Official English translation

Ultra- and hyper-wideband differentially coherent information transmission based on chaotic radio pulses

A.S. Dmitriev[1], *T.I. Mokhseni*[1], *C.M. Sierra-Teran*[2]

[1]Kotelnikov Institute of Radioengineering and Electronics of RAS
11–7, Mokhovaya, 125009 Moscow, Russia
[2]Moscow Institute of Physics and Technology
9, Institutskiy pereulok, 141700 Dolgoprudny, Moscow Region, Russia
E-mail: chaos@cplire.ru, mokhseni@gmail.com, serra@phystech.edu
Received 2.08.2018; accepted for publication 17.08.2018

Subject of the study. Differentially coherent information transmission scheme using chaotic signals as carriers – DCSK (Differential Chaos Shift Keying) was proposed as an alternative to communication systems based on chaotic synchronization. It is resistant to noise and other disturbances at the same level as classic transmission systems based on regular signals. However the requirement of using long time delay lines makes difficult practical implementation of wireless communication systems based on DCSK. A differentially coherent data transmission scheme using chaotic signals as information carriers is considered in the given paper. The scheme includes delay elements only with short duration, which simplifies its practical implementation in microwave frequency ranges in comparison with known analogs. **Methods**. Computer based simulation of the transmission process was carried out in Matlab environment. Simulation model is described by a system of differential-difference equations. The variables of the system of equations represent the signal at various points of the circuit during the transmission of information. Analytical estimation of noise immunity for channels with white noise and of noise immunity as the function of processing gain are given. **Results**. It is shown that for small values of processing gain the scheme is affected by its own noise, which complicates its operation even in the absence of external noise. However, its efficiency dramatically increases with the use of ultra-wideband and hyper-wideband signals with big processing gain up-to 10^6. At such processing gain values stable reception of transmitted pulses can be provided from under the noise even with signal-to-noise ratio around -20 dB. **Discussion**. An analysis of the results shows that in the proposed differentially-coherent transmission scheme based on chaotic radio pulses as information carriers there is no problem with the requirement of using long-duration delays, which is critical for DCSK-based scheme. In the considered scheme only short-duration delays are used. This radically simplifies practical realization of the scheme in microwave frequency ranges.

Keywords: communication system, chaotic radio pulse, ultra-wideband signal, hyper-wideband signal, differentially coherent detection, correlation.

https://doi.org/10.18500/0869-6632-2018-26-4-59-74

Reference: Dmitriev A.S., Mokhseni T.I., Sierra-Teran C.M. Differentially coherent information transmission based on chaotic radio pulses. *Izvestiya VUZ, Applied Nonlinear Dynamics,* 2018, vol. 26, iss. 4, pp. 59–74. https://doi.org/10.18500/0869-6632-2018-26-4-59-74

Introduction

Works devoted to the utilization of dynamic chaos for information transmission, in particular, wireless data transmission, began in the 1990s. In addition to the general and long-standing interest in communication systems using noise and noise-like signals [1–4], researchers' attention was paid to such phenomenon as chaotic synchronization of dynamic chaos [5]. In the mid-1990s after identifying problems with the practical use of chaotic synchronization in wireless transmission of information, attempts were made to apply dynamic chaos to information transmission based on differentially coherent methods. By that time, these methods were well known, including those intended for noise and noise-like signals [3, 4]. However, chaotic signals "breathed" new life into them. The most popular was Differential Chaotic Shift Keying scheme (DCSK), proposed in [6, 7]. Its noise immunity in channels with white noise is close to the characteristics of classical transmission schemes with regular signals. In DCSK scheme, each binary information symbol with a duration T_b is represented by two fragments of a chaotic signal with a duration $T_b/2$ each, with the second fragment of the chaotic signal being either a copy of the first one or its inverted copy. The first fragment is interpreted as reference, the second fragment carries information. The sequence of such pairs of chaotic fragments is transmitted to the communication channel. In the receiver binary information symbol for each pair of transmitted chaotic signal fragments is determined by comparing the correlation result between the first and the second fragments of the chaotic signal from the pair with zero threshold. Correlation result greater than zero (first and second fragments of the chaotic signal in the pair coincide) corresponds to logical "1", correlation result less than zero (second fragment of the chaotic signal in the pair is inverted with respect to the first) corresponds to logical "0". To obtain identical reference and information-carrying fragments of chaotic signal during transmission, a signal delay equal to half the time duration of a bit is used. When implementing a communication scheme using DCSK modulation method, modulation and demodulation blocks responsible for signal delay will have a tract with length $cT_b/2$, where c is the speed of light. Accordingly, with a delay time on the order of a microsecond, the required signal-delay tract length will be about 300 m. Such requirements significantly complicate the implementation of compact communication systems using DCSK and analog chaotic signals. A potential solution to the problem of large delays is the use of digital techniques for chaotic signal synthesis. However, in this case serious limitations on the possible maximum transmission rate come into effect.

