponds to the transmission of symbol “0”.

The receiver (Fig. 1, c) is composed of a broadband antenna, a filter that passes the signal within the frequency band of the transmitter, a low-noise amplifier, and a signal processing system. The sequence of chaotic radio pulses comes to antenna and passes through filter and amplifier. The signal-processing system finds the pulses and determines their parameters and location in time domain. Then, the signal-processing system retrieves useful information from the signal either by means of integrating the pulse power over the pulse interval (noncoherent receiver), or by means of convolving the chaotic radio pulses with corresponding reference pulses generated in the receiver (coherent receiver).

3 The signal structure and modulation methods

Information is transmitted by means of forming a sequence of chaotic radio pulses. Here, each pulse duration is τ, and the the pulse position is located within the time window of length T (in the average). The parameter

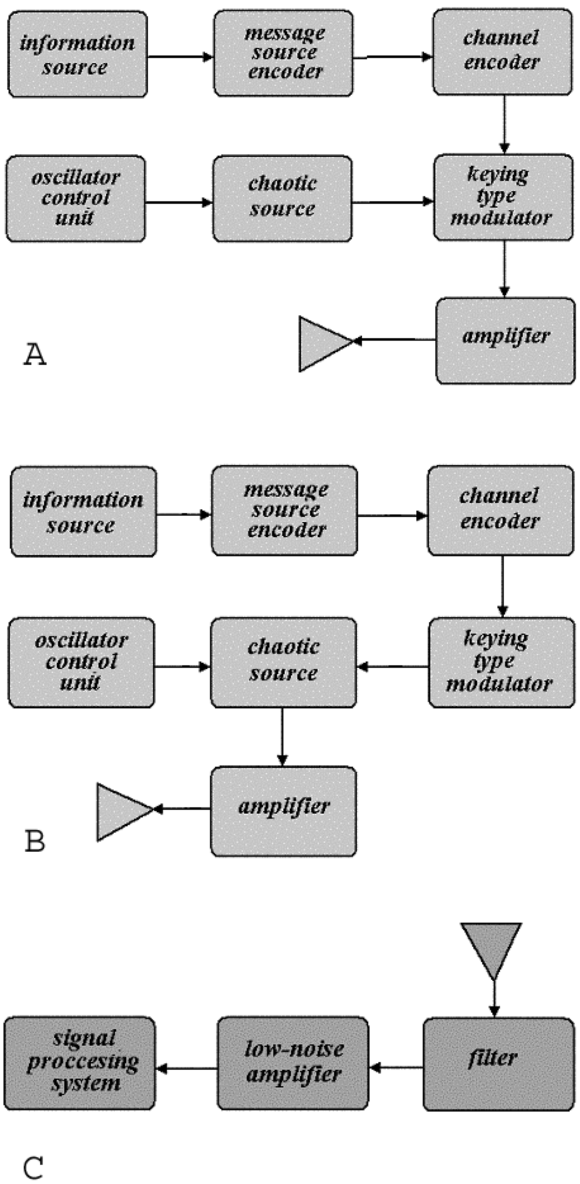

FIG. 1. Block-diagram of direct chaotic communications system: (a) transmitter with external modulation; (b) transmitter with internal modulation; (c) receiver.

$$D = \frac{\tau}{T} \quad (4)$$

will be called the duty cycle.

Let P be the power of the original chaotic signal, and let the transmission of information bit "1" be encoded by the presence of a chaotic radio pulse in the corresponding position and by "0" by its absence in this position. Then, the average power of the chaotic signal in the communication channel is equal to

$$P_{av} = \frac{P}{2} D. \quad (5)$$

The factor 1/2 come from the fact that in average only half the pulses is present, provided that "1"'s and "0"'s have the same probability.

Let us denote the power spectral density of the chaotic signal by $s(f)$. As a rule, the spectral density is not constant within the frequency band ΔF. So, it is useful to know the mean-over-the-band spectral density of the signal

$$< s >= \frac{1}{F_u - F_l} \int_{Fl}^{F_u} s(f)df = \frac{1}{\Delta F} \int_{Fl}^{F_U} s(f)df. \quad (6)$$

The signal base is a quantity [10–11]

$$B = 2\Delta F \tau \quad (7)$$

Judging from the value of base B, elementary signals with base

$$B = 2\Delta F \tau \sim 1 \quad (8)$$

and complex signals with

$$B = 2\Delta F \tau >> 1 \quad (9)$$

are distinguished.

Since $2\tau\Delta F$ is the signal base, then increasing the duration of chaotic radio pulse gives greater signal base. If the chaotic radio pulse duration is

$$\tau >> \frac{1}{2\Delta F}$$

then the power spectrum of the sequence of chaotic radio pulses is practically the same as that of the original chaotic signal.

As an example, let us consider chaotic RF pulses obtained from the chaotic signal of a ring-structure oscillator with 2.5 freedom degrees that is passed through a band-pass filter (2000-5000 MHz) with –40 dD side-band suppression. Normalized equations of the oscillator are as follows:

$$T\dot{x} + x = F(z)$$
$$\ddot{y} + \alpha_1\dot{y} + y = x$$
$$\ddot{z} + \alpha\dot{z} + \omega^2 z = \alpha_2\dot{y}$$
$$F(z) = M\left[|z+E_1| - |z-E_1| + \frac{1}{2}\left(|z-E_2| - |z+E_2|\right)\right]$$

with the parameters set at $\alpha_1 = 0.0577; T = 0.7996; \alpha_2 = 0.2803; \omega = 0.7253; E_1 = 0.5; E_2 = 1; M = 20$.

The power spectrum of a periodic sequence of chaotic RF pulses as a function of the pulse length is presented in Fig. 2,a. As can be seen, in a wide range of the pulse length variation the form of the main spectrum lobe changes weakly and with a decrease of the pulse length the level of spectrum density outside the main band increases.

Dependencies for random sequences of chaotic pulses (Fig. 2, b) are presented in Fig. 3. As can be seen from comparison of Figs. 2, a and 2, b, in both cases the levels of the background spectrum outside the main lobe are approximately equal, however it is more smooth in the case of random sequence.

