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## METHOD OF WIRELESS TRANSMISSION OF DIGITAL INFORMATION ON THE BASIS OF ULTRA-WIDE SIGNALS

**Abstract.** The subject of the study are the organization of wireless transmission of digital information based on ultra-wideband signals. The goal is the development of models and methods for organizing broadband wireless communications operating in difficult interference environments. The task is to ensure the stable and safe operation of communication systems. The methodology is based on the method of generating ultra-wideband digital signals and the method of extracting ultra-wideband information signals in the communication channel with interference. The methods used: methods of analytical, simulation and inverse Fourier transform. The following results are obtained. A technique has been developed for wireless transmission of digital information based on ultra-wideband signals, which includes a method for generating ultra-wideband information signals with code spectral modulation and a method for extracting information signals in a communication channel with interference. An assessment of the effect of interference on the quality of the information being restored is performed. A special class of intra-system interference has been identified, which appears due to the multiplicity of delays in the information bit stream  $T_0$  or  $T_1$ . It is shown that their appearance leads to an increase in the bit error when extracting information signals in the communication channel. A mechanism is proposed for eliminating these errors by setting the multiple delays  $T_0$  and  $T_1$  when generating ultra-wideband information signals. **Conclusions.** The use of communication channels with an ultra-wide frequency band makes it possible to simultaneously implement a set of requirements for the electromagnetic compatibility of telecommunication systems, high-speed transmission of information with high noise immunity with respect to external interference.

**Keywords:** ultra-wideband signal; wireless transmission; correlation technique; coherence.

### Introduction

The rapid development of communication devices and their widespread practical application in private life for "smart homes" and at work (Industry Internet of Things - IIoT) in the implementation of the concept of "spatial intelligence" [1-3] requires the organization of communication between devices by introducing wireless digital information transfer. However, mobile wireless networks today are faced with two trends that will become in conflict with each other. The growth of the processing power of mobile terminals entails the growth of the processing capacity of applications running on them. This, in turn, leads to an increase in bandwidth requirements for mobile communication channels. It should be noted that the volume of mobile traffic is growing exponentially, and its appearance is becoming more diverse.

At the same time, the efficiency of the available frequency spectrum is close to saturation. The maximum bandwidth that can be achieved is approaching (within  $\approx 20\%$ ) to the border with Shannon. And further improvements are likely to be too expensive to implement and provide only limited benefits.

In order to cope with such a significant increase in traffic, modern telecommunication systems must provide the possibility of noise immunity of transmitting digital information in a wireless network at a speed of 1-2 Mbps, the probability of error per bit of information is at least  $10^{-5}$  and low radiation power in the frequency band up to 10 GHz. The 10 GHz frequency band is due to the fact that less attenuation of the radio signal that propagates in free space is observed in this frequency range [4, p.34].

An analysis of existing technological solutions [5] shows that they do not have the possibility of simultaneously implementing a set of modern requirements for high data transfer rates, the requirements of electromagnetic compatibility of telecommunication systems and their noise immunity with respect to external noise and interference, as well as countering the multipath propagation of radio signals. Therefore, the development of models and methods for organizing ultra-wideband (UWB) wireless communications, corresponding to a complex of modern requirements, is an extremely urgent problem.

### 1. Analysis of technical solutions

An analysis of existing and promising technical solutions in the field of organizing UWB wireless communications, conducted in 2002 by the US Federal Communications Commission [5], proved that the main place to use UWB signals is wireless personal area networks (WPAN), which have a low cost equipment and low power consumption. The Commission also proposed a frequency range (3.1 ... 10.6 GHz) and a power spectral mask for unlicensed UWB communication systems ( $-41.3$  dBm / MHz) [5].

Previously, ultrashort pulses (frequency band of 7.5 GHz, pulse length of 150 nsec.) were used as an information carrier to increase the speed of information transfer when implementing UWB communication.

In addition, each pulse corresponds to one bit of information, which makes signal processing at the receiver very simple. Use of this technology is included in the IEEE 802.15.3a standard. However, due to limitations on the amplitude, the distance for transmission does not exceed 10 m., which is a significant limitation

for its use. To eliminate this limitation and increase the communication range, the signal level should be increased to 3 V, which contradicts the tendency to reduce the supply voltage and power consumption. Even more problems arise if it is necessary to ensure a transmission range of more than 50-60 m.