Two other differentially coherent modulation schemes have been proposed and analyzed: Correlation Delay Shift Keying (CDSK) scheme and Symmetric Chaos Shift Keying (SCSK) scheme [8]. But, as the authors themselves showed, the characteristics of these circuits turned out to be 2–3 dB worse in channels with white noise than DCSK scheme. Therefore, these schemes have not been further developed.

Thus, by the beginning of the present century schemes of applying chaotic signals to wireless communication systems, based on differentially coherent methods, have appeared. Their statistical characteristics are close to those of classical narrowband communication systems. However, even the best of them had difficulties in practical implementation.

It should be noted that the techniques for generating chaotic signals in microwave range were already developed by that time, as well as critical elements necessary to implement wireless communication systems. These facts contributed to the development of new feasible schemes.

In the 2000s a Direct Chaotic Communication (DCC) scheme, that used chaotic radio pulses as information carriers, was proposed [9, 10]. In the following years this scheme was successfully developed, and small-size ultra-wideband (UWB) transceivers and networks based on this scheme were designed. The scheme was adopted as an optional solution in the IEEE 802.15.4a standard for UWB wireless personal area communications. At present, DCC is the only practically implemented and utilizable chaotic communication scheme.

At present, new requirements are being imposed on wireless communications. First of all, this refers to massive application of wireless, low-power, high rate communication systems for IoT (Internet of Things), IoRT (Internet of Robotic Things), and other massive applications. These requirments increase the attention paid to the extension of capabilities of chaotic signal applications in wireless communication systems.

In this work, a differentially coherent direct-chaotic communication scheme based on chaotic radio pulses used as information carriers [11], which is lacking long-delays problem is considered. It is shown that the scheme is suitable for creating ultra-wideband and hyper-wideband wireless communication systems.

1. Differentially coherent transmission scheme based on chaotic radio pulses

In the original DCC scheme [9, 10], chaotic pulses located in certain time positions within bit intervals are employed as information carriers. The presence of a chaotic pulse on such position represents transmission of logical 1, while the absence represents logical 0. The remaining part of the bit interval is used as a guard interval, e.g., for the case of multipath propagation.

In the proposed communication scheme, information is also transmitted with a stream of chaotic radio pulses with guard intervals between them. However, the modulation method is different.

Before we proceed to the description of the communication scheme, it should be noted that in real direct-chaotic communication systems chaotic signals with big processing gain $K = \Delta F \Delta T$ are used, where ΔF is the bandwidth of the information carrier signal and ΔT is its duration. Normally, the value of the processing gain is 50 or more. This implies that the autocorrelation time of chaotic radio pulses is small and constitutes an insignificant part of their duration. For example, the autocorrelation time of UWB chaotic signals of microwave range with 2-GHz bandwidth (Fig. 1, *a*) is less than 1 ns (Fig. 1, *b*). In this case, such a chaotic signal is almost orthogonal with its delayed version, as far as the delay time is equal to or greater than the autocorrelation time. Such delays are easily and compactly implemented, e.g., using thin microwave cables with the length of several tens of centimeters.

The structure of the proposed transmission system is shown in Fig. 2 and 3. The system transmitter (Fig. 2) consists of chaotic radio-pulse source (CRS), a power divider (D), a modulator (M) controlled by an external information signal, a time-delay block (τ) (its delay time τ exceeds the autocorrelation time of the signal); an adder (Σ) and a transmitting antenna. The source of chaotic radio pulses generates pulses with duration T_i.

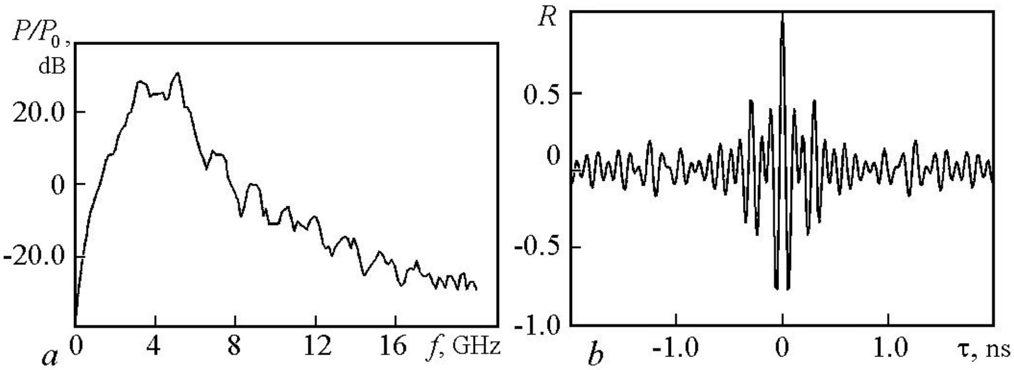

Fig. 1. Characteristics of chaotic signal: *a* – power spectrum, *b* – autocorrelation function

