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Experiments on direct chaotic differentially coherent data transmission in a wired communication channel

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Abstract. Methods of differentially coherent information transmission using noise signals are of interest because of the impossibility of implementing the known methods of correlation reception for such signals. With a potentially higher noise immunity compared to the methods of information transmission based on chaotic synchronization, however, they have a feature that does not allow transceivers to be implemented in practice. The transmitter and receiver of the scheme, based on already known methods of differentially coherent transmission, require a time delay comparable to the duration of the transmitted bits. With an analog implementation of the scheme this leads to a physical length of the delay line of tens of meters or more. Previously, the authors proposed and studied a differentially coherent transmission scheme in which there are no long delays. In this scheme, the duration of delays in the transmitter and receiver is determined not by the duration of the bit, but by the decay time of the autocorrelation function of the chaotic signal. *Purpose* of this work is to experimentally demonstrate the possibility of physical implementation of a direct-chaotic differentially coherent information transmission scheme in a wired communication channel. *Methods.* For this, a layout of the communication scheme, transmitting a binary data stream in the frequency range from 200 to 500 MHz, was designed and assembled. The layout is an ultra-wideband differentially coherent transmitter and receiver connected via a wired channel. *Results* of the experiment are in full agreement with the previously obtained results of the analytical evaluations, as well as with the data of computer simulation. *Conclusion.* In the course of the research, a transceiver layout of a differentially coherent ultra-wideband direct chaotic communication scheme was developed, designed and manufactured. For the first time, experiments on the transmission of digital information were carried out on it, and thereby the practical feasibility and operability of the proposed direct chaotic differentially coherent transmission scheme were proved.

Keywords: dynamic chaos, ultra–wideband signals, differentially coherent information transmission, correlation technique.

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Introduction

Differentially coherent information transmission schemes have been investigated since the mid-50s of the twentieth century [1–3]. The main advantages of schemes providing differentially coherent transmission/reception of data include the simple design of the receiver circuit. Therefore, with the emergence of interest in the use of chaos as a carrier of information in communication systems, they quickly attracted the attention of researchers. The first proposed differentially coherent transmission scheme based on chaos DCSK (Differential Chaos Shift Keying), proposed in the late 90s in [4], demonstrated higher noise immunity than methods based on the phenomenon of chaotic synchronization known at that time [5–9]. However, due to the peculiarity of the DCSK scheme, which consists in the presence of a signal delay on the receiving and transmitting sides for a time comparable to the time of the transmitted bits, the practical implementation of the scheme leads to the need to create a delay line tens and hundreds of meters long. As a result, attempts to physically implement the DCSK scheme are not related to its analog implementation, but to its digital implementation [10, 11].

In [12, 13], an alternative to the DCSK scheme was proposed — a direct chaotic scheme of differentially coherent information transmission DC^2 (Direct Chaotic Differently Coherent scheme). In this scheme, a much shorter delay time is needed to implement a differentially coherent communication system. This makes such a system suitable for practical implementation. Unlike the DCSK scheme, the length of the delay lines in the transmitter and receiver of the proposed scheme is determined not by the bit length, but by the time τ of the decay of the autocorrelation function of the chaotic signal. In order of magnitude, τ can be estimated as $1/\Delta F$, where ΔF is the band of a chaotic signal. For example, if the chaotic signal band is 300 MHz, then the autocorrelation time will be on the order of 3 ns. Accordingly, the distance that an electromagnetic wave travels in a vacuum during this time will be about 0.9 m.

Later, the possibility of the DC^2 scheme working not only in point-to-point mode, but also the possibility of functioning in multi-user access mode [14] was demonstrated. This significantly expands the range of its potential applications.

In the DC^2 scheme, chaotic radio pulses with a duty cycle and a large base (processing coefficient) are used for data transmission. This should theoretically contribute to ensuring high noise immunity in conditions of multipath propagation and with a significant level of distortion and noise.

The purpose of this work is to develop, create and study an experimental layout of the DC^2 scheme designed to transmit information over a channel in the form of a cable fragment. The purpose of the experiments is to demonstrate the operability of the proposed method of transmitting and receiving data, as well as to verify that its characteristics correspond to previously obtained theoretical estimates and computer modeling data.

