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Spatiotemporal coherent summation of Ultra-Wideband chaotic radio pulses. Experiment

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Abstract. *The aim* of this work is to experimentally confirm the physical possibility of coherent summation of chaotic signals (ultra-wideband chaotic radio pulses) in space and time. Coherent summation is used in modern physics in various ways, but to date there are no examples of explicit demonstration of coherent summation of ultra-wideband chaotic signals. The practical feasibility of such summation faces at least two difficulties: firstly, it has been unclear how to obtain signals of the same shape (a necessary condition for coherent summation), and secondly, how to implement the summation method itself. *Methods.* The approach of full-scale modeling of the processes of emission of ultra-wideband chaotic signals, their reception and digital processing after digitization by an oscilloscope is used. The results are obtained on the basis of an experimental setup including four identical emitters and one receiver. *Results.* A linear increase in the root-mean-square amplitude of the signal at the reception point with coherent and a linear increase in the power of the total signal with incoherent summation of ultra-wideband chaotic radio pulses with an increase in the number of emitters has been experimentally demonstrated. *Conclusion.* The experimental demonstration of the phenomenon of coherent summation of ultra-wideband chaotic signals is the basis for further development and application of this phenomenon in wireless multi-antenna ultra-wideband systems.

Keywords: ultra-wideband signals, chaotic signals, coherent reception of chaotic signals, coherent emission of chaotic signals, generation of chaotic oscillations.

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Introduction

Coherent processing of radio signals in time and space is one of the central ideas of modern radiophysics and wireless technologies. There are several reasons why the coherent summation of signals in space is of scientific and practical interest.

The first is related to the limited bandwidth of the «point to point», channel, which, as is known, is proportional to the frequency band W of the signal and the binary logarithm of the signal to noise ratio S/N. To increase the channel capacity, for example, by ten times, it is necessary to increase the signal-to-noise ratio by 1000 times, which is very significant for radio engineering and practically excludes the possibility of straightforward implementation.

Increasing the bandwidth in practice is also not always possible, as there are restrictions on the bandwidth of the wireless channel from government regulatory authorities. A striking example of this is the ultra-wideband (UWB) systems [1, 2], which are subject to greater restrictions on emitted signal power compared to narrowband solutions [3, 4]. The power of UWB signals should not exceed fractions of a milliwatt according to foreign legal restrictions (rules vary depending on the country) and units of microwatts according to Russian standards. These are very small values: for comparison, the typical signal power in narrow-band systems (Wi-Fi, Bluetooth, and the like used in the ISM — Industrial Scientific Medicine band) is units and tens of milliwatts.

In order to achieve the highest possible transmission rates, developers of wireless systems either have to use more complex radio signal modulation/encoding methods that increase spectral efficiency (the number of bits per Hertz), or develop equally complex spatial-temporal encoding schemes in which user separation is achieved by forming a given spatial-temporal directionality diagram, based on the coherent summation of radio signals at user locations (MIMO — Multiple Input-Multiple Output of the system). This ensures the repeated use of the same frequency band due to the interference phenomenon, which is basic to physics, and an increase in bandwidth. The price for this is the complication of the information transmission scheme: on the transmitting side, it is necessary to use multiple antennas to form a given directionality of radio signal emission. The task of the transmitter is to create interference maxima of the useful signal at the points of the receiving antennas. Formally, the maximum channel capacity in this case increases by a factor proportional to the number of pairs of transmitting and receiving antennas.

It is essential in this case to use narrow-band (harmonic) signals, which, as is known, in any combination (addition, multiplication) give a harmonic signal. The theory of generation and reception of such signals has been developing for several decades, and the level of the modern radio electronic allows developers to completely move away from the physics and focus exclusively on the mathematical aspects of harmonic signal conversion, using well-developed apparatus of linear algebra and theory of harmonic functions.

Developments in the field of narrowband signals for the implementation of spatio-temporal coding and the organization of independent data transmission between users in a wireless channel have shown great promise in the application of the phenomenon of coherent summation of radio signals. Harmonic signals are not the only type of carrier that can be used for this. In this context, it makes sense to consider broadband or ultra-wideband chaotic signals [5–11] and chaotic sequences [12–14], which are suitable for solving communication problems based on the use of interference phenomena. The wider the band, the narrower the autocorrelation function of the signals and, consequently, the higher the immunity to multipath propagation, and the greater the potential for increasing the spatial density of receiver placement. In particular, of great interest is the coherent summation of chaotic signals, which should add up in amplitude in the same way as harmonic signals if certain spatiotemporal relationships are maintained between their emission points and the reception point. Specifically, at the reception point, where chaotic signals with the same shape arrive simultaneously, the amplitude of the summed signal is proportional to the number of emitters (summation by amplitude). At other points, where the signals arrive out of sync, the amplitude of the summed signal will be proportional to the square root of the number of emitters (summation by power).