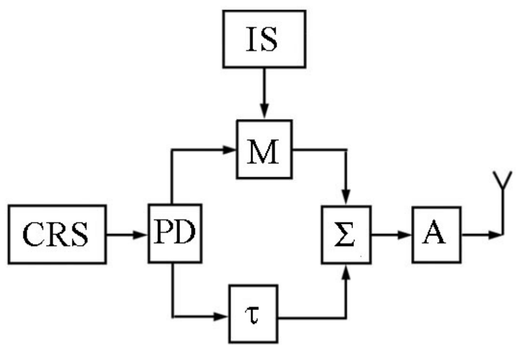

Fig. 2. Transmitter structure: CRS – chaotic radio pulses source, PD – power divider, IS – information sequence, M – modulator, τ – time delay, Σ – adder, A – amplifier

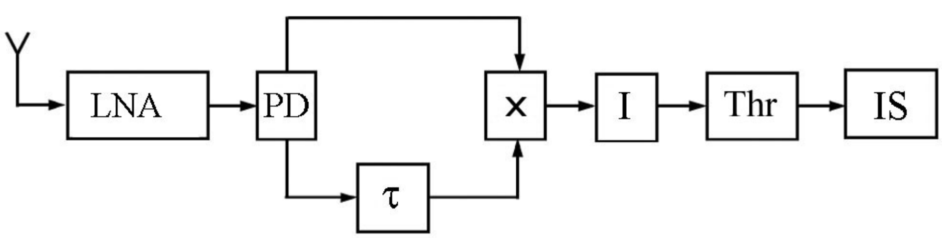

Fig. 3. Receiver structure: LNA – low-noise amplifier, PD – power divider, τ – time delay, × – multiplier, I – integrator, Thr – threshold device, IS – information sequence

Intervals between the pulses have duration T_{gi}. Total duration of the pulse and its guard interval make the duration of transmitted bit T_b. Each pulse comes at the divider and goes through two channels. In the first channel, the pulse is modulated by information signal via multiplication by ± 1. In the second channel, it is delayed by time τ. Multiplication by $+1$ or -1 correspond to transmission of "1" or "0", respectively. Then this signal is transmitted by the antenna. In this case, the emitted pulse length is $T_{emit} = T_i + \tau$.

The signal received by the antenna is amplified to the required level in the LNA, halved, and fed into two channels. In the first channel, nothing is done with the signal and it arrives at the multiplier. In the second channel, it is delayed by time τ. Afterward, the signal also arrives at the multiplier. It should be noted that the duration of the pulse obtained via multiplication of pulses coming into the multiplier is T_i. After the multiplier the pulse is integrated over time T_i. Then the signal is fed to zero-threshold detector. If the obtained signal is greater than zero, then the threshold device output is "1", otherwise the output is "0".

Let $S_k(t)$ be the k-th chaotic pulse of the chaotic pulse flow formed by the chaotic radio pulse source (the pulses are indexed because they are all different, as they are chaotic). It is assumed that $\alpha_k \in \{-1, 1\}$ is the modulating information signal. In the transmission of the k-th binary information symbol, the output signal of the receiver is represented as:

$$Y_k(t) = \frac{\alpha_k S_k(t) + S_k(t-\tau)}{2}. \tag{1}$$

At the receiver, in the absence of noise, the pulse corresponding to k-th information symbol at the integrator output acquires the form:

$$Z_k(t) = \frac{\int\limits_{\tau}^{T_i+\tau} \alpha_k S_k(t-\tau) S_k(t-\tau)\,dt}{4} + \theta_k(t), \tag{2}$$

Where

$$\theta_k(t) = \left[\int\limits_{\tau}^{T_i+\tau} S_k(t) S_k(t-\tau)\,dt + \int\limits_{\tau}^{T_i+\tau} \alpha_k S_k(t) S_k(t-2\tau)\,dt + \right. \\ \left. + \int\limits_{\tau}^{T_i+\tau} S_k(t-\tau) S_k(t-2\tau)\,dt\right] /4. \tag{3}$$

The component $\theta_k(t)$ of signal (2) is noise created by the scheme itself. Since the delay time τ exceeds the autocorrelation time, all components $\theta_k(t)$ are considerably less than the first term in the expression (2), which is the useful signal. Thus, the sign of α_k ("+" or "−") specifies the sign of $Z_k(t)$. The signal from the integrator output arrives at the decision block, where it is compared with zero threshold. The sign determines the value of the output binary information symbol.

2. Super- and hyper-broadband communication facilities

Ultra-wideband communication systems are currently considered as systems using signals with a relative bandwidth of at least 20 % or an absolute band of at least 500 MHz (in the frequency range from 3.1 to 10.6 GHz). This definition was introduced by the US Federal Communications Commission in 2002 and is the basis for all further documents on ultra-wideband communications (in the Russian Federation this range is from 2.85 to 10.6 GHz).