The structure of the direct chaotic differentially coherent data transmission scheme DC^2, its principles of operation and properties are described in [12, 13].

1. Layout Flowchart DC^2

The block diagram of the experimental layout of the DC^2 transmission scheme is shown in Fig. 1.

1.1. Transmitter. The DC^2 scheme transmitter (Fig. 1) consists of: a chaos generator (Chaos source), a microcontroller (MC — MCU), a field-programmable gate array (FPGA), a divider (D), a modulator (M), time delay (τ) and an adder (+).

An FPGA is connected to the source, controlling its power supply. The FPGA turns on the chaos source for a time equal to the pulse duration T_p. Then it turns off for a time equal to $2T_p$. Thus, the output of the source receives a stream of chaotic pulses with a duty cycle of 3. Then the pulse stream of the source falls on the power divider D. The signal from the upper output of the divider (Fig. 1) gets to the modulator. The signal from the lower output of the divider gets to the delay block, where it is delayed for a time τ greater than or equal to the autocorrelation time of the source signal.

The modulator circuit (Fig. 2) consists of a two-position switch S (Single pole double throw switch), an adder (+) and an inverter (I).

The input information signal is sent via the MCU to the FPGA, which controls the pulse flow and is connected to the information input of the key (info input in Fig. 2). The MCU transmits the stream of incoming characters to the FPGA via the SPI interface. Depending on the value of the information symbol ("+1"or "−1") from the input stream and in accordance with pulses time of arrival at the input of the key, the FPGA supplies different voltage to the information input of the key. Depending on the voltage level at the information input of the key, it is either in the upper or lower position. In the upper position, the key passes a signal (pulse) through path 1, and path 2 is open (Fig. 2). Accordingly, in the lower position, the key passes the signal through path 2, and path 1 is open. When the key is in the upper position, the pulse passes through path 1 unchanged and enters the output of the modulator. This corresponds to the transfer "+1". When the key is in the lower position, the pulse enters the inverter unit, where it is inverted. Then, from the output of the inverter, the signal goes to the output of the modulator. This corresponds to the transfer "−1". The adder generates the output stream of the modulator. From the output of the modulator, the signal enters the upper input of the adder located at the output of the transmitter (Fig. 1). The signal from the output of the delay unit goes to the lower input of the adder located at the output of the transmitter. Then, from the output of the adder, the resulting signal is transmitted to the wired communication channel.

1.2. Receiver. The receiver of the DC^2 scheme (Fig. 1) consists of: a divider (D), a time delay (τ), a multiplier ($\times$) and a low-pass filter (LPF).

The pulse flow from the channel enters the divider. The signal from the upper output of the divider goes unchanged to the upper input of the multiplier. The signal from the lower output of the divider enters the input of the delay unit for the time τ (identical to the delay in the transmitter). The signal from the output of the delay unit goes to the lower input of the multiplier. Then the signals from the upper output of the divider and the delay output are multiplied. The result of multiplication goes to the input of the LPF, which performs the role of an integrator. The cutoff frequency of the integrating filter is inversely proportional to the pulse duration of the source. The signal from the LPF output is compared with the zero threshold.

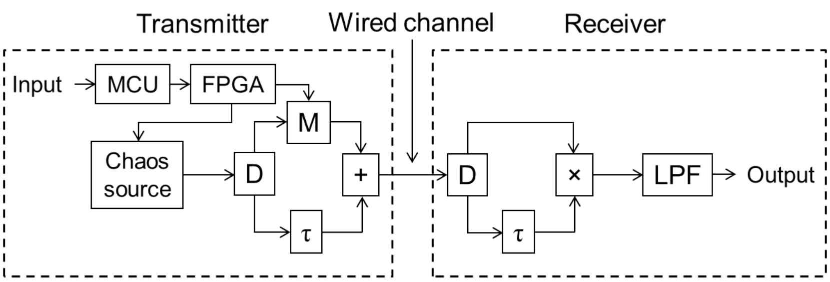

Fig. 1. Direct chaotic differentially coherent transmission scheme: Chaos source — chaos generator, Input — information input, MCU — microcontroller, FPGA — field-programmable gate array, D — divider, M — modulator, τ — time delay, "+" — adder, "×" — multiplier, LPF — low pass filter, Output — scheme's output