Of course, it is not possible to achieve complete orthogonality of the signals [15, 16], but by eliminating complete orthogonality, the emitting system can be simplified.

This work is devoted to the experimental study of the possibility of coherent summation of UWB chaotic signals. It is based on the method of forming chaotic radio pulses with the same shape, described in [17, 18]. The identity of the signal shape for coherent summation is, of course, a necessary condition for its implementation.

The problem discussed in this paper is divided into several stages: the development of methods for generating chaotic signals of the same shape; ways to coordinate the moments of their emission to achieve simultaneous arrival of pulses from different emitters at a given point in space; the development of emitting systems that can be reproduced with a high degree of accuracy; a method for comparing signals from a different number of emitters at a receiving point.

The purpose and novelty of this work is to experimentally demonstrate the practical possibility of coherent summation of UWB chaotic radio pulses at a given point in space; to analyze the variability of the shape of chaotic signals when passing through a channel and show that the property of repeatability of the shape of UWB chaotic radio pulses is preserved after passing through the channel.An experimental study has demonstrated that the process of coherent summation of ultra-wideband chaotic radio pulses is indeed possible. The results of this study form the basis for the development of a wireless multi-antenna system that enables directional transmission of information by coherent summation of ultra-wideband radio pulses.

The article is organized as follows. Section 1 describes the experimental scheme, the layout structure and its functional blocks. Section 2 describes experiments on incoherent and coherent addition of UWB chaotic signals and their results.

1. Scheme of the experiment

The results described in the article were obtained on the basis of an experimental setup, the diagram of which is presented in Fig. 1.

The experimental stand consists of four UWB emitters of chaotic radio pulses (generators of chaotic oscillations that are connected to emitting antennas). The oscillators are controlled by modulators, which are supplied with a modulating video signal generated using a hardware and software control system. A photo of the emitter (antenna with generator) and the cross-board controlling the generators is shown in Fig. 1, *a*. The modulating signal is transmitted from the cross-board to the emitters via a cable. Experiments on incoherent and coherent summation in space, according to the scheme in Fig. 1, *a*, were conducted in an office space measuring 6.6×6×4 m. The antennas were placed around the perimeter of the square with a side length of about 3.5 m at the same distance from the receiving antenna located in the center of the square. The distance between the transmitting and receiving antennas was 1.75 m.

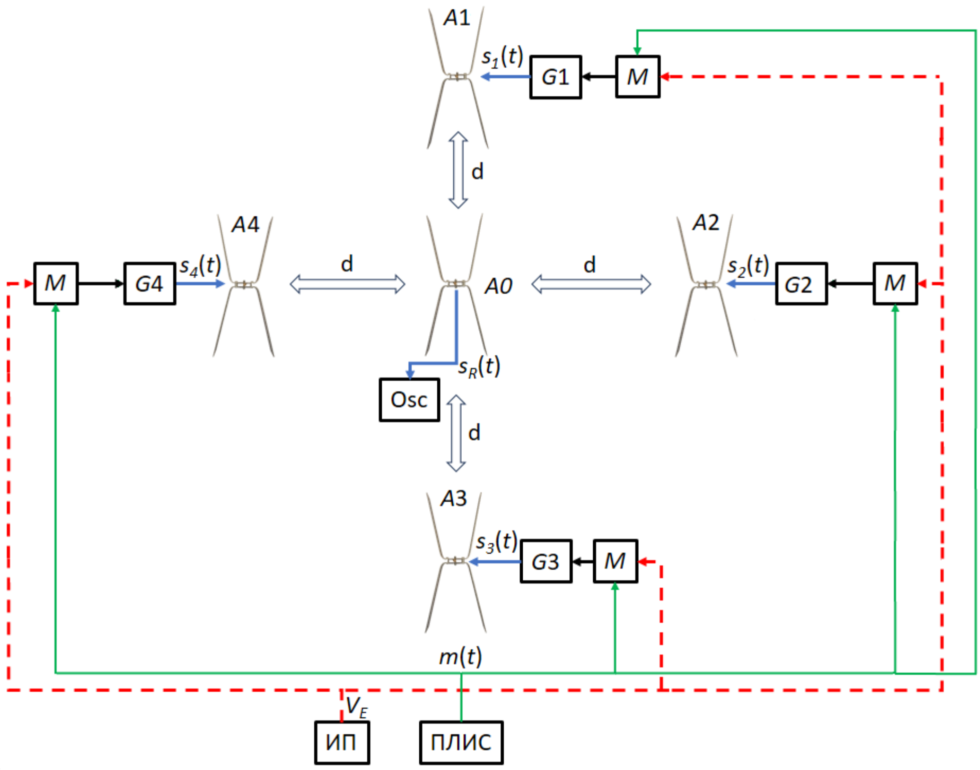
The experiment was conducted based on the following provisions:

- several independent UWB pulse emitters are used;
- UWB generators of chaotic radio pulses are used, which can generate pulses of different shapes and durations;
- time points of the beginning of the emission of chaotic radio pulses are selected so that the pulse signals from different emitters arrive at the receiving point simultaneously;
- there is no fundamental restriction on the choice of the receiving point.