To understand the main features of chaotic radio pulse as an information carrier, let us compare it with two other carriers: harmonic signal and ultra-short ultra-wideband video pulses.

Radio pulses obtained by means of multiplication of a harmonic signal of frequency f_0 and video pulses of duration τ are elementary, because the bandwidth of such pulses is $\Delta F \sim 1/\tau$ and their base equals $B = \tau\Delta F \sim 1$ [13–14]. Simple-form ultra-short pulses [15], despite their super-wide bandwidth are also elementary, because the product of their duration by their bandwidth is also $B = 2\tau\Delta F \sim 1$. In contemporary communication systems, especially those operating under difficult signal propagation conditions (cellular systems, local wireless communications, etc.) large-base signals

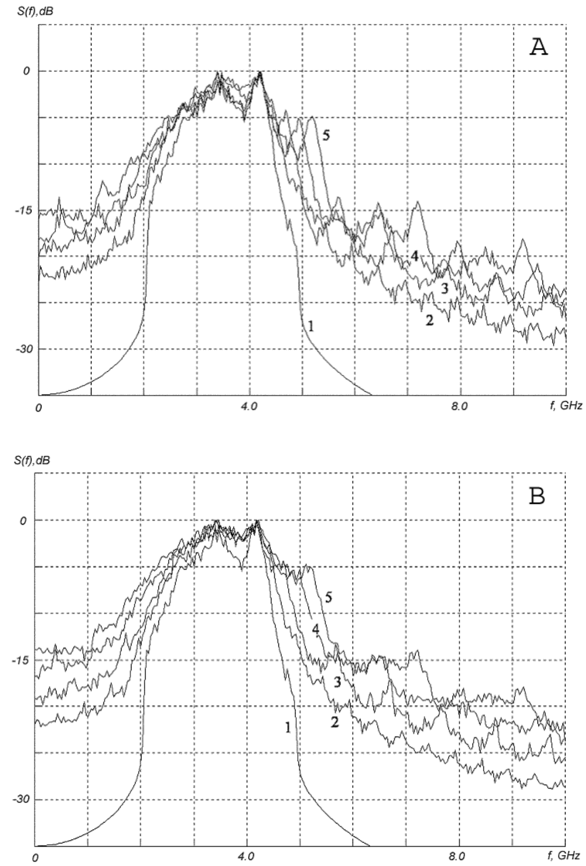

FIG. 2. The power spectrum of the periodic (a) and random (b) sequence of chaotic RF pulses for four values of the pulse length τ: 1 – chaotic signal, 2 – τ_1=2ns, 3 – τ_2=1ns, 4 – τ_3=0.3ns, 5 – τ_4=0.25ns.

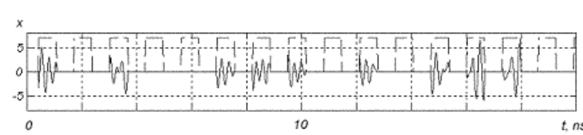

FIG. 3. Waveform fragments of random sequence of chaotic RF pulses for the pulse length τ_3=0.3ns.

are preferably utilized. When operating with the signals based on harmonic carrier, spectrum spreading techniques (direct spread sequences or frequency hopping) are used, where the signal base is increased in proportion to the spectrum spreading factor [12–14]. To obtain large-base signals using ultra-wideband pulses, either the energy of several pulses is accumulated, or the pulse shape is complicated so as to increase their duration and retain the ultra-wide bandwidth.

In contrast to the above signals, the signal base in DCC is determined by only the duration of chaotic radio pulses. No supplementary elements are necessary in the system to change the value of B. Moreover, at various transmission rates the input circuits of the receiver and the base values may be kept constant.

Note also that direct chaotic signals may be accomplished in any necessary frequency band (which is impossible, e.g., in ultra-wideband systems with ultra short pulses).

We distinguish below two classes of receivers. In a coherent receiver exact copies of all possible signals the transmitter could sent in a given time interval are present. In opposite to this, in the case of noncoherent receiver we do not use the information about of the waveform of the transmitted signal.

In the case of noncoherent receiver, a pair of orthogonal signals can be represented by the above signals: the presence of chaotic radio pulse in a prescribed position or its absence (Fig. 4, a). Another variant of the pair of orthogonal signals can be the pair of chaotic pulse signals shifted against some known position in opposite directions. In this case, “0” is related to the signal shifted to the left of the fixed position, and “1” to the right of it (in time domain) (Fig. 4, b).

Both these pairs of orthogonal signals can be also used with the coherent receiver. However, additional possibilities are available here.

Indeed, two arbitrary fragments of a chaotic signal that are of same length are practically uncorrelated, i.e., orthogonal. This fact can be used to organize pairs of “orthogonal” signals as follows.

The transmitter and receiver incorporate chaotic sources that form identical chaotic signals. For ex-