In 2014, the Defense Advanced Research Projects Agency (DARPA) began to use the term hyper-wideband communication. According to DARPA hyper-wideband communication refers to any connection with a bandwidth of not less than 10 GHz. The Agency has announced a competition for research in the field of hyper wideband communications (HERMES program – Hyper-wideband Enabled RF Messaging).

In this competition DARPA requested innovative research proposals to explore the possibility of using wideband radio frequency system with bandwidth of more than 10 GHz. The system will have to operate at frequencies below 20 GHz in order to reduce atmospheric absorption and also to use processing gain and spectral filtering for ensuring operability. The research was supposed to develop in two directions: 1) study of system architectures, channel propagation effects, spectrum management, signal processing techniques, implementation using commercial components and 2) development of new receiver technologies, presumably based on photonics, with size, weight and power corresponding to a hand-sized device [12]. At the first stage, it was proposed to create working mock-up of a system with a bandwidth, demonstrating the possibility of reaching a spread spectrum band of at least 10 GHz, with processing gain of at least 40 dB and with bandwidth of at least 100 Kbps. The demonstration was assumed to take place in an overloaded radio-frequency environment. In 2016 the first publications related to the subject of the program appeared [13, 14]. In section 5 below, it will be shown that differentially coherent scheme considered in this paper can demonstrate characteristics close to those requested by the HERMES program.

3. Computer modeling

A mathematical model of the novel differentially coherent communication scheme with chaotic radio pulses used as information carriers, was designed.

In this paper, we discuss communications over radio channel, so the chaotic signal suitable for this must be a bandpass signal. ITherefore, a bandpass chaotic generator with 2.5 degrees of freedom was used as a source of chaotic oscillations [15]. The generator's self-oscillating system incorporates a closed feedback loop, consisting of a nonlinear element characterized by $F(y) = My\exp(-y^2)$, a first-order low-pass filter (LPF), a second-order LPF and a bandpass filter. The equations of the self-oscillatory system have the form:

$$\begin{aligned} &T_1\dot{y}_1(t) + y_1(t) = F(y_3)D(t),\\ &\ddot{y}_2(t) + \beta_2\dot{y}_2(t) + \omega_2^2 y_2(t) = \omega_2^2 y_1(t),\\ &\ddot{y}_3(t) + \beta_3\dot{y}_3(t) + \omega_3^2 y_3(t) = \omega_3^2 \dot{y}_2(t), \end{aligned} \tag{4}$$

where T_1 is the time constant of the first order LPF, while β_k and ω_k $(k = 2, 3)$ are the dissipation coefficients and the resonance frequencies of the filters. The power spectrum and the autocorrelation function for a typical operation mode of the generator, which is used later in simulation of the communication scheme, are shown in Fig. 1.

To provide generation of a stream of chaotic pulses instead of a continuous chaotic signal, in the righthand side of the first equation of generator (4) we introduced a time-varying coefficient $D(t)$:

$$D(t) = \frac{\mathrm{sgn}\,(\sin(2\pi t/T_b)) + 1}{2}. \tag{5}$$

System (4) generates a stream of chaotic pulses with pulse duration $T_i = T_b/2$ and a duty cycle of 1/2. The transmitter's output signal is described by (6):

$$y_4(t) = \frac{\alpha(t)y_3(t) + y_3(t-\tau)}{2}. \tag{6}$$

Function $\alpha(t)$ in (6) is the input information signal and takes the value of -1 or 1 during each bit period $\alpha(t) = \{-1,\ 1\}$, depending on the information symbol "1" or "0" transmitted at moment t. Afterward, the signals are summed. An output signal comes into the communication channel and then arrives at the receiver.

In the receiver, the received signal and its delayed copy are multiplied:

$$y_5(t)=\frac{y_4(t)y_4(t-\tau)}{4}.$$

Then the resulting pulse goes through the second-order LPF, which simulates integration. In general, the receiver model dynamics is described by the equation:

$$\ddot{y}_6(t) + \beta_6\omega_6\dot{y}_6(t) + \omega_6^2 y_6(t) = \omega_6^2 y_5(t), \tag{7}$$

where β_6 and ω_6 are the filter's dissipation coefficient and resonance frequency, respectively.

The decision about the received information symbol is made on the basis of a comparison of the signal at the output of the filter with a zero threshold. Thus, the system of equations (4)–(7) describes the model of differentially coherent communication scheme. The model is represented by a system of difference-differential equations with delays. The model was simulated in MATLAB using dde23 function to solve difference-differential equations with fixed delays.