During the implementation of this measurement scheme, methods, software and hardware solutions have been developed that make it possible to experimentally implement the coherent summation of UWB chaotic radio pulses at a given point in space based on separate chaotic sources. The implementation of this approach is described below.

1.1. Chaotic oscillators. The work used solid-state single-transistor oscillators on lumped elements [19,20], providing the generation of chaotic oscillations with a power of 1.5 MW in the frequency band of 50...500 MHz. The principle of operation of oscillators and the principle of forming identical chaotic radio pulses are described in detail in [17,18]. The essence of the approach is that by modulating such a generator with video pulses under certain conditions, it generates pulses with the same shape. In [17, 18] this is demonstrated for the case of signal transmission over a wire.

In the case of wireless signal transmission, the situation is complicated by the influence of the transmitting and receiving antennas and the wireless channel itself. Therefore, the possibility of preserving the similarity of the shape of the pulses from different emitters after passing through the wireless channel is not obvious. The transmitting antenna, which is a linear oscillatory system, when connected to the



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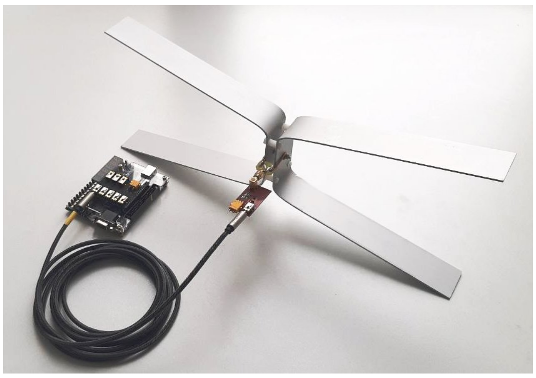


b

Fig. 1. *a* — Schematic diagram of the experimental setup for spatio-temporal pulse summation: $s_1(t), ..., s_4(t)$ — signals of chaotic oscillators $G_1, ..., G_4$, respectively; ПЛИС (FPGA) — source of the periodic sequence of video pulses $m(t)$ based on the DE10-Lite FPGA breadboard; ИП (PS) — power supply, V_E — supply voltage value; M — switch modulating the power supply; $A_1, ..., A_4$ — emitting antennas connected to the chaotic oscillators; A_0 — receiving antenna; d — values of the distances between the receiving and transmitting antennas (1.75 m). Red dotted line — the generator power supply, green solid line — the modulating signal. OSC — digital storage oscilloscope. *b* — Photograph of an emitter consisting of an antenna, a generator of UWB chaotic radio pulses and a cross-board that controls the emitters (color online)

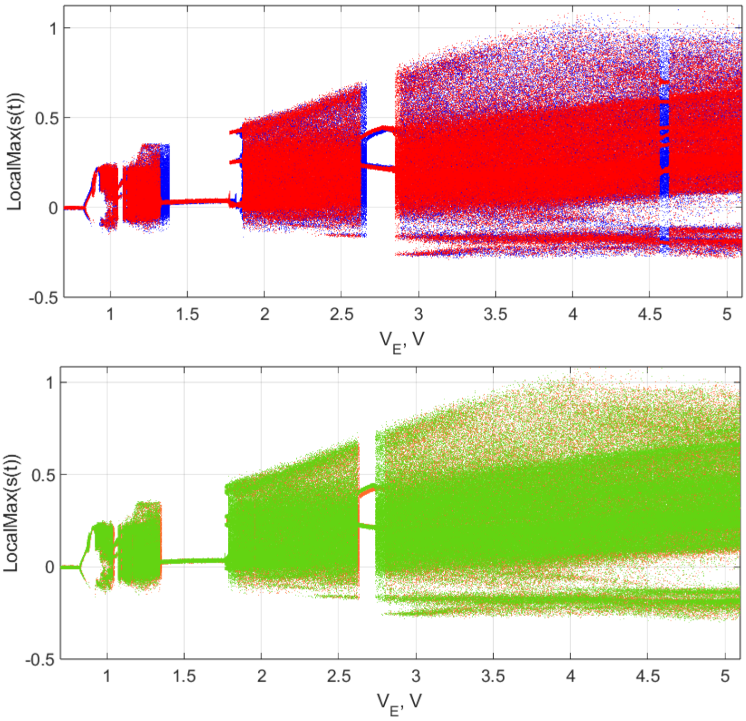


Fig. 2. Bifurcation diagrams of oscillation modes for the first pair of generators (1 and 2, blue and red), and the second (3 and 4, orange and green) obtained in the experiment (color online)

oscillatory circuit of the generator, becomes part of the dynamic system of the emitter, which affects the oscillation mode.