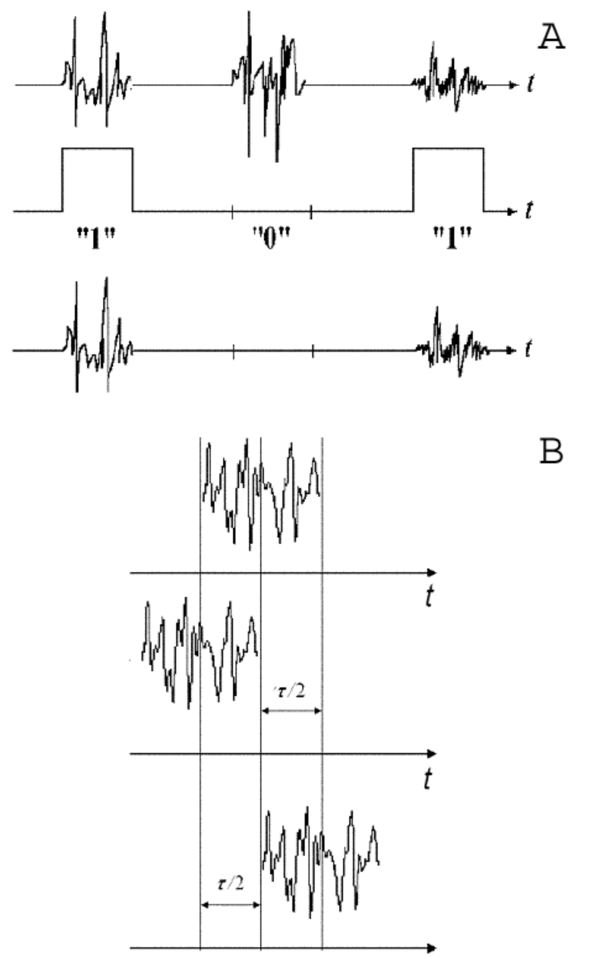

FIG. 4. Examples of orthogonal pairs of signals for direct chaotic communication systems: (a) simplest system of signals; (b) pulse position modulation.

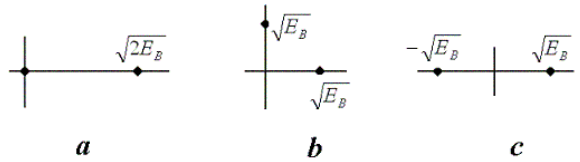

FIG. 5. Geometrical interpretation for orthogonal (a, b) and antipodal (c) signals.

ample, sequences of chaotic radio pulses are formed. Each sequence is divided into pairs, each containing two practically orthogonal signals.

Such a way of creating "orthogonal" signal system is naturally generalized to groups of m signals which allows to transmit $\log_2 m$ information bits during one active interval.

With coherent receiver antipodal signals can also be used. As in the case of orthogonal signals, identical sequences of chaotic radio pulses are formed in the transmitter and receiver. When transmitting "0", the radio pulse is inverted by sign, while by transmission of "1" it is emitted in its original form.

Geometrically, the discussed signal systems can be presented as in Fig. 5.

Note that uncorrelated character (orthogonality) of chaotic radio pulses is approximate. The same is the situation with the chaotic radio pulse energy. In general, it varies from pulse to pulse and this fact must be taken into account by calculation of communication system parameters.

4 Noncoherent and coherent receiver models

Information transmitted with chaotic radio pulses can be received with two main methods: noncoherently or coherently. Here we restrict our analysis of the receiver operation to the case when "0" is transmitted by the absence and "1" by the presence of a chaotic radio pulse in the corresponding time position.

Let $S_0(t)$ and $S_1(t)$ be signal forms that correspond to two different transmitted bits. In our case, $S_0(t) = 0$ and $S_1(t)$ is a chaotic radio pulse. At the input of signal-processing unit the signal $y(t)$ is fed

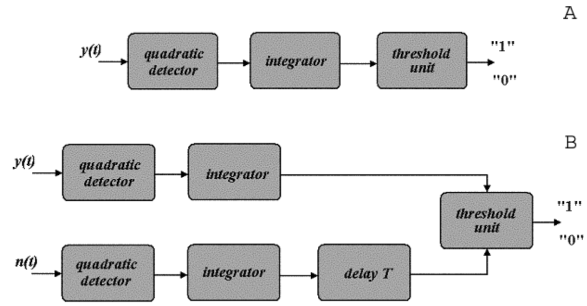

FIG. 6. Noncoherent receiver structure: (a) threshold value is taken outside the processing unit; (b) threshold value is set inside the processing unit.

$$y(t) = \begin{cases} S_0(t) + \eta(t), & \text{the case of "0"} \\ S_1(t) + \eta(t), & \text{the case of "1"} \end{cases} . \quad (10)$$

where $\eta(t)$ is Gaussian noise with spectral density N_0.

In the *noncoherent* receiver, the signal processing comprises its detection with a quadratic detector, integration over the time interval τ, and comparison with a threshold value (Fig. 4, a). The signal at the threshold unit is

$$d_0 = \int_0^T \eta^2(t) dt,$$

if the transmitted signal is "0", and

$$d_1 = \int_0^T (S(t) + \eta(t))^2 dt,$$

is symbol "1" is transmitted.

The decision on "0" or "1" is taken judging from comparison of the obtained value d_i with the threshold d. If $d_i < d$, then the receiver concludes "0", otherwise, symbol "1".

In the circuit in Fig. 6, a, the threshold value is taken from preliminary observations of the noise level, i.e., outside the processing unit. Alternatively, in the circuit presented in Fig. 6,b, the noise energy is estimated on the time interval τ preceding the position with the chaotic radio pulse. With this estimate, the threshold value is set automatically.

In the *coherent* receiver, the signal forms $S_0(t)$ and $S_1(t)$ that correspond to two different transmitted signals are assumed to be present. In our case, $S_0(t) = 0$ and $S_1(t)$ is a chaotic radio pulse.

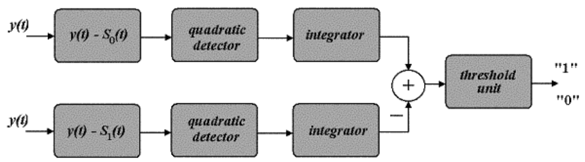

FIG. 7. Coherent receiver structure.

Then the following operations are performed in the signal-processing unit (Fig. 7).

The incoming signal $y(t)$ is fed to the upper and lower processing channels, where $S_0(t) \equiv 0$ and $S_1(t)$ are subtracted from it, respectively. The obtained difference signals are detected with a quadratic detector and integrated over the time interval τ, equal to the chaotic radio pulse duration. The processed signals are directed to a summer, and after that the threshold unit makes decision which symbol is received.

Let a signal corresponding to symbol "0" come to the receiver. Then, in the upper channel we have

$$d_0 = \int_0^T \eta^2(t)dt,$$

while in the lower chanel

$$d_1 = \int_0^T (S_1(t) - \eta(t))^2 dt$$

and the difference $d_0 - d_1 < 0$.