The communication system was simulated using pulses with processing gain $K{=}10$ at the following normalized values of the parameters: $M = 32$; $T_1 = 1$; $\beta_2 = 0.3$; $\omega_2 = 1.0$; $\beta_3 = 0.2$; $\omega_3 = 1.55$; $T_b = 300$; $\tau = 10$; $\beta_6 = 0.9$; $\omega_6 = 0.063$. A scaling factor $L = 2 \cdot 10^{10}$ is used for the conversion of those parameters into real values of frequencies and delays. The simulation results are shown in Fig. 4.

The generator creates a chaotic radio pulses flow with a duty cycle of 1/2 (Fig. 4, *a*). The flow comes into the power divider. The signal from the first output of the divider is multiplied with input binary information signal (Fig. 4, *b*). Thus, depending on the transmitted information symbol, the chaotic pulse passes unchanged ("1") or inverted ("0"). The power divider's second output goes to time delay block. The adder output signal is shown in Fig. 4, *c*.

At the receiver, the signal arrives at the antenna and then is fed to the power divider. Power divider's upper output signal is sent to time delay block with delay time τ. Power divider's lower output signal is sent directly to the multiplier, where it is multiplied

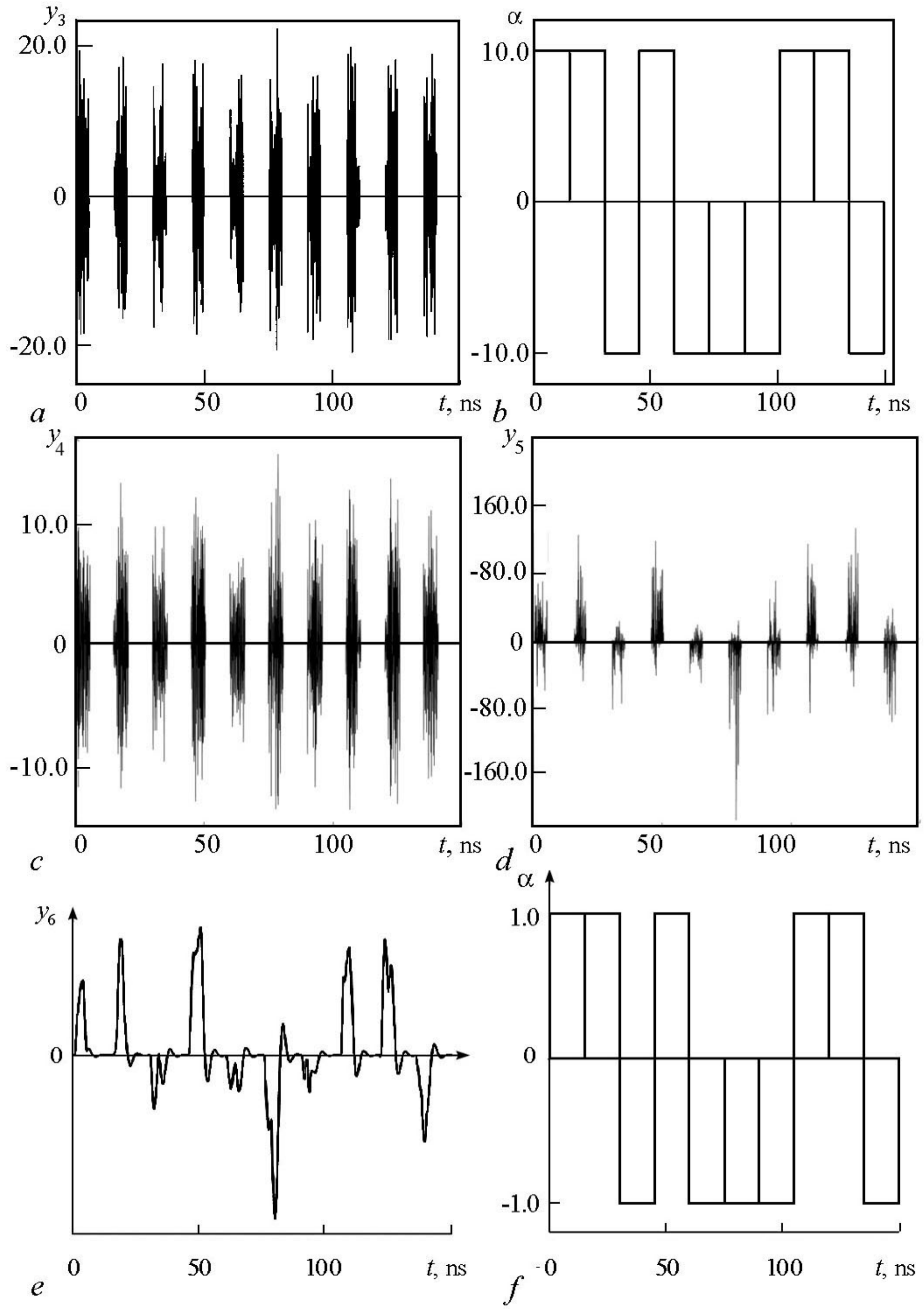

Fig. 4. Signal form during transformations in transmitter and receiver: *a* – chaotic radio pulses flow at the output of CRS (fig. 2), *b* – input modulating sequence, *c* – signal at the output of the adder, *d* – signal at the output of the multiplier, *e* – signal at the output of the integrator, *f* – two-level output information sequence