Solving the problem of reproducing pulses with the same shape requires solving two subtasks: repeating the shape of pulses generated by one generator, and repeating the shape of pulses generated by different generators and emitted using antennas.

In order to make sure that the various generators used in the experiment demonstrate the same operating modes and generate oscillations with the same characteristics, a study of their dynamic modes was conducted.

Using a digital oscilloscope, bifurcation diagrams of the dependence of the dynamic modes of the generators on the supply voltage were evaluated (Fig. 2). The diagrams were obtained by sequentially increasing the supply voltage in increments of 0.001 V, fixing the time realization of the generator signal and then selecting local maxima from these realizations.

The similarity of the bifurcation diagrams indicates a high degree of reproducibility of the oscillation modes in different instances of generators.

For further experiments, the mode corresponding to the supply voltage $V_E = 5$ V was selected, for which the generators demonstrate a chaotic oscillation mode. The dependence of the spectral power density on the frequency for this oscillation mode is shown in Fig. 3 (curves $G_1 ... G_4$).

1.2. Antennas. Standing wave ratio (SWR) of antennas used in this work are shown in Fig. 4. SWR measurement was carried out using the Libra VNA device [21], which provides SWR measurement in the range from 0 to 6 GHz.

Antennas with generators connected to them form an emitter that generates either a pulsed or continuous signal under the influence of an external modulating video signal. After passing through the wireless channel, the power spectrum of the continuous chaotic signal at the output of the receiving antenna has the form shown in Fig. 3.

1.3. Modulating system. The task of the emitters in this work is to generate pulses with the same waveform at specified time points. For certainty, we can assume that the center of the signal

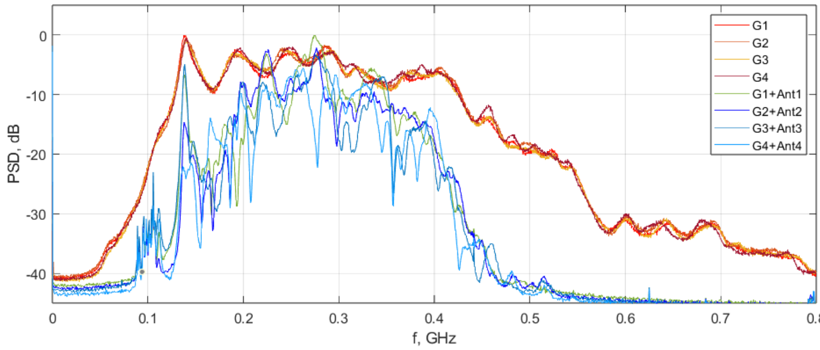


Fig. 3. Power spectral density of the signal at the chaotic oscillator outputs ($G_1...G_4$) and after passing the emitting and receiving antennas and the wireless channel ($G_1 + Ant_1...G_4 + Ant_4$) (color online)

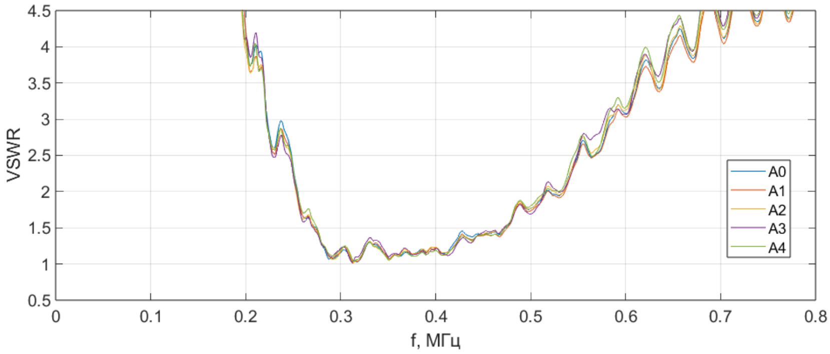


Fig. 4. Standing wave ratio of antennas used in the experiment: A_0 — receiving antenna, $A_1...A_4$ — transmitter antennas (color online)

frequency band is at 300 MHz, which corresponds to a wavelength of 1 m. To meet the condition of coherent summation of chaotic radio pulses, it is necessary that the mutual spatial shift in the arrival of pulses at the receiving point be less than one tenth of the wavelength, that is, 10 cm. This corresponds to the mutual time shift of pulse emission of 330 ps. The chaotic oscillator modulation system, which enable the simultaneous pulse generation with such precision, is implemented on the basis of the DE10–Lite FPGA breadboard.