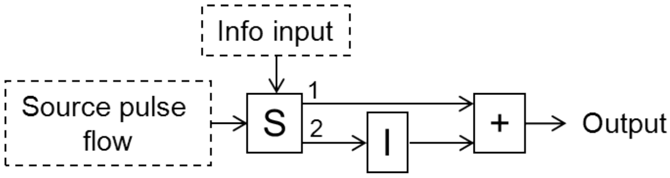

Fig. 2. Modulator of direct chaotic differentially coherent transmission scheme: Source pulse flow — modulator source pulse flow input, Info input — modulator information signal input, S — single pole double throw switch, I — inverter, "+" — adder, Output — modulator output

If the signal at the output of the LPF exceeds the zero threshold, then "+1"is detected. If the output signal is below the zero threshold, then "−1"is detected.

Let $S_k(t)$—k be the chaotic pulse in the stream formed by the source of chaotic radio pulses; $\alpha_k \in \{-1, 1\}$ — the value of the information modulating signal. When transmitting the kth binary information symbol, the signal at the output of the transmitter in the scheme DC^2 will look like this:

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

In the receiver, in the absence of noise and external distortions, the pulse at the output of the multiplication unit corresponding to the kth information symbol enters the integrator, after which it takes the form:

$$Z_k(t) = \frac{1}{16}\mathrm{M}[\alpha_k S_k^2(t-\tau) + S_k(t)S_k(t-\tau) + \alpha_k S_k(t)S_k(t-2\tau) + S_k(t-\tau)S_k(t-2\tau)], \tag{2}$$

where $\mathrm{M}[X(t)] = \int_t^{t+T_p} X(t)dt$ — time averaging operator. Since τ — is a time greater than or equal to the autocorrelation time of the source signal, then in the expression (2) the value of the summand $\alpha_k S_k^2(t-\tau)$ is an order of magnitude higher than the values of the other three terms: $S_k(t)S_k(t-\tau)$, $\alpha_k S_k(t)S_k(t-2\tau)$ and $S_k(t-\tau)S_k(t-2\tau)$, which represent the internal the noise of the transmitter and receiver of the system that occurs during modulation. Thus, the value of $Z_k(t)$ will always have the sign of $\alpha_k S_k^2(t-\tau)$, that is, the sign α_k. Setting a zero threshold at the output of the integrator allows the detection of the received symbols flow.

2. Layout of the scheme DC^2

The experimental layout (Fig. 3) of the DC^2 transmission scheme was assembled based on the flowchart in Fig. 1.

2.1. Transmitter layout. A generator with a frequency spectrum band from 200 to 500 MHz was used as a chaotic signal source (Fig. 4).

The source of the chaotic signal – FPGA, which forms the pulse stream of the source and controls the information input of the modulator, as well as the MCU receiving the input information stream, were located on the same board (digit 1 in Fig. 3). The pulse duration was 2 µs. A divider/adder with an operating frequency band up to 1 GHz was used as a power divider. When inverted, the divider/adder can be used as an adder. A divider/adder similar to the power divider used was used as an adder. A fragment of a coaxial cable was used in the experiment as a delay line for a time equal to or greater than the autocorrelation time of the source pulses. In Fig. 5 the autocorrelation function of the source pulses is presented.