with time delay block output signal. Multiplier's output signal (Fig. 4, *d*) is fed to the integrator. The integrator output signal is depicted in Fig. 4, *e*. It shows the envelope of the pulses of positive and negative polarity and guard intervals. These pulses correspond to the transmitted information bits: positive to "1", negative to "0". The resulting signal goes in the decision block, where it is compared with the zero threshold. The sign of the comparison result defines the output binary information symbol (Fig. 4, *f*).

4. Analytical estimates

Along with computer modeling, analytical estimations of the scheme's characteristics were carried out [11]. This estimation method is described in [3]. The algorithm of the receiver's operation, described in the previous sections, can be written as follows:

$$\operatorname{sign}\left(y_5(t)\right) = \operatorname{sgn} \int\limits_{\tau}^{T_i+\tau} y_4(t) y_4(t-\tau)\, dt. \tag{8}$$

In the presence of noise, signals under the integral have the form:

$$\begin{aligned} y_4(t) &= y_3(t) + y_3(t-\tau) + \eta(t), \\ y_4(t-\tau) &= y_3(t-\tau) + y_3(t-2\tau) + \eta(t-\tau), \end{aligned} \tag{9}$$

where $y_3(t)$ is a signal that simulates the chaotic radio pulse, it is represented here by a fragment of a continuous random process with normal amplitude distribution and uniform spectral density N_s; $\eta(t)$ is Gaussian white noise with spectral density N_0.

Substituting (9) into (8), we have:

$$\begin{aligned} \int\limits_{\tau}^{T_i+\tau} y_4(t) y_4(t-\tau)\, dt &= \int\limits_{\tau}^{T_i+\tau} y_3(t-\tau) y_3(t-\tau)\, dt + \int\limits_{\tau}^{T_i+\tau} y_3(t) y_3(t-\tau)\, dt + \\ &+ \int\limits_{\tau}^{T_i+\tau} y_3(t) y_3(t-2\tau)\, dt + \int\limits_{\tau}^{T_i+\tau} y_3(t-\tau) y_3(t-2\tau)\, dt + \int\limits_{\tau}^{T_i+\tau} y_3(t) \eta(t-\tau)\, dt. \end{aligned} \tag{10}$$

In (10), only the first term carries the useful information while other terms represent noise caused by both fluctuation noise $\eta(t)$ and the signal itself. In order to find the distribution of random variables in (10), let these variables be represented by their Fourier series on interval $(\tau, T_i + \tau)$ [3]. The resulting expression for the received message error probability has the form (11):

$$P_{er} = f\left(N_s \Delta F T_i \Big/ \sqrt{N_s N_0 \Delta F T_i \left(2 + \frac{N_0}{2N_s} + \frac{5N_s}{2N_0} \right)} \right), \tag{11}$$

where

$$f(x) = \left[1 - \frac{2}{\sqrt{2\pi}} \int\limits_{0}^{x} e^{-\frac{t^2}{2}} \right],$$

N_s is the spectral density of the chaotic radio pulse, ΔF is the chaotic signal's bandwidth, T_i is the chaotic radio pulses duration and N_0 is gaussian white noise spectral density.

This error probability has an interesting asymptotic property. When the signal-to-noise ratio (SNR) tends to infinity, the error probability tends to the certain limit:

$$P_{\text{lim\_er}} = f\left(\sqrt{\frac{2\Delta F T_i}{5}}\right). \tag{12}$$

Such unordinary behavior of the error probability can be explained as follows. It can be seen from (10) that, even if fluctuation noise $\eta(t)$ is equal to zero, there still remains an internal noise caused by the useful signal components delayed relative to each other. This noise power is proportional to the power of the useful signal. So, for any finite processing gain value, the error probability is not equal to 0 even in the absence of external noise. However, if the processing gain tends to infinity, the marginal error probability (12) tends to zero, since in this case this internal noise is better averaged in the receiver.