If the signal corresponding to "1" comes to the receiver, then in the upper channel we have

$$d_0 = \int_0^T (S_1(t) + \eta(t))^2 dt,$$

in the lower chanel

$$d_1 = \int_0^T \eta^2(t)dt$$

and the difference $d_0 - d_1 > 0$.

Thus, the threshold for decision is zero and the threshold unit makes decision on symbol "0" received, if the signal at the summer's output is negative, and on symbol "1", if the signal at the summer's output is positive.

Noise resistance of DCC can be analyzed with a continuous model discussed above, as well as with the signal sampled in time domain. In the latter case, signals samples $S_0(t)$ and $S_1(t)$ are substituted by signals $S_0(i)$ and $S_1(i)$, and noise $\eta(t)$ by noise samples $\eta(i)$, where $S_0(i) = S_0(i\tau/n)$, $S_1(i) = S_1(i\tau/n)$, $\eta(i) = \eta(i\tau/n)$.

The filter passband is assumed to be matched with the chaotic signal band. So, the noise signal has the same correlation time and bandwidth as the chaotic signal.

In discrete case, main relations for noncoherent and coherent receivers are as follows.

Noncoherent case.

$d_0 = \sum_{i=1}^{n} \eta^2(i)$– for symbol "0" transmitted.

$d_1 = \sum_{i=1}^{n} (S_1(i) + \eta(i))^2$– for symbol "1".

The problem of noncoherent receiver in discrete case as in continuous case is that d_0 and d_1 are compared not to each other, but each with a threshold that is estimated separately, which contributes additional uncertainty.

Coherent case. At the output of the upper channel we have

$d_0 = \sum_{i=1}^{n} \eta^2(i)$– for symbol "0" transmitted and

$d_0 = \sum_{i=1}^{n} (S_1(i) + \eta(i))^2$– for symbol "1".

At the output of the lower channel we have:

$d_1 = \sum_{i=1}^{n} (S_1(i) - \eta(i))^2$– for symbol "0" transmitted and

$d_1 = \sum_{i=1}^{n} \eta^2(i)$– for symbol "1".

As in continuous case, if the signal at the summer's output is negative, the decision is symbol "0" received, if positive, then the received symbol "1".

5 DCC performance

We expect that the error probability for the discussed modulation and reception methods approximately correspond to standard characteristics of signal systems that permit geometrical interpretation as in Fig. 5, namely (for error probability $P = 10^{-3}$, Gaussian noise spectral density N_0 and average energy of chaotic radio pulse per transmitted informa-

tion bit E_b):
noncoherent receiver, orthogonal signals (Fig. 5, a) – $E_b/N_0 = 13$–14 dB;
coherent receiver, orthogonal signals (Fig. 5, a) – $E_b/N_0 = 10$–12 dB;
coherent receiver, orthogonal signals (Fig. 5, b) – $E_b/N_0 = 10$–12 dB;
coherent receiver, antipodal signals (Fig. 5, c) – $E_b/N_0 = 7$–8 dB.

We test this conjecture by means of direct numerical simulation. Note that the signal energy varies from pulse to pulse due to its chaotic nature which is not the case for classical career signal. Besides, in the noncoherent receiver, one expects a decrease of the receiver efficiency at large values of the signal base. The results of direct simulation for a pair of orthogonal signals (Fig. 5, a) are given in Figs. 8–11. By the simulation, the chaotic signals were assumed to have three variants of instantaneous chaotic signal distribution: (1) Gaussian distribution, (2) uniform distribution with zero mean, and (3) ± 1 values with equal probability.

As a whole, Fig. 8 (noncoherent receiver) and Fig. 9 (coherent receiver) confirm the preliminary estimates. However, statistical distribution of the signal values appears to be important. For example, for the *noncoherent receiver* the worst is the Gaussian distribution (Fig. 8, a). In this case, error probability $P \leq 10^{-3}$ is achieved only beginning from the value $(E_b/N_0) > 15$ dB in the range of 20 $< B < 60$. For small value of B error probability $P \leq 10^{-3}$ is never achieved at any reasonable values of E_b/N_0. This is associated with long tails of the distribution of the sum of squares of normally distributed random variable.

For uniform distribution (Fig. 8, b) the situation is much better. In this case, error probability $P \leq 10^{-3}$ is achieved beginning from the value $(E_b/N_0) > 14$ dB in the range of $10 < B < 30$. For small $B \sim 4$–6 error probability $P \leq 10^{-3}$ is also achievable, though at a slightly greater value of E_b/N_0, namely, at value $(E_b/N_0) > 15$ dB.

Finally, for the distribution of a kind of random telegraph signal the most effective are the signals with small base values. In this case, error probability $P \leq 10^{-3}$ can be obtained already at the value $(E_b/N_0) > 11$ dB.

Note that the receiver efficiency decreases with increasing base beginning from the base $B > 50$ and at the base $B = 300$ error probability $P \leq 10^{-3}$ is obtained in all three cases only for $(E_b/N_0) >$ 16.5 dB.

In the case of the *coherent receiver* (Fig. 9), asymptotically at $B \to \infty$ for all distributions error probability $P \leq 10^{-3}$ is achieved if $(E_b/N_0) >$ 10 dB. However, in the case of random telegraph distribution the asymptotic condition is satisfied already at low values of B, whereas in the worst case (Gaussian distribution) it is achieved only for $B >$ 100. Note also that in the case of Gaussian distribution and small base, $P \leq 10^{-3}$ cannot be obtained by means of moderate increase of E_b/N_0 (Fig. 9, a). At the same time, this can be easily achieved with the uniform-distribution signal.

As follows from the above analysis, Gaussian-distribution signals are the least favorable for direct chaotic communications as in the case of noncoherent as well as coherent receivers. Under all other equal conditions they provide transmission rates 3–4 times lower than the signals with uniform or random telegraph distribution. In the range where the transmission rate for all three types of signals is approximately equal ($10 < B < 50$), the systems with Gaussian-distribution signals provide $P \leq 10^{-3}$ at (E_b/N_0) about 1–1.5 dB greater than the systems with two other types of signals.