The modulating system includes:

- a FPGA DE10–Lite breadboard equipped with a cross-board to which cables are connected to transmit modulating video pulses from the FPGA breadboard to each emitter, the cable length is 3 m;
- node for transmitting commands from a PC to a FPGA DE10–Lite breadboard (USB-UART converter);
- a software application equipped with a graphical interface running on a PC.

The Terasic DE10–Lite development board is based on the MAX10 family FPGA chip: 10M50DAF484C7G (Altera Corporation). The FPGA generates video pulses (modulating signals for the generators) of a specified duration with the ability to select the signal start moment. The latter is necessary to ensure the simultaneous arrival of UWB radio pulses at a given point in space. The selection of a particular pulse emission moment for each generator individually is determined with a high degree of accuracy using the FPGA's internal PLL circuits [22]. The PLL generates video pulses using clock pulses from the FPGA's internal crystal oscillator as an input signal. The PLL outputs are connected via the FPGA's I/O outputs to a cross-board, to which cables are connected for transmitting the modulating signal to the generators.

To visualize the selection of the mutual timeshifts between the modulating pulses, an application with a graphical interface has been developed, the tasks of which include calculating the mutual timeshifts between the modulating signals based on the known coordinates of the emitters and the receiving antenna and controlling the operation of the FPGA via the USB-UART channel.

Using the control system, during the experiment, the coordinates of the receiving/emitters point were entered in the graphical interface of the program; the necessary delays were calculated for the formation of modulating signals; the calculated delay values were sent to the FPGA; the FPGA generated modulating signals (periodic sequences of video pulses) for the emitters, taking into account individual mutual delays.

2. Experimental results

During the experiment, the following assumptions were tested:

- reproduction of the pulse shape after passing through the wireless channel;
- reproducibility of pulse shapes from different generators;
- the possibility of coherent addition of pulses at a given point in space.

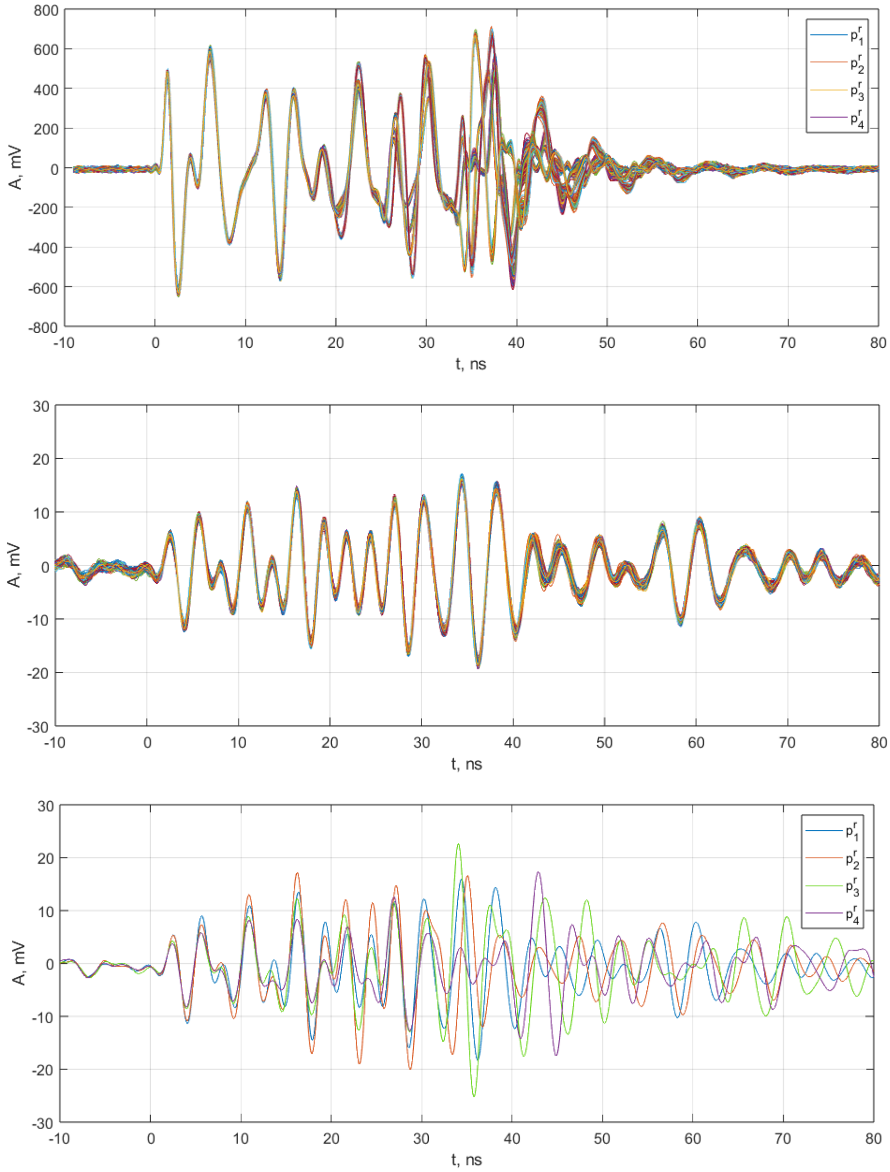
Before the experiment began, the airwaves at the receiving point were analyzed in the absence of a useful signal. This was necessary to assess how accurately pulse shapes could be reproduced, taking into account the presence of interference. In the operating frequency band, there was a significant level of interference associated with the operation of modern communication systems, therefore, when performing experiments on the receiving device, a filter was used, developed according to the methodology described in [23], which is consistent with the frequency-oscillation system of the chaos generator. The use of this filter has significantly reduced the level of interference signals in the operating frequency band of the system.