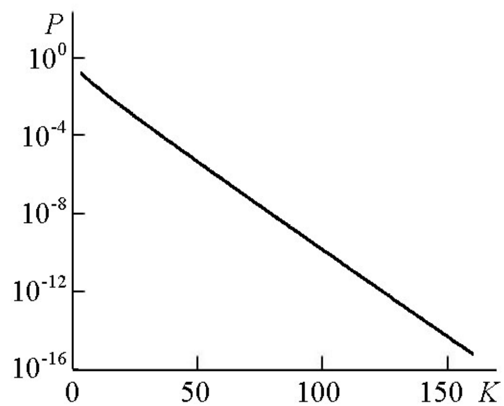

Fig. 5. Error probability as function of signal processing gain in the absence of fluctuation noise

Figure 5 presents the bit error probability (BER) versus processing gain for the receiver that operates according to algorithm (8). Fluctuation noise is considered zero. BER is calculated using (12). As can be concluded from Fig. 5, despite the internal noise, with an increase of the signal processing gain the receiver BER in the absence of external noise rapidly decreases. Moreover, its value is already less than 10^{-10} if processing gain is 100. Thus, the internal noise of this scheme has practically no effect on the noise immunity with respect to external noise in the case of large processing gain values (see below). However, as follows from the practice of direct-chaotic communications, the signals with large processing gain are of the most interest.

5. Characteristics of the circuit in the ultrabroadband and hyperbroadband cases

Fig. 6 depicts error probabilities in the presence of external noise at small, medium and large processing gain values, respectively. Processing gain K depends both on the signal bandwidth and on its duration. In principle, the processing gain values of both ultra-wideband and hyper-wideband signal elements carrying information can vary widely, starting from ones to hundreds of thousands or more. However, it is the processing gain value that will mainly determine the immunity of the communication scheme to noise. From Fig. 6, *a* it can bee seen that at $K \leq 20$ the error probability in the considered transmission scheme can not be reduced to less than 10^{-3} even at very high signal-to-noise ratios. On the other hand, at $K > 100$ the error probability is already less than 10^{-5} with E_b/N_0 less than 20 dB (Fig. 6, *b*). Note that for such processing gain values signal-to-noise ratio (SNR) at which the signal can be extracted becomes already less than 0 dB. With a further increase in the processing gain useful signal can be extracted even

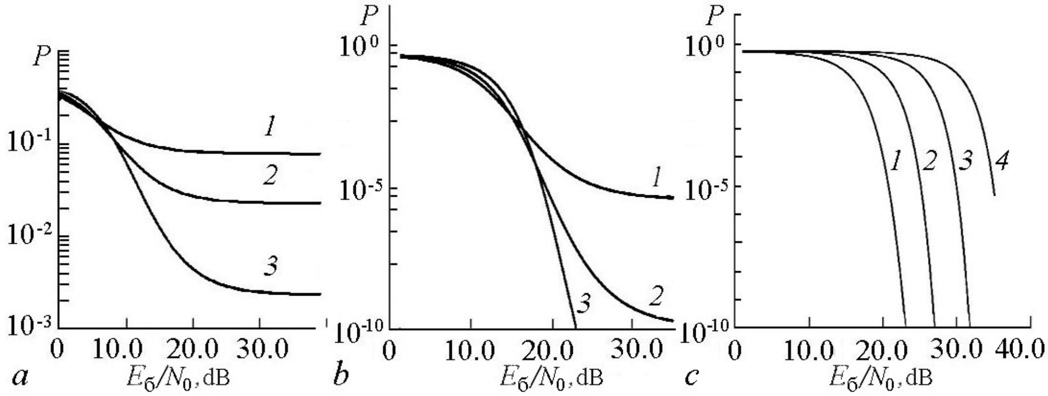

Fig. 6. Error probability as function of the ratio of bit energy to noise spectral density (E_b/N_0): *a* – for small values of processing gain K, curves *1–3* correspond to K: 5; 10; 20; *b* – for medium values of processing gain K, curves *1–3* correspond to K: 50, 100, 200; *c* – for large values of processing gain K, curves *1–4* correspond to K: 10^3, 10^4, 10^5, 10^6

from under the noise. SNR level required for this decreases to -20 dB with K increasing up to 10^6 (Fig. 6, *b* and Fig. 7).

What are the parameters of the chaotic radio impulse, for example, with a processing gain $K = 105$ (50 dB) (this is ten decibels greater than the minimum requirements of the HERMES program)? If the signal bandwidth is 10 GHz, then the chaotic pulse length will be 10^{-5} seconds, and the maximum transmission speed is about 100 Kbit/s. While the received signal's average power can be reduced to -15 dB with error probability per bit (BER – Bit Error Ratio) no more than 10^{-5}.