The solution to this problem is the transition from the transmission of one bit by one pulse to the transmission of one bit of information by a series of pulses [6]. In this case, while maintaining the radiation energy by one bit, it is possible to reduce the energy that falls on one pulse proportional to the number of pulses in a series. This means moving from signals with a single base to signals with a large base. Moreover, the basis of an ultrashort pulse signal is the product of the signal duration by the width of its spectrum.

The use of a sequence of ultrashort pulses for encoding an information bit is proposed in the IEEE 802.15.4a standard. However, in this case, the radiation signal in the framework of the implementation of this standard impose certain restrictions:

1. The maximum spectral density of UWB signals is limited to -41.3 dBm/MHz. Therefore, even when using the entire permitted range, the integrated radiation power should not exceed -2.4 dBm.

2. Limit peak power. It should not exceed 0 dBm in the 50 MHz band. Thus, for the frequency band of 500 MHz, we have limitations of 20 dBm, and for the band of 2 GHz - 32 dBm.

3. Typically, the supply voltage of UWB communication systems in unlicensed systems does not exceed 2 V. Therefore, the voltage to the antennas will not exceed 1 V. Thus, when the antenna is matched to 50 Ohms, the peak power should be limited to 10 mW.

### 2. Methods of wireless transmission of digital information on the basis of UWB signals

Information is transmitted in radio systems with UWB spectrum by simultaneously emitting a coherent reference signal and a modulated information signal. In this case, the frequency range for communication systems is selected based on the requirements for the frequency resource for the unlicensed use of UWB signals with a low power of isotropic radiation, does not exceed the established limit [5].

#### 2.1 Method for the formation of UWB information signals with code spectral modulation

An ultrawideband signal is formed in the form of a normal random process  $n(t)$  with a zero mean value, a uniform spectrum  $S(f)$  a frequency band  $\Delta f$  and a short-range correlation  $R_n(\tau) = \sigma_n^2 R_n(\tau)$  for a short coherence time  $\tau_c = 1/\Delta f$ . The variance  $\sigma_n^2$  characterizes the average power of a random signal  $n(t)$ .

The functional diagram that implements the proposed method is shown in Fig. 1.

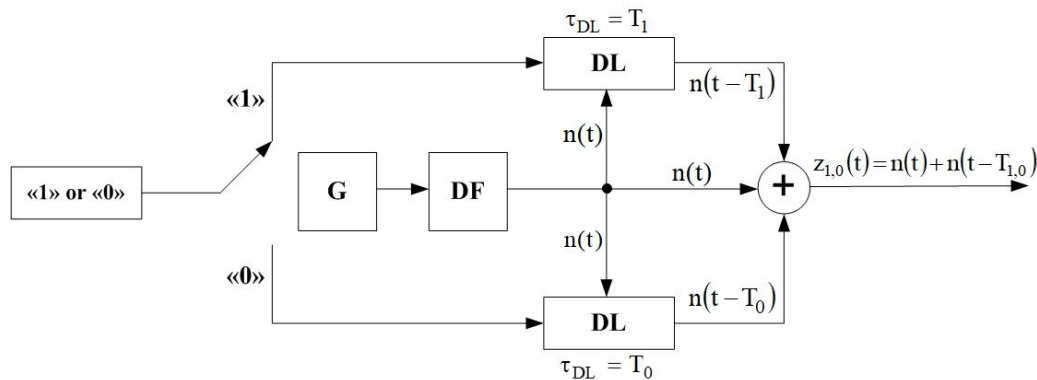


Fig. 1. Functional diagram of the formation of ultra-wideband information signals

The generator (G) in self-oscillating mode generates a sequence of ultrashort pulses - chips with a period of arrival  $t_d$ , which is fed to the input of a digital bandpass filter (DF), which generates a signal  $n(t)$ . From the output of the DF, the ultra-wideband signal  $n(t)$  goes to the input of the modulator, in which the division into information and reference signals is carried out. The transmission rate of information binary bits  $C_B$  depends on the duration  $T_B$  of each information bit  $C_B = 1/T_B$ . The number of chips on the duration of each information bit determines the following ratio  $N_B = T_B/t_d$ .