During the experiments, two situations were analyzed: incoherent summation of signals and coherent summation. As is known, with incoherent summation of delta-correlated random processes, their variances add up additively, which, means a linear increase in signal power at the receiving point with an increase in the number of emitters-independent sources [24]. With coherent summation, the amplitude of the total signal increases linearly. The design of this study allows us to evaluate both situations and, through comparison, determine the quantitative differences between incoherent and coherent summation of UWB chaotic signals. The experimental steps are described below: incoherent summation as a starting point and coherent summation..

2.1. The waveform of chaotic radio pulses. Before starting experiments on transmitting chaotic radio pulses via a wireless channel, it is necessary to make sure that the pulses of each generator and the pulses of different generators have the same shape. To do this, the signal was measured directly from the outputs of four generators before being fed to the emitting antenna (Fig. 5, *a*). The purpose of the measurement was to establish the identity of the waveform produced by the generators and to synchronize the moments of pulse emission by the generators, which is necessary for further measurements. The synchronization accuracy was set within 100 ps. Comparison of the pulse waveform of different generators shows that the initial fragments of the pulses coincide, the coherence time is approximately 35 ns, and then the oscillations diverge.

In the next step, the characteristics of the signals were measured after passing through the emitting system, channel and receiving antenna in the «point to point» mode (measurements were carried out for each emitter separately). To ensure that the pulse shape repeatability was maintained after passing through the wireless channel, their shapes were compared in two ways. Pulses from each generator were compared individually, and the average pulse profiles from different generators were compared. The results of this comparison are shown in Fig. 5, *b*, *c*. Fragments of the time realization of the signals of the four emitters at the receiving point were digitized using an oscilloscope with a sampling rate of 20 Gsmp/s. In Fig. 5, *b* shows 400 pulse waveforms from one of the emitters. In Fig. 5, *c* shows the result of averaging the pulse realizations of each of the emitters.

It can be seen from the presented data that the channel and antennas inevitably distort the original shape of the pulses, but despite this, the pulse shape remains repeatable both for each emitter individually and for different emitters. The data obtained at the waveform level convincingly proves that the basic condition of coherent summation, the similarity of the waveform, is observed.



a *b* *c*

Fig. 5. Pulse waveforms of four different generators, combined at the moment of their start and superimposed on each other: *a* — pulse waveforms of 400 pulses of each of the generators before feeding to the antenna, *b* — 400 pulses of one generator after emission by the antenna and passage of the radio channel, *c* — averaged pulse waveforms of 400 pulses of each of the generators after emission by the antenna and passage of the radio channel (color online)

2.2. Incoherent summation in space. Signal propagation and their reception at different points in space is an unpredictable process in which it is impossible to achieve complete identity of the emitters, as a result, they emit a signal with different power (and RMS amplitude). Moreover, after passing through the channel, the amplitude of each of the signals changes independently. Therefore, in order to correctly evaluate the result of adding chaotic signals by power, it is necessary to measure the power of each signal individually at a given receiving point. During the experiment, the emitters were turned on one at a time, the signal strength from each emitter was measured individually, and then the signal strength from one, two, three, and four simultaneously operating emitters was measured cumulatively.