As follows from the above, in particular, in the case of uniform or random telegraph distributions the limit information-carrying capacity of the channel can reach its bandwidth (e.g., with 1 GHz bandwidth the transmission rate can achieve 1 Gbit/sec), whereas in the case of Gaussian signal the limit rate is 3–4 times less.

It is interesting to note that for the signal with random telegraph distribution the efficiency of noncoherent and coherent receivers at low base values is nearly the same.

Finally, let us compare the effectiveness of signal energy accumulation with increasing base for noncoherent and coherent receivers. If in the range of base values $10 < B < 50$ the coherent receiver is 2.5–4.5 dB more effective than the noncoherent

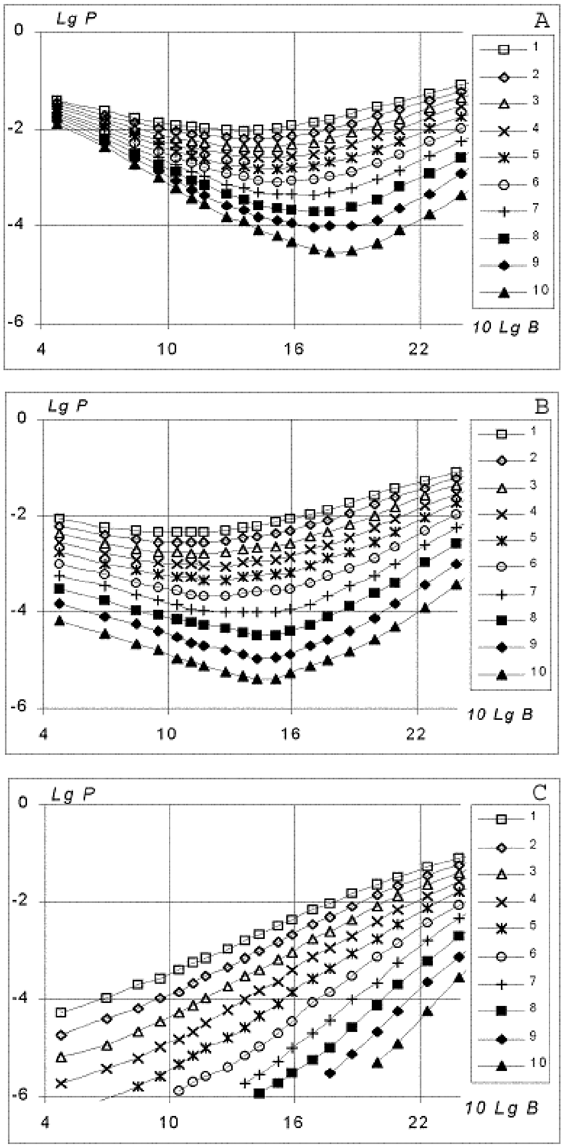

FIG. 8. Noncoherent receiver efficiency as a function of signal base (B) for different E_b/N_0 values: (a) chaotic signal with Gaussian distribution; (b) chaotic signal with uniform distribution; (c) chaotic signal with equal probability of ±1 values. 1 – 12.5 dB (contour square), 2 – 13 dB (contour rhombus), 3 – 13.5 dB (contour triangle), 4 – 14 dB (diagonal cross), 5 – 14.5 dB (asterisk), 6 – 15 dB (contour circle), 7 – 15.5 dB (vertical cross), 8 – 16 dB (solid square), 9 – 16.5 dB (solid rhombus), 10 – 17 dB (solid triangle).

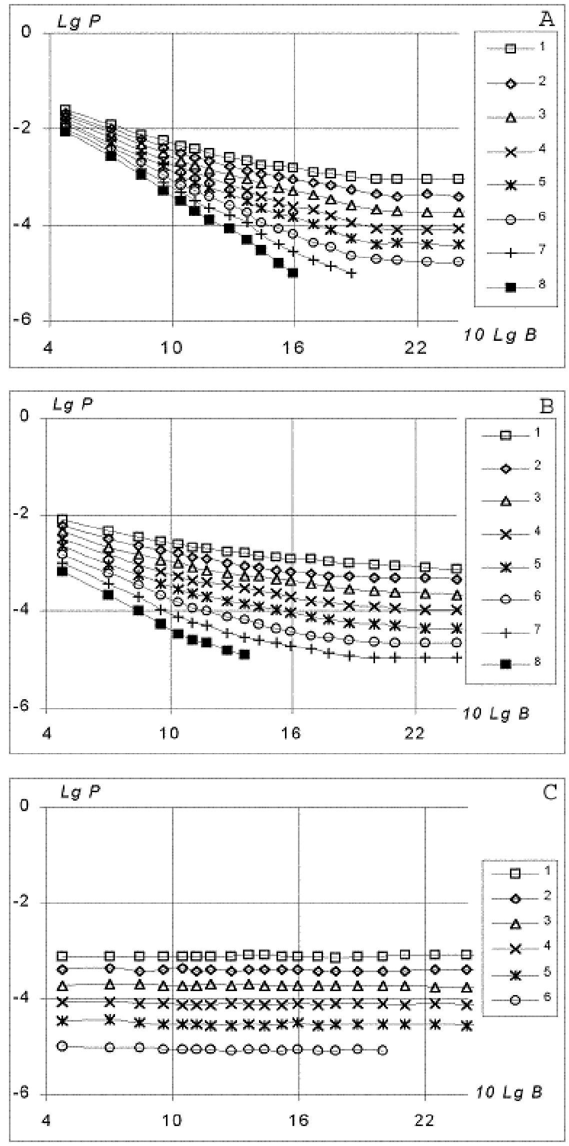

FIG. 9. Coherent receiver efficiency as a function of signal base (B) for different E_b/N_0 values: (a) chaotic signal with Gaussian distribution; (b) chaotic signal with uniform distribution; (c) chaotic signal with equal probability of ±1 values. 1 – 10 dB (contour square), 2 – 10.5 dB (contour rhombus), 3 – 11 dB (contour triangle), 4 – 11.5 dB (diagonal cross), 5 – 12 dB (asterisk), 6 – 12.5 dB (contour circle), 7 – 13 dB (vertical cross), 8 – 13.5 dB (solid square).

one, then for base 200 the difference in efficiency is already 6 dB (Figs. 8 and 9). Error probabilities are presented for various average signal-to-noise ratio average values in Fig. 10 (noncoherent receiver) and in Fig. 11 (coherent receiver). All curves are for the case of duty cycle $D = 1/2$. As can be seen in the Figures, at $P < 10^{-3}$ both with coherent receiver (Fig. 11) and with noncoherent receiver (Fig. 10) the average power of the transmitted signal can be lower than the noise power. This effect is strengthened in proportion to the duty cycle.