It was noted that all implementations of a random signal in a stream of information bits are mutually orthogonal.

The modulator has two delay lines. The reference sequence of chips of the information signal is delayed in

the first line at the time  $T_1$  upon receipt of the symbol «1», or in another delay line at the time  $T_0$  upon receipt of the symbol «0». Switching delay lines from  $T_1$  to  $T_0$  is performed respectively by the stream of binary bits «1» or «0» from the information source. The channel switching process is shown in Fig. 1.

Moreover, we believe that the transmission coefficients  $H_{1,0} = h_{1,0} \cdot \exp(i\theta_{1,0})$  and the delay  $T_{1,0}$  of both lines are independent of the frequency  $f$  in the UWB band  $\Delta f$  of the signal  $n(t)$  so that the following conditions are met:

$$h_1 = h_0 = 1; \theta_1 = \theta_0 = 0. \tag{1}$$

In the linear adder, the reference signal  $n(t)$  is added to one of the UWB chips of the signals delayed by the time  $T_1$  or  $T_0$  depending on the arrival of the characters «1» or «0».

$$Z_{1,0}(t) = n(t) + n(t - T_{1,0}), \quad (2)$$

where  $Z_{1,0}(t)$  – total signal;  $n(t)$  – UWB reference signal;  $n(t - T_{1,0})$  – information chip, delayed for a while  $T_{1,0}$ .

The power spectrum of the total UWB signal  $Z_{1,0}(t)$  is calculated over a duration time  $T_B$  of one information symbol modulated by a periodic function in the form:

$$\hat{S}_z(f) = 2\hat{S}_n(f) \cdot \left(1 + \cos(2\pi f T_{1,0})\right), \quad (3)$$

where  $\hat{S}_z(f)$  and  $\hat{S}_n(f)$  are random estimates of the power spectrum for the total  $Z_{1,0}(t)$  and reference  $n(t)$  UWB signals for a finite analysis time  $T_B$ .

Compilation of completely incoherent signals occurs when delays  $T_0$  and  $T_1$  of information signals  $n(t - T_1)$  and  $n(t - T_0)$  relative to the reference signal  $n(t)$  significantly exceed the coherence time

$$\tau_c \approx 1/\Delta f$$

UWB signal  $n(t)$ :

$$T_{1,0} \gg \tau_c \quad \text{or} \quad T_{1,0}(\Delta f) \gg 1. \quad (4)$$

In the case of interference of completely incoherent UWB signals, when conditions (4) are satisfied, the spectral density (3) is modulated by a harmonious function depending on the frequency  $f$  with a periodicity scale equal to

$$\delta \cdot f_{1,0}(t) = 1/T_{1,0}.$$

Power spectra calculated over a finite time  $T_B$ , equal to the length of the information bit are random functions. The frequency band of UWB signals is  $\Delta f$ , and the coherence time is on the order of

$$\tau_c \approx 1/\Delta f.$$

The power of the total UWB signal  $Z_{1,0}(t)$  determines its dispersion  $\sigma_z^2$  and is equal to twice the power

$$\sigma_z^2 = 2\sigma_n^2$$

of the initial signal  $n(t)$  under conditions of complete incoherence of the reference and delayed UWB signals [7, 8]. The total signal from the transmitter output enters the communication channel with additive Gaussian white noise.

We assume that the transmission coefficient of the communication channel does not depend on the frequency and is equal to unity in the band  $\Delta f$  of the UWB signal  $n(t)$ .

## 2.2 Method for extracting information UWB signals in a communication channel with interference

The received signal in the form of an additive mixture of the total signal and the Gaussian noise is fed to the input of the DF with the same passband  $\Delta f$ , as in the transmitter (Fig. 2).