As a result of the experiment, the signals from each emitter individually and the combined signals at the receiving point were recorded using an oscilloscope. The individual received signal powers from

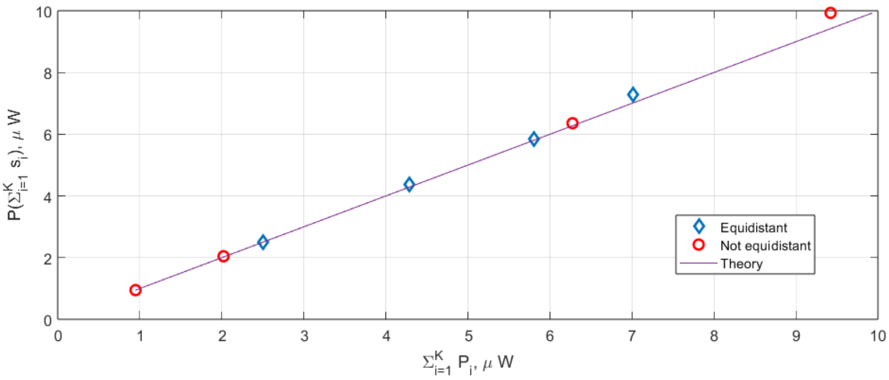


Fig. 6. Dependence of the total signal power of several emitters on the sum of the signal powers of the emitters, measured separately. Blue diamonds — the reception point is located at an equal distance from the emitters, red circles — the emitters are located at different distances from the reception point. The purple line is the theoretically expected picture (color online)

each emitter were estimated based on the signal realizations $P(s_i)$, $i = 1, 2, 3, 4$, and the power of the total signals from two, three, and four emitters $P(\sum_{i=1}^{K} s_i)$, $K = 1, 2, 3, 4$, where s_i is a continuous chaotic signal, and K is the number of simultaneously operating emitters.

In Fig. 6 shows the dependence of the total signal power from several emitters on the sum of $\sum_{i=1}^{K} P(s_i)$, $K = 1, 2, 3, 4$ the signal powers of the emitters measured individually.

Such measurements were performed for two scenarios: when the receiver was located at a point equidistant from the emitters, and at a point located at unequal distances from the emitters. In both cases, the measured values with good accuracy fit the theoretically expected dependence (diagonal): a linear increase in signal power at the receiving point with an increase in the number of UWB emitters of the chaotic signal.

2.3. Coherent summation. Since the experiment aimed to achieve coherent pulse summation, it was necessary to ensure the same signal reception conditions. The antennas used are not strictly omnidirectional, therefore it is highly desirable to ensure that the same mutual orientation of the emitting and receiving antennas is observed. In the case of emitting antennas located on the sides of a square, this can be achieved if the planes of all the antennas are located along the sides of the square, and the plane of the receiving antenna is oriented at an angle of 45 degrees to the side of the square.

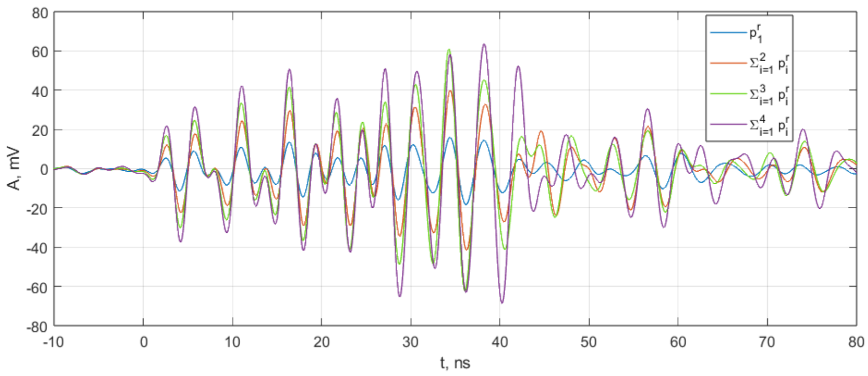
During measurements, it's difficult to achieve conditions under which the signal amplitudes arriving at the receiver from different emitters are completely identical. They most likely differ due to non-identical emitting antennas and non-isotropic signal propagation conditions. Therefore, to estimate the amplitude increase at the receiving point as the number of emitters increases, it's necessary to first determine the individual contribution of each emitter.

This is illustrated in Fig. 5, *c*, where it can be seen that the amplitude of the signal at the receiving point from each emitter is slightly different from each other and at its maximum is about 20 mV. At the same time, the pulse shapes are similar, that is, we can indeed expect their coherent summation. As noted in section 1.3, the necessary condition for this is the simultaneous arrival of pulses at the receiving point.

The result of the coherent summation was estimated by the nature of the change in the RMS value of the amplitude and waveform with an increase in the number of emitters in Fig. 7.

In Fig. 7, *a* shows a change in the waveform when the number of emitters increases from one to four. The pulse shapes are similar to each other, and their amplitude increases in proportion to the number of emitters.