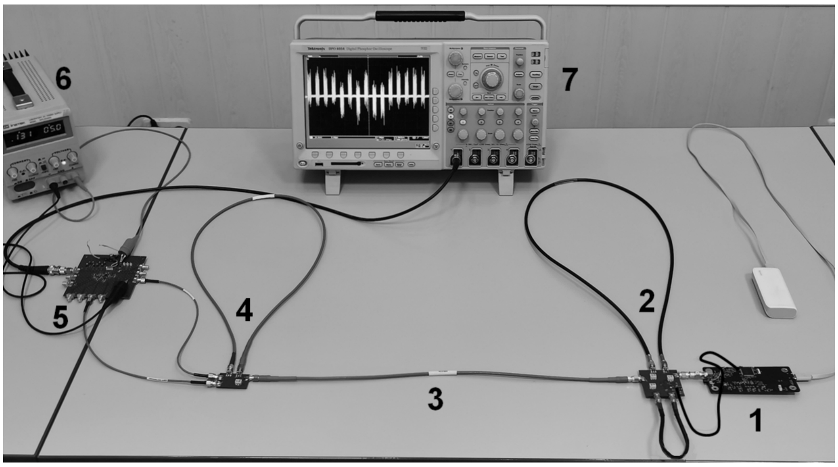

Fig. 3. Photo of direct chaotic differentially coherent transmission scheme experimental layout: 1 — board, that includes a source of chaotic radio pulses and a microcontroller that forms an information sequence; 2 — board that contains a divider into two channels, a modulator, a delay line for a time greater than or equal to the autocorrelation time of the source signal, and an adder; 3 — cable that serves as a communication channel; 4 — board that contains a divider into two channels, a delay line in one of the channels and two outputs; 5 — multiplier board; 6 — power supply; 7 — oscilloscope

The graph shows that in 4-5 ns the autocorrelation function decreases by about an order of magnitude relative to the maximum. To ensure the delay, a cable fragment with a length of $L = 1$ m was used. The signal propagation velocity in the applied cable is approximately 70% (velocity propagation factor $v_p = 0.7$) of the speed of light in a vacuum. Taking this parameter into account, the delay duration is $\tau = L/(v_p \cdot c) = 1/(0.7 \cdot 3 \cdot 10^8) \approx 4.8$ ns. This corresponds to the autocorrelation time of the source pulses (Fig. 5). The divider, delay line and adder, as well as the entire modulator unit (Fig. 2) were combined on one board (marked with the number 2 in fig. 3). The modulator consists of a key, an inverter and an adder. A two-position key with an operating frequency band up to 6 GHz was used as the key. A time delay for the decay time of source autocorrelation function to a minimum was used as an inverting block (Fig. 5). The minimum of source pulses autocorrelation function is opposite in sign to the maximum, and in absolute value is less than the maximum by 20–30% (Fig. 5). Thus, a comparison with a zero threshold of the values of the maximum and minimum of the autocorrelation function will always give the opposite result. This corresponds to the criterion of detecting information symbols on