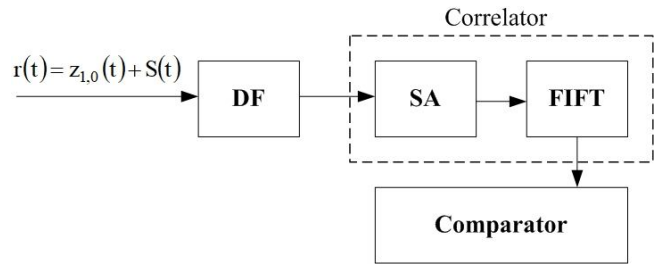


Fig. 2. Functional diagram of the receiver with UWB signal processing

At the output of the DF filter, a signal is generated in the form of the sum of the transmitted UWB signal  $Z_{1,0}(t)$  and the Gaussian noise spectrum  $S(t)$  matched by the spectrum.

$$\begin{aligned} r(t) &= Z_{1,0}(t) + S(t) = \\ &= \left(n(t)n(t - T_{1,0})\right) + S(t). \end{aligned} \quad (5)$$

The interference  $S(t)$  has a dispersion  $\sigma_s^2$  with a fast-falling correlation

$$R_s(\tau) = \sigma_s^2 R_s(t)$$

and the uniform spectrum  $S_s(t)$  in the same frequency band  $\Delta f$ , as for the information signal  $Z_{1,0}(t)$ . The signal-to-noise ratio (SNR) at the receiver input determines the ratio of the received signal power and Gaussian interference in the form

$$q = \sigma_z^2 / \sigma_s^2 = 2\sigma_n^2 / \sigma_s^2.$$

We assume that the useful signal is  $Z_{1,0}(t)$  and random interference  $S(t)$  is completely incoherent with each other.

Then the power spectrum for the received signal  $r(t)$  is defined as:

$$\begin{aligned} \hat{S}_r(f) &= \\ &= 2\hat{S}_n(f) \cdot \left(1 + \cos(2\pi f T_{1,0})\right) + \hat{S}_s(f). \end{aligned} \quad (6)$$

Spectrum (6) has the function of periodically modulated in frequency according to the bit stream and component  $\hat{S}_s(f)$  in the form of an interference spectrum. In formula (6), the spectra  $\hat{S}_r(f)$ ,  $\hat{S}_n(f)$  and  $\hat{S}_s(f)$  for the received signal  $r(t)$ , reference signal  $n(t)$  and interference  $S(t)$  are random estimates for a finite time duration  $T_B$ , information transfer bit.

The solution to the problem of removing UWB information signals in a communication channel with interference is carried out by the inverse Fourier transform of the measured power spectrum (6) for the received signal (5) [9].

The receiver coherently compresses the received UWB signals (5) into the frequency band of the transmitted messages according to the results of double spectral analysis.

The expected correlation  $R_r(\tau)$  is calculated from the inverse Fourier transform of the measured power spectrum  $S_r(\omega)$ ,  $\omega = 2\pi f$  the received signal  $r(t)$ .

$$R_r(\tau) = \int_{-\infty}^{\infty} S_r(\omega) e^{j\omega\tau} d\omega. \quad (7)$$

The complex autocorrelation function calculated by formula (7) using relation (6) for the power spectrum of the received signal (5) has the following form:

$$\begin{aligned} \hat{R}_r(\tau) = \\ = \sigma_n^2 [2\hat{R}_n(\tau) + \hat{R}_n(\tau - T_{1,0})] + \sigma_s^2 \hat{R}_s(\tau). \end{aligned} \quad (8)$$

The complex autocorrelation function of the received signal has an information correlation peak  $\sigma_n^2 \hat{R}_n(\tau - T_{1,0})$  with offset  $T_1$  or  $T_0$  according to the binary bit stream (1; 0). also has autocorrelation functions  $2\sigma_n^2 \hat{R}_n(\tau)$  and  $\sigma_s^2 \hat{R}_s(\tau)$  for the reference UWB signal  $n(t)$  with double power  $2\sigma_n^2$  and external interference  $S(t)$  with power  $\sigma_s^2$ .

The correlator in the receiver (Fig. 2) has a digital AS spectrum analyzer and a digital Fourier processor - BZPF.