For comparison, similar measurements were conducted (Fig. 7, *b*) with the receiving antenna offset from the center of the square so that the distances from the receiving antenna to each emitter were different. In this case, the pulses arrive at the receiving point with different mutual time delays, inconsistent with the receiving point. Therefore, the condition of coherent summation is violated, the



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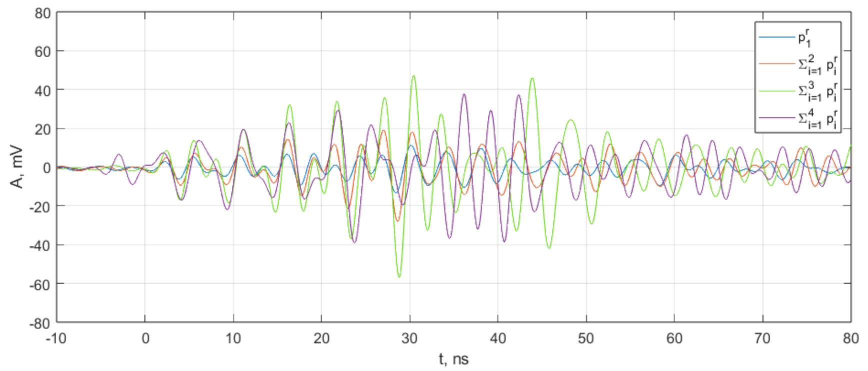

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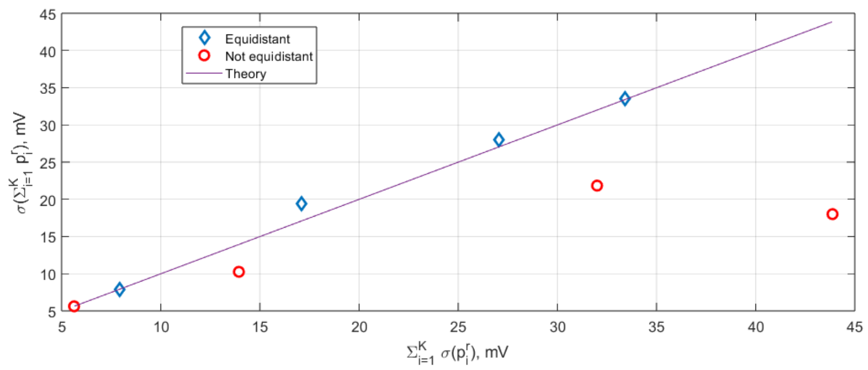

c

Fig. 7. *a* — Averaged pulse shapes of the sum signal of one, two, three and four emitters at the reception point located equidistant from the emitters. *b* — Averaged pulse shapes of the sum signal of one, two, three and four emitters at different distances from the reception point. *c* — Dependence of the root-mean-square amplitude of the sum signal of several emitters on the sum of the root-mean-square amplitudes of the emitter signals measured separately. Blue diamonds indicate that the reception point is equidistant from the emitters, red circles indicate that the emitters are located at different distances from the reception point. The purple line is the theoretically expected pattern (color online)

pulse shapes are not similar, and their amplitude is not directly related to the number of emitters. That is, the amplitude increases, but there is no linear relationship..

This is clearly seen in Fig. 7, *c*, which shows the dependence of the RMS amplitude of the total signal from two, three and four emitters at the receiving point $\sigma(\sum_{i=1}^{K} p_i^r)$, $K = 1, 2, 3, 4$, where p_i^r is a chaotic pulse signal, and K is the number of simultaneously operating emitters, from the sum of $\sum_{i=1}^{K} \sigma(p_i^r)$, $K = 1, 2, 3, 4$ RMS amplitudes of the pulse signals of individual emitters.

Conclusion

This paper experimentally demonstrates the feasibility of coherent summation of UWB chaotic signals arriving at a given point in space from several separate emitters of UWB chaotic radio pulses.

Solving this problem required developing a method for generating UWB chaotic radio pulses with identical shapes, generated by different (separate) chaotic oscillators. The generators are completely analog devices, modulated by video pulses.

A control system has been developed that can implement coherent summation of pulse signals from independent emitters at an arbitrary point in space.

A linear increase in the amplitude of the UWB chaotic signal at the receiving point with an increasing number of emitters is demonstrated, provided the pulses are coordinated and arrive coherently at the receiving point, and a linear increase in power provided the UWB chaotic signal is summed incoherently.

The obtained results show that predictable results can be obtained in analog systems with chaos, based on the sensitivity of chaotic oscillations to initial conditions, which creates a basis for the further development of wireless systems based on UWB chaotic signals, where such an important and interesting physical phenomenon as the coherent addition of radio signals in space is used.

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