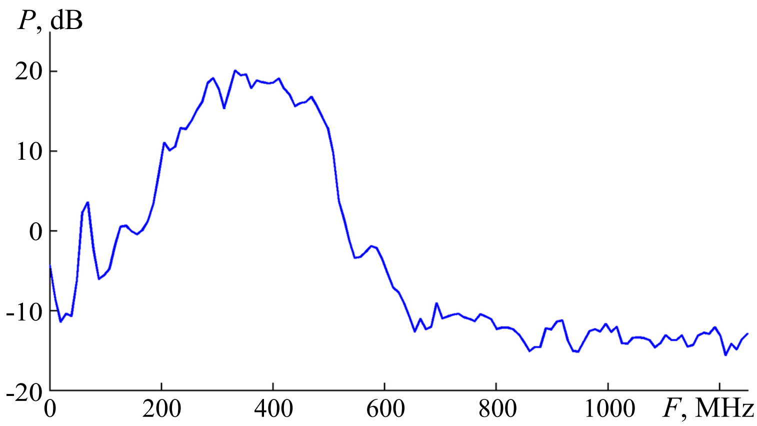

Fig. 4. Source pulses power spectrum

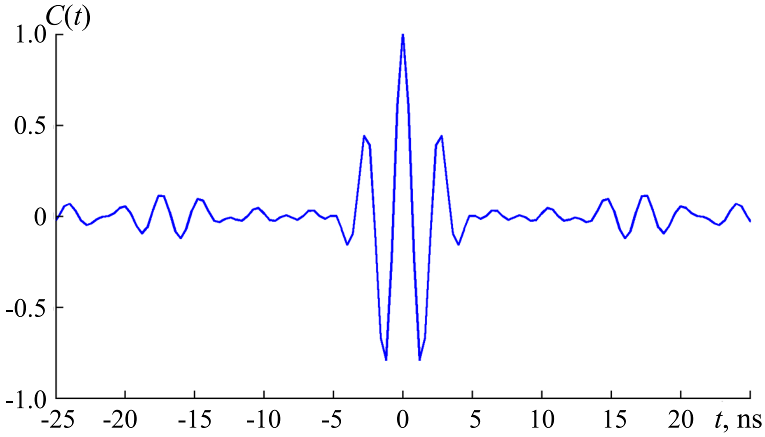

Fig. 5. Source pulses autocorrelation function

the receiver of the scheme DC^2.

According to the graph in Fig. 5, the minimum of the autocorrelation function is at a distance of approximately 1 ns. This corresponds to a path length of about 0.3 m. As an inverting delay, a fragment of a cable with a length of $L_{\text{inv}} = 0.23$ m ($v_p = 0.7$) was taken. Taking into account the cable parameters, this corresponds to the delay duration $\tau_{\text{inv}} = L_{\text{inv}}/(v_p \cdot c) = 0.23/(0.7 \cdot 3 \cdot 10^8) \approx 1.1$ ns. This corresponds to the distance from the maximum to the minimum of source pulses autocorrelation function from the graph in Fig. 5.

The generator output was connected to the divider input using SMA connectors. The programmable logic integrated circuit of the FPGA was connected to the information input of the key using a thin wire. Coaxial cables, acting as a delay line for the time of autocorrelation and inverting delay, were connected to the board using sma connectors. The output of the transmitter was also presented in the form of an SMA connector. The communication channel was a fragment of a coaxial cable ($v_p = 0.7$) with a length of 25 cm (marked with the number 3 in Fig. 3).

2.2. Receiver layout. The input sma connector that received the signal from the communication channel; the divider; sma connectors for connecting the delay; sma connectors for connecting the board with the multiplier were combined on one board (marked with the number 4 in Fig. 3). The multiplier, which has a working frequency band up to 1 GHz, was located on a separate specialized board (marked with the number 5 in Fig. 3). The inputs and outputs of the multiplier on the board through which it was connected to the oscilloscope were also SMA connectors. The divider /adder and the delay line, implemented in the form of coaxial cable fragment with a length of 1 m, are completely similar to those used in the transmitter.

The output of the multiplier was connected to an oscilloscope with an operating frequency band up to 500 MHz using a coaxial cable. The sampled signal coming from the multiplier in the form of a CSV file was transmitted from an oscilloscope to a PC. Further, signal processing was performed in the MATLAB software environment, including integration/filtering of the LPF with a finite impulse response.

3. Results of the experiment

The system operated in continuous mode, transmitting a pulse stream with a duration of 2 µs and a duty cycle of 3 (transmission rate of 167 Kbit). Fig. 6 shows a fragment of 10 pulses taken at different points of the DC^2 scheme during the operation of the experimental layout: a — at the output of the source generator, b — at the information input of the modulator key, c — at the output of the transmitter (the output of the adder), d — at the output of the receiver multiplier, e — at the output of the receiver's LPF . It can be seen from the figure that by comparing with the zero threshold a sequence of symbols 1011011000 can be detected out of these 10 pulses (positive and negative envelopes of the pulses in Fig. 6, e).

4. Receiver response to an unmodulated noise pulse

What happens if noise pulses identical in power to chaotic pulses modulated by the DC^2 method interfere with the transmission of a useful signal?

Since when integrating at the receiver, one noise pulse will be shifted relative to the other for the time of autocorrelation, they will be almost uncorrelated with each other. And at the output of the receiver, a pulse of small amplitude will be obtained.