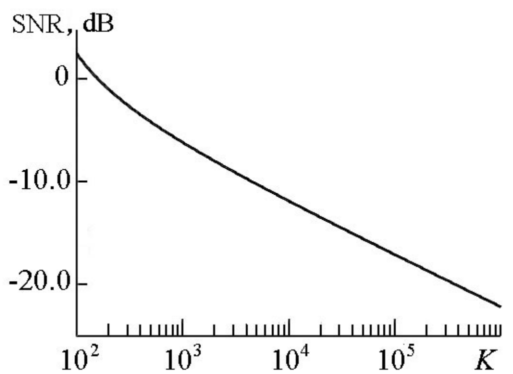

Fig. 7. Minimum signal-to-noise ratio SNR, at which the provided error probability for the received bit is 10^{-5}, as function of processing gain K

Based on the estimations made, it can be argued that Differentially coherent information transmission system with chaotic radio pulses is a good candidate for the wireless hyper-wideband information transmission systems' class. It remains to add that the possibility of obtaining chaotic oscillations with a hyper wideband spectrum in the range up to 30 GHz is shown in [16].

Conclusion

Differentially coherent information transmission scheme, using chaotic signals as carriers, belongs to the class of differentially coherent transmission schemes. In contrast to the DCSK scheme, the proposed scheme uses delays of much shorter duration, which facilitates its practical implementation in microwave frequency range. For example, the delay required for 1 GHz signal bandwidth is 1–2 nanoseconds, and be implemented using modern cable with lengths up to 50 cm.

It should be noted that in the proposed scheme even in the absence of external noise the error probability per received bit is not zero, but tends to some limit. This is caused by the noise created by components of the useful signal delayed with respect to each other. However, for sufficiently large processing gain values (starting from 100), this factor has practically no effect on the system performance. Moreover, such values of processing gain are of great interest for practical applications.

Estimates show that the considered differentially coherent transmission scheme can be used to create not only ultra-wideband but also hyper-wideband communication devices with signal processing gain up to 10^6. With such processing gain stable reception of transmitted signals can be provided from under external noise.

Also, an important property of this scheme is zero threshold decision maker.

The work was carried out within the framework of the state task.

References

1. Kotelnikov V.A. Signals with maximum and minimum probability of detection. *Radiotechnika I Electronica*, 1959, no. 3, pp. 354–358 (in Russian).
2. Kharkevich A.A. Transmission of signals by modulated noise. Electrosvyaz., 1957, no. 11, pp. 42–46 (in Russian).
3. Petrovich N.T., Razmakhnin M.K. Communication systems with noise-like signals. Moscow: Soviet Radio, 1969 (in Russian).
4. Varakin L.E. Communication systems with noise-like signals. M.: Radio I Svyaz. 1985 (in Russian).
5. Pecora L.M., Carroll T.L. Synchronization in Chaotic systems. *Phys. Rev. Lett.*, 1990, vol. 64, no. 8, pp. 821–824.
6. Kolumban G., Kennedy M. The role of synchronization in digital communications using chaos – Part I: Fundamentals of digital communications. *IEEE Trans. Circuits and Systems*, 1997, vol. 44, no. 10, pp. 927–936.
7. Kolumban G., Vizvari B., Schwarz W., Abel A. Differential chaos shift keying: A robust coding for chaotic communication. In *Proc. NDES'96*, 1996, pp. 87–92.
8. Sushchik M., Tsirming L.S., Volkovskii A.R. Performance analysis of correlation-based communication schemes utilizing chaos. *IEEE Trans. Circuits and Systems*, 2000, vol. 47, no. 12, pp. 1684–1691.
9. Dmitriev A.S., Kjarginsky B.E., Panas A.I., Starkov S.O. Direct-chaotic schemes of information transmission in the microwave range. *Journal of Communications Technology and Electronics*, 2001, vol. 46, no. 2, pp. 224–233.
10. Dmitriev A.S., Kyarginsky B. Ye., Panas A.I., Starkov S.O. Experiments on ultra wideband direct chaotic information transmission in microwave band. *Int. J. Bifurcation and Chaos*, 2003, vol. 13, no. 6, pp. 1495–1507.
11. Dmitriev A.S., Mokhseni T.I., Sierra-Teran K.M. Differential information transfer based on chaotic radio pulses. *Journal of Communications Technology and Electronics*, 2018, vol. 63, no. 10. (in print).
12. Broad Agency Announcement Hyper-wideband Enabled RF Messaging (HERMES) Microsystems Technology Office DARPA-BAA-14-34. 30 June 2014. 36 p.

13. Subramanian, Vijayan. Hyper-wideband wireless communication link empowered by silicon photonics for low cast RF systems. *IJARTET*, 2018, vol. 5, no. 1, pp. 25–29.
14. Esman D., Ataie V., Kuo B. P.-P., Alic N., Radic S. Subnoise Signal Detection and Communication. *Journal of Lightwave Technology*, 2016, vol. 34, no. 22, pp. 5214–5219.
15. Dmitriev A.S., Efremova E.V., Maksimov N.A., Panas A.I. Generation of chaos. M.: Technosphere, 2012 (in Russian).
16. Efremova E.V. Model of a chaotic self-oscillating system of the range 10–30 GHz based on SiGe-technology 130 nm. *Technical Physics Letters*, 2018, vol. 44, no. 5, pp. 378–380.