Real chaotic signals have finite amplitude and their distributions do not have long tails as the Gaussian does. Therefore, the estimates pertaining to uniformly distributed signal and to random telegraph signal are more suitable for them. Moreover, the model with random telegraph signal matches especially good to the signals with phase chaos, that are obtained, e.g., in phase-locked loop systems [16].

6 Multiple access

All three conventional techniques of sharing the channel between many users, such as frequency-division multiple access (FDMA), time-division multiple access (TDMA) and code-division multiple access (CDMA), can be accomplished in DCC.

The most interesting is time-division multiple access discussed below.

Time-division multiple access. Let there be an ideal Gaussian channel with bandwidth W and the noise spectrum density N_0. The throughput of such a channel in the case of an information signal with mean power P equals to

$$C = W \log_2(1 + \frac{P}{WN_0}). \quad (11)$$

In the case of DCC, $W = \Delta F$, where ΔF is the chaotic signal bandwidth. Let us compare the throughput of this channel with that of the channel with K TDMA users in assumption that the mean signal power of ith user is $P_i = P$ (i =1..K).

In TDMA system each user transmits information during $1/K$th part of the total time in the entire frequency bandwidth ΔF with the signal power KP. So, the throughput per each user is

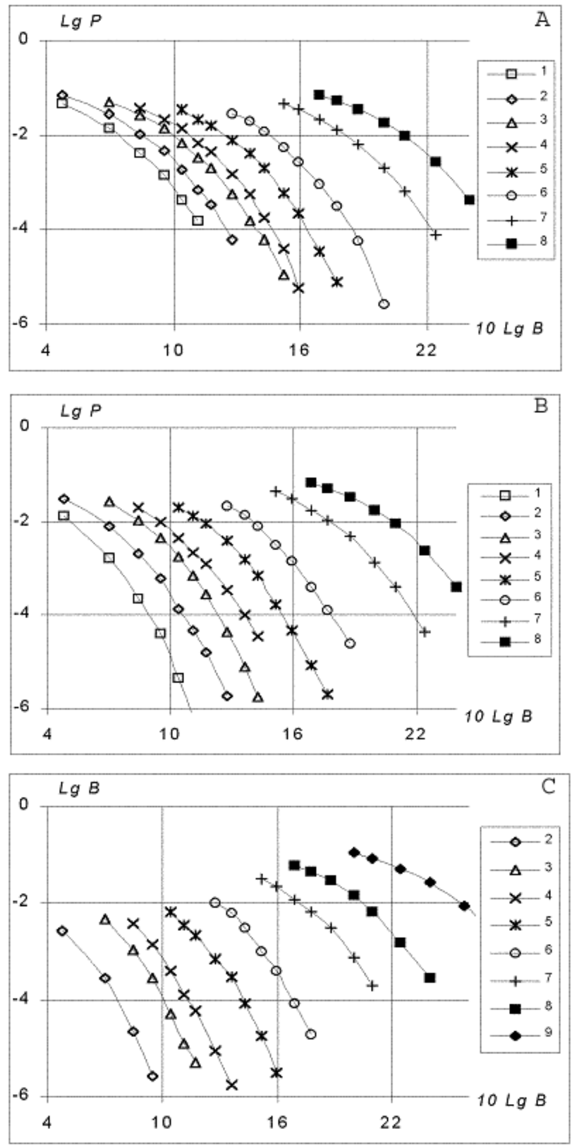

FIG. 10. Noncoherent receiver. Error probability as a function of signal base (B) for different SNR values: (a) chaotic signal with Gaussian distribution; (b) chaotic signal with uniform distribution; (c) chaotic signal with equal probability of ±1 values. 1 – 7 dB (contour square), 2 – 5 dB (contour rhombus), 3 – 3 dB (contour triangle), 4 – 2 dB (diagonal cross), 5 – 0 dB (asterisk), 6 – -2 dB (contour circle), 7 – -5 dB (vertical cross), 8 – -7 dB (solid square), 9 – -10 dB (solid rhombus).