To estimate the degree of noise pulses influence on the transmission of a useful signal in

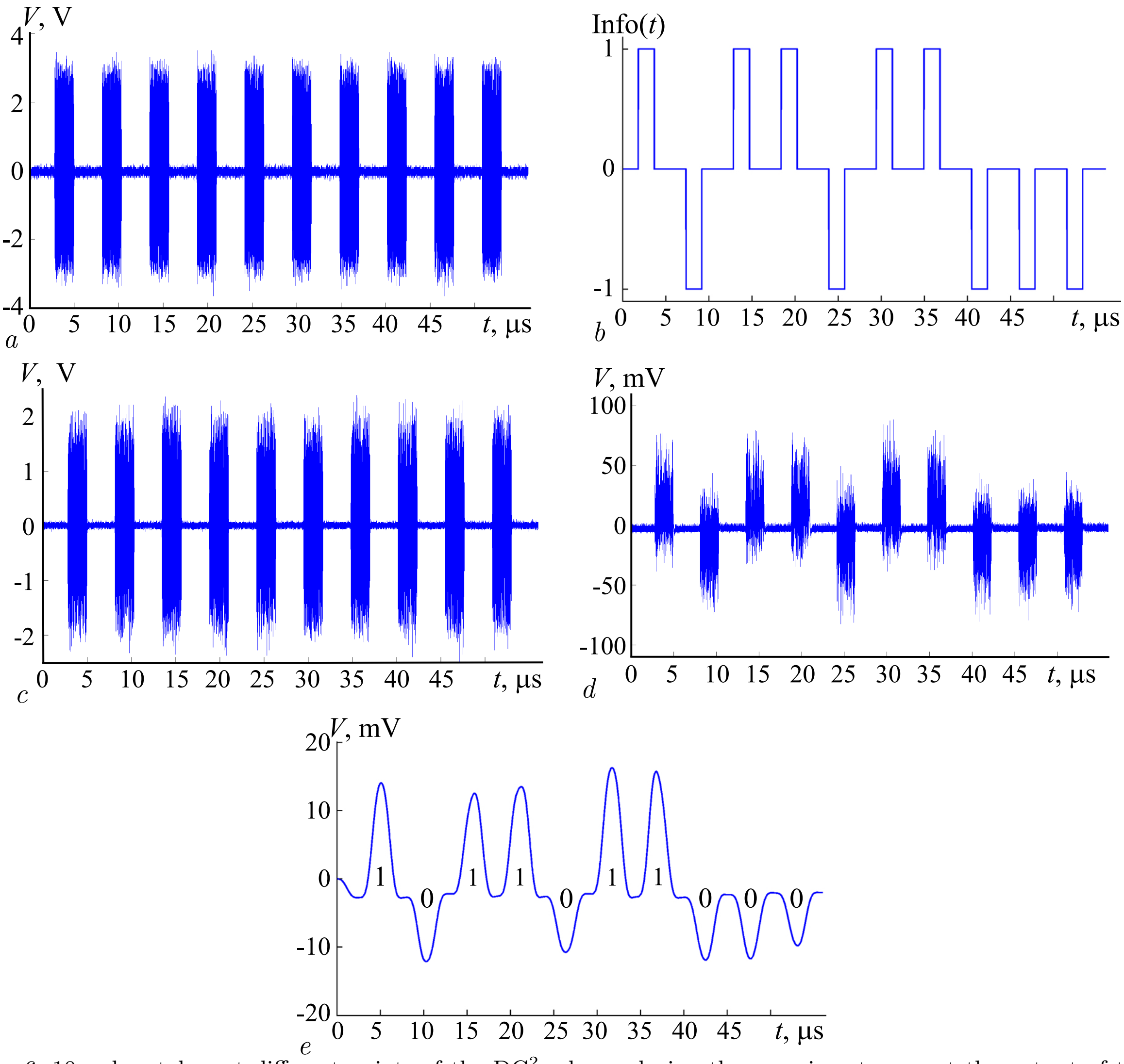

Fig. 6. 10 pulses taken at different points of the DC^2 scheme during the experiment: a — at the output of the source generator, b — at the information input of the modulator switch, c — at the output of the transmitter (output of the adder), d — at the output of the receiver multiplier, e — at the output of the receiver low-pass filter

this experiment a comparison between the flow of chaotic pulses from the transmitter output carrying the useful signal.