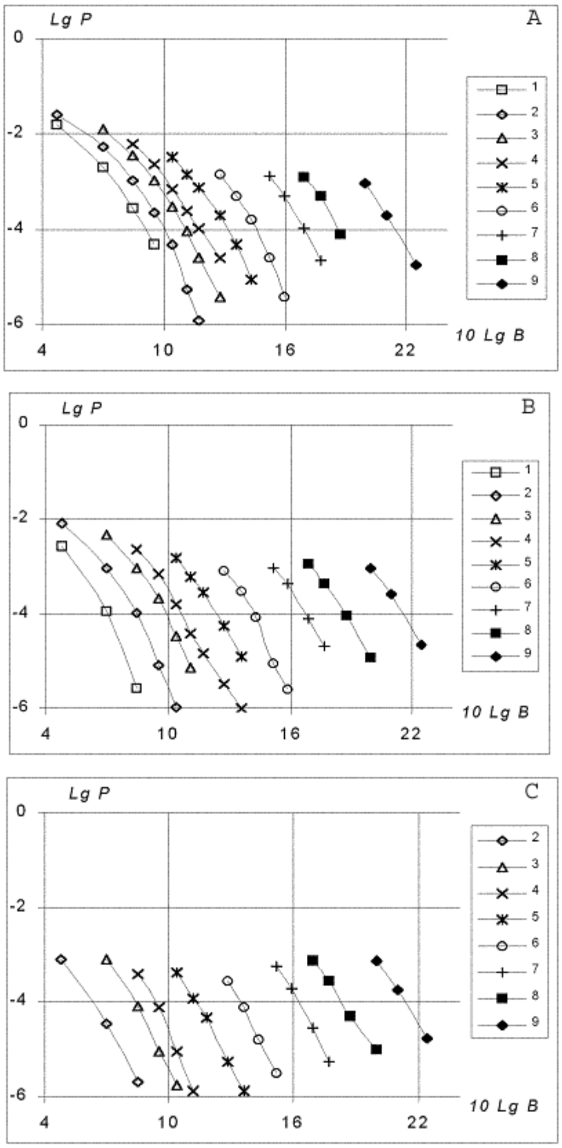

FIG. 11. Coherent receiver. Error probability as a function of signal base (B) for different SNR values: (a) chaotic signal with Gaussian distribution; (b) chaotic signal with uniform distribution; (c) chaotic signal with equal probability of ±1 values. 1 – 7 dB (contour square), 2 – 5 dB (contour rhombus), 3 – 3 dB (contour triangle), 4 – 2 dB (diagonal cross), 5 – 0 dB (asterisk), 6 – -2 dB (contour circle), 7 – -5 dB (vertical cross), 8 – -7 dB (solid square), 9 – -10 dB (solid rhombus).

$$C_K = \frac{\Delta F}{K} \log_2(1 + \frac{KP}{WN_0}). \tag{12}$$

The total throughput of a multiple-access DCC channel is

$$C_K = \Delta F \log_2(1 + \frac{KP}{WN_0}), \tag{13}$$

i.e., theoretically it is somewhat higher than the capacity of a channel with a single user. It is provided due to an increase of the signal-to-noise ratio (factor K is under logarithm).

Relations (8)–(10) show that multiple access can be efficiently realized in DCC by means of time division.

Let $E_b = P/C_K$ be the signal energy per bit of transmitted information. Then, relation (9) can be rewritten as

$$\frac{KC_K}{\Delta F} = \log_2(1 + \frac{KC_K}{\Delta F}\frac{E}{N_0}), \tag{14}$$

and (8) as

$$\frac{C}{\Delta F} = \log_2(1 + \frac{C}{\Delta F}\frac{E}{N_0}). \tag{15}$$

All relations (8)–(12) are limits. In real schemes, the throughput in multiple-access mode is determined by the single-user system throughput as a function of the signal-to-noise ratio. For example, in TDMA DCC the same throughput per user can be achieved both with coherent or noncoherent receivers. However, with noncoherent receiver it can be achieved at a slightly higher value of E_b/N_0.

Multiple access in DCC can also be organized using packet data transmission under IEEE 802.11 standard.

7 Electromagnetic compatibility

In the case of small duty cycle, the sequence of wideband (ultra-wideband) chaotic radio pulses interferes with the signals of conventional radio circuits only on very small time intervals. For example, at a rate of 10^6 bps and the length of each chaotic pulse 10^{-8} sec., the duty cycle is $D = 10^{-2}$, so, the time of interference is 0.5% of the system operation time.

Besides, the average emitted power is by a factor of 200 lower than the mean power during emission of chaotic radio pulses. If, e.g., the transmitter power during the pulse emission is 200 mW, then the average power is only 1 mW.

Let us consider the interaction of narrowband and wideband signals in more detail. A typical interference of narrowband communication systems is wideband noise. The method combating the noise is frequency filtering. By means of matching the receiver bandwidth with that of the received signal, one manages to cut the most part of the noise energy off. The remaining noise energy $\frac{N_0}{2}\Delta F$ makes the energy of interference.

With wideband and ultra-wideband DCC systems the situation is different. Here, besides the Gaussian white noise the interference is represented by narrowband signals of the devices operating within its frequency range. In noncoherent receiver, the average power of the interference signal at the input is

$$P_{int} = \int\limits_{F}^{F} \frac{N_0}{2} df + \int\limits_{F_1}^{F} S(f) df, \qquad (16)$$

where $S_{nb\eta}(f)$ is the spectral density of narrowband signal. Take for simplicity that there is a single narrowband signal whose spectral density is constant within certain frequency range and zero outside that range.

Let us denote the bandwidth ratio of the chaotic signal to the narrowband signal by M, and the power ratio of the narrowband signal to the Gaussian signal within the bandwidth of the narrowband interference signal, necessary to receive information with admissible error probability, by L. (This ratio is equal to the ratio of spectral densities). Then the total power of the interference signal is

$$P_n = (1 + \frac{L}{M})\frac{N_0}{2}\Delta F. \qquad (17)$$

Example. The receiver bandwidth is 100 MHz, the narrowband signal bandwidth is 1 MHz, $L =$ 15 dB, then

$$P_{int} = (1 + \frac{30}{100})P_{int}^0 = 1.3P_{int}^0, \qquad (18)$$

where P_{int}^0 is the power of interference determined by Gaussian noise in the frequency range of the chaotic signal.

If the information sequence of chaotic radio pulses has duty cycle D, then the effective average interference power is lower by a factor of D

$$P_e = D \cdot P_{int}. \qquad (19)$$

Let the same volume of information be transmitted with the rate 1 Mbps using narrowband and wideband signals, and the chaotic signal duty cycle be 10^{-2} and $L = (E_b/N_0) = 15$ dB. Denote the energy of the narrowband signal, obtained by wideband receiver when receiving one information bit, by $E_{nb,n}$. As follows from (15) and (16), effective excess to the Gaussian noise level is 30%, and interference added by the narrowband signal is $(E_{nb,n}/E_b) = –20$ dB. Thus, distortions induced by narrowband information signal are below the admissible level of $L = 15$ dB, consequently, are not an interference for the wideband information signal.

Consider now the effect of the wideband information signal on the narrowband information signal under the same conditions ($(E_b/N_0) = 15$ dB). Denote the energy of the wideband chaotic signal, obtained by narrowband receiver when receiving one information bit, by $E_{w,n}$. With the duty cycle $D = 10^{-2}$ taken into account, this energy is 5 dB less than the interference energy induced by Gaussian noise. Hence, $(E_{w,n}/E_b) = –20$ dB, i.e., narrowband signal distortions due to reception of a part of wideband signal are also negligible.

Thus, information-carrying traditional narrowband and wideband (ultra-wideband) direct chaotic signals have but a little effect on each other and in many cases can be used together. Actually, this gives a chance of repeated use of the already occupied regions of microwave band.

8 Ecological safety

The degree of an effect of electromagnetic radiation on living systems is determined by the total power of electromagnetic radiation and by its structure. In the case of signals based on harmonic carrier, distinct spectral components are present in the electromagnetic spectrum that can have selective (resonant) effect on various subsystems of living organisms. In the case of ultra-short almost periodic video pulses, potential danger may be in "percussive" periodic effect of electromagnetic pulses.

Unstructured in time domain and "spread" over the frequency band, direct chaotic signals are less dangerous, because their potential negative effect is determined by only an increase of the environmental electromagnetic background radiation. Besides, in the majority of practically interesting cases the added radiation level is below the natural background. Thus, DCC are ecologically more safe than traditional radio systems.

9 Conclusions

In conclusion, note two other useful aspects of DCC. The first is the stability of communications in multipath environment.

Multipath propagation is a less problem to DCC than to conventional communication systems. Actually, Rayleigh fading that takes place due to signal interference by multipath propagation is caused by the narrowband character of signals. In order to make interference between individual chaotic radio pulses possible, certain conditions must be fulfilled. However, even if such an interference takes place, it doesn't lead to as unpleasant consequences as in the case of sinusoidal signals, because wideband chaotic signals have rapidly decreasing autocorrelation functions.

The second aspect is simplicity of the transmitter and receiver design and, as a consequence, low cost of mass production. The transmitter is a chaotic source containing a little number of components, and information is put directly to the carrying chaotic signal. So, the transmitter layout is rid of a number of elements used in conventional communication systems, and restrictions to the remaining parts are more soft than in classical systems. In particular, there are no strong restrictions on the linearity of the output amplifier, which decreases the cost and energy consumption.

The receiver is also more simple in structure than the narrowband receiver, because the stage of signal processing at an intermediate (heterodyne) frequency is not necessary here. Besides, in contrast to conventional spread-spectrum receivers, the control circuits operate here not at microwave frequencies but at pulse repetition frequencies. Preliminary analysis shows that DCC transceivers can be accomplished in the form of single inexpensive chip.

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References

[1] A.S. Dmitriev, B.Ye. Kyarginsky, N.A. Maximov, A.I. Panas, S.O. Starkov. Prospects of Direct Chaotic Communications Design in RF and Microwave Band. Radiotehnika. **42**, no. 3, 2000 9-20.

[2] A.S. Dmitriev, B.Ye. Kyarginsky, N.A. Maximov, A.I. Panas, S.O. Starkov. Direct Chaotic Communications in Microwave Band. Preprint IRE RAS, no. 1(625), Moscow, 2000.

[3] A.S. Dmitriev, B.Ye. Kyarginsky, A.I. Panas, S.O. Starkov. Direct Chaotic Communication Schemes in Microwave Band. Radiotehnika I Elektronika. **46**, no. 2, 2001 224-233.

[4] A. Dmitriev, B. Kyarginsky, A. Panas, S. Starkov. Direct Chaotic Communication System. Experiments. Proc. of NDES'01. Delft. Netherlands, 2001 157-160.

[5] A.S. Dmitriev, A.I. Panas, S.O. Starkov. Direct Chaotic Communication in Microwave Band. Electronic NonLinear Science Preprint, nlin.CD/0110047, 2001.

[6] A. Dmitriev, B. Kyarginsky, A. Panas, D. Puzikov, S. Starkov. Experiments on Ultra Wideband Direct Chaotic Information Transmission in Microwave Band. Proc. of NDES'02. Turkey, 21-23 june 2002 5-1 – 5-4.

[7] A.S. Dmitriev, A.I. Panas, D.Yu. Puzikov, S.O. Starkov. Wideband and Ultrawideband Direct Chaotic Communications. Proc. of ICCSC'02, St. Petersburg, Russia, 26-28 June 2002 291-295.

[8] A.S. Dmitriev, B.Ye. Kyarginsky, A.I. Panas, D.Yu. Puzikov, S.O. Starkov. Experiments on Ultrawide Band Direct Chaotic Information Transmission in Microwave Band. Radiotehnika I Elektronika. **47**, no. 10, 2002 (in print).

[9] A.S. Dmitriev, B.Ye. Kyarginsky, A.I. Panas, S.O. Starkov. Experiments on Direct Chaotic Communications in Microwave Band. Int. J. of Bifurcation and Chaos. **17**, no. 8, 2003 (in print).

[10] N.T. Petrovich, M.K. Razmahnin. *Communication Systems with Noise Like Signals.* (Sovetskoe Radio, Moscow, 1969).

[11] L.Ye. Varakin. *Theory of complex Signals.* (Sovetskoe Radio, Moscow, 1970).

[12] J.G. Proakis, M. Salehi. *Contemporary Communications System using Matlab.* (CA: Book/Cole, 2000).

[13] J.G. Proakis. *Digital Communications.* (McGraw-Hill Inc, NY, 1995).

[14] S. Haykin. *Communication Systems.* (John Wiley & Sons, Inc, NY, 1994).

[15] M.Z. Win, R.A. Scholtz. Impulse radio: how it works? IEEE Comm. Lett. **2**, no. 1, 1998 10.

[16] V.D. Shalfeev, G.V. Osipov, A.K. Kozlov, A.R. Voilkovsky. Chaotic Oscillations – Generation, Synchronization, Control. Uspehi Sovremennoy Radioelektroniki. no. 10, 1997 27-49.