To experimentally verify the degree of influence of noise pulses on the transmission of a useful signal, a stream of unmodulated noise pulses with a spectrum and power identical to the spectrum and power of the pulses at the output of the transmitter of the direct-chaotic differentially coherent scheme was formed. The flow was obtained as follows: the delay between the lower output of the divider and the input of the adder and the entire modulator block was removed from the transmitter of the direct chaotic differentially coherent scheme (Fig. 1). The signal from the adder output was fed to the receiver via a wired channel. Fig. 7 shows 3 noise pulses at the output of the receiver multiplier, obtained by the method described above.

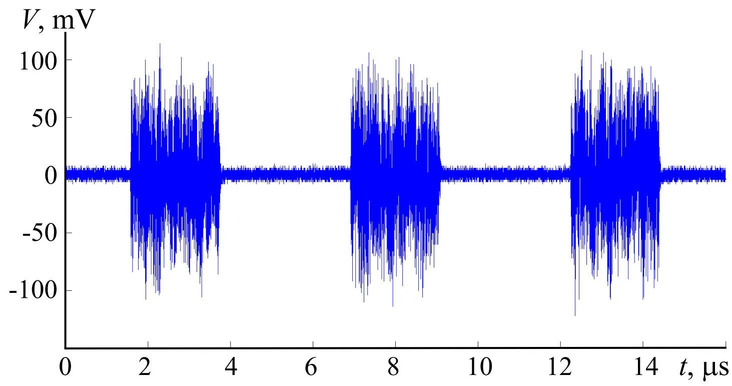

Fig. 7. Unmodulated noise pulses at the output of the receiver multiplier

To demonstrate the transmission of a useful signal by the direct chaotic differentially coherent method, the streams of symbols "+1"and "−1"were transmitted separately. On fig. 8 a solid line shows 3 pulses at the output of the receiver's LPF received during the transmission of "+1"symbols stream„ a dashed line shows 3 pulses at the output of the LPF received during the transmission of "−1"symbols stream. For comparison, in Fig. 8 together with the pulses carrying the useful signal, a dashed line shows 3 unmodulated noise pulses at the output of the LPF.

It can be seen from the figure that when transmitting "+1"and "−1 the amplitude of the pulses at the output of the LPF in absolute value significantly exceeds the amplitude of the pulses received during the transmission of unmodulated noise. Thus, it is shown that the transmission of a useful signal leads to a significantly larger signal amplitude at the receiver output compared to the transmission of unmodulated noise with the same initial power. It can be expected that with an increase in the signal base with the same power of modulated and unmodulated pulses, the difference between their amplitudes at the receiver output will also grow.

Conclusion

In the work, an experimental setup that allows testing the possibility of transmitting and detecting the flow of information symbols "+1"and "−1"according to the principles of modulation and demodulation of the direct chaotic differentially coherent transmission scheme DC^2 was invented and created. This layout has been assembled. The operability of the proposed method of transmitting and receiving data and the compliance of its characteristics with previously obtained theoretical estimates and computer modeling data was demonstrated.

The layout consisted of a receiver, a transmitter and a wired communication channel between them and worked on the "point-to-point"principle. The layout functioned in the mode of continuous transmission of information flow. The data transmitted in the experiment was

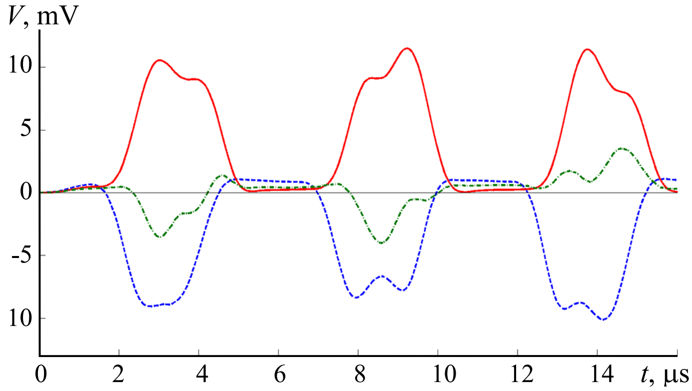

Fig. 8. Pulses at the output of the low-pass filter at the receiver: the solid line shows 3 pulses during the transmission of "+1" symbol stream, the dashed line shows 3 pulses during the transmission of "−1" symbol stream, the dash-dotted line shows 3 pulses during the transmission of unmodulated noise

successfully delivered to the receiver. The results taken with the help of an oscilloscope in some nodes of the layout (Fig. 6) during data transmission are quite consistent with the results obtained at previous stages during modeling. It was experimentally shown that the unmodulated noise pulses when passing through the receiver have amplitude by an order of magnitude lower than the modulated chaotic pulses that come from the transmitter of the direct chaotic scheme with the same initial power.

References

1. Petrovich NT, Razmakhnin MK. Communication Systems With Noise-Like Signals. Moscow: Sovetskoe Radio; 1969. 233 p. (in Russian).
2. Varakin LE. Communication Systems With Noise-Like Signals. Moscow: Radio I Svyaz; 1985. 384 p. (in Russian).
3. Petrovich NT. Differentially Coherent Information Transmission Methods. Moscow: Kniga-M; 2003. 108 p. (in Russian).
4. Kolumban G, Kennedy MP, Chua LO. The role of synchronization in digital communications using chaos. I . Fundamentals of digital communications. IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications. 1997;44(10):927–936. DOI: 10.1109/81.633882.
5. Kocarev L, Halle KS, Eckert K, Chua LO, Parlitz U. Experimental demonstration of secure communications via chaotic synchronization. International Journal of Bifurcation and Chaos. 1992;2(3):709–713. DOI: 10.1142/S0218127492000823.
6. Cuomo KM, Oppenheim AV, Strogatz SH. Synchronization of Lorenz-based chaotic circuits with applications to communications. IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing. 1993;40(10):626–633. DOI: 10.1109/82.246163.
7. Downes PT. Secure communication using chaotic synchronization. SPIE. 1993;2038:227–234.
8. Dedieu H, Kennedy MP, Hasler M. Chaos shift keying: modulation and demodulation of a chaotic carrier using self-synchronizing Chua's circuits. IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing. 1993;40(10):634–642. DOI: 10.1109/82.246164.
9. Parlitz U, Chua LO, Kocarev L, Halle KS, Shang A. Transmission of digital signals by chaotic synchronization. International Journal of Bifurcation and Chaos. 1992;2(4):973–977. DOI: 10.1142/S0218127492000562.
10. Kaddoum G, Olivain J, Samson GB, Giard P, Gagnon F. Implementation of a differential

chaos shift keying communication system in GNU radio. In: 2012 International Symposium on Wireless Communication Systems (ISWCS). 28–31 August 2012, Paris, France. New York: IEEE; 2012. P. 934–938. DOI: 10.1109/ISWCS.2012.6328505.
11. Hasan FS, Salah-Addin Ibrahim D. Design and implementation of reverse-DCSK communication system using FPGA technique. International Journal of Advanced Science and Technology. 2020;29(3):12893–12905.
12. Dmitriev AS, Mokhseni TI, Sierra Teran KM. Differentially coherent information transmission based on chaotic radio pulses. J. Commun. Technol. Electron. 2018;63(10):1183–1190. DOI: 10.1134/S1064226918100078.
13. Dmitriev AS, Mokhseni TI, Sierra-Teran CM. Differentially coherent information transmission based on chaotic radio pulses. Izvestiya VUZ. Applied Nonlinear Dynamics. 2018;26(4):59–74. DOI: 10.18500/0869-6632-2018-26-4-59-74.
14. Dmitriev AS, Mokhseni TI, Sierra-Teran CM. Multiuser access in systems of differentially coherent information transmission based on chaotic radio pulses. Tech. Phys. Lett. 2020;46(7):669–672. DOI: 10.1134/S106378502007007X.