At the output of the digital spectrum analyzer, during  $T_b$  of each transmitted bit, the power spectrum of the received UWB signal is determined in the form (6). The digital Fourier processor performs fast inverse Fourier transform for an array of digital reviews, which are formed at the output of the AS spectrum analyzer.

Based on the results of double spectral processing during the appearance of each bit of information, the quadrature components for the complex autocorrelation function (8) are determined in the form:

$$\hat{R}_{r,\cos}(\tau) = 2 \int_0^{\infty} S_r(f) \cos(2\pi f\tau) df; \quad (9, a)$$

$$\hat{R}_{r,\sin}(\tau) = 2 \int_0^{\infty} S_r(f) \sin(2\pi f\tau) df. \quad (9, b)$$

The module for the complex autocorrelation function is calculated as the mean square value of the real and imaginary parts in the form:

$$|\hat{R}_r(\tau)| = \left[ \hat{R}_{r,\cos}^2(\tau) + \hat{R}_{r,\sin}^2(\tau) \right]^{1/2}. \quad (10)$$

The quadrature components  $\hat{R}_{r,\cos}(\tau)$  and  $\hat{R}_{r,\sin}(\tau)$  of the complex autocorrelation function  $\hat{R}_r(\tau)$  are determined by the fast inverse Fourier transform using the basic functions  $\cos(\omega\tau)$  and  $\sin(\omega\tau)$  from  $T_1$  or  $T_0$  the power spectrum (6) for the received signal [10].

The comparator at the output of the digital Fourier processor (Fig. 2) compares the information correlation peaks with a shift of  $T_1$  or  $T_0$  for module (10) and

determines from them the largest correlation peaks that correspond to the transmitted bit «1» or «0». Thus, the receiver performs unambiguous restoration of the transmitted binary information.

### 2.3 Assessing the impact of interference on the quality of information recovery

The influence of external noise in the communication channel is accompanied by an increase in random outliers for the autocorrelation function  $\hat{R}_r(\tau)$  in the region of information peaks  $2\sigma_n^2 \hat{R}_n(\tau - T_{1,0})$  with a shift  $\tau = T_{1,0}$  which leads to an increase in the error when restoring the transmitted binary information to the receiver.

Level of random lateral emissions for the module  $|\hat{R}_r(\tau)|$  depends on the shift  $\tau$ , which complicates the procedure for subsequent extraction of the transmitted information. Under the influence of external noise, the relative value of information peaks with a shift of  $\tau = T_{1,0}$  decreases. Abnormally large lateral emissions for the module  $|\hat{R}_r(\tau)|$  observed at multiple shifts  $\tau = jT_{1,0}$  ( $j=2,3,4$ ). First of all, this concerns the double delay multiplicity  $\tau = 2T_{1,0}$  both in the absence of interference and under the influence of interference in the communication channel.

Lateral outliers with a triple delay  $\tau = 3T_{1,0}$  are characterized by a lower amplitude so that they are difficult to identify by the arrival of one information bit.

The autocorrelation functions  $2\sigma_n^2 \hat{R}_n(\tau)$  and  $\sigma_s^2 \hat{R}_s(\tau)$  also have correlation peaks with zero shift  $\tau = 0$ . The total value of the correlation peaks  $2\sigma_n^2 \hat{R}_n(0)$  and  $\sigma_s^2 \hat{R}_s(0)$  with a zero shift  $\tau = 0$  can significantly exceed the level of information peaks  $\sigma_n^2 \hat{R}_n(\tau - T_{1,0})$  when exposed to powerful interference.

Long-range random outliers for the autocorrelation functions  $2\sigma_n^2 \hat{R}_n(\tau)$  and  $\sigma_s^2 \hat{R}_s(\tau)$  with a time shift  $\tau \gg \tau_c$  also reach the position of information peaks  $\sigma_n^2 \hat{R}_n(\tau - T_{1,0})$  with offset  $T_1$  or  $T_0$  and affect them, which leads to a shift in the estimate for information peaks and an increase in bit error during information retrieval at the receiver.

Thus, a special class of intra-system interference is determined due to the multiplicity of information delays  $T_0$  or  $T_1$ .

Random emission of correlation peaks with multiple landslides  $jT_{1,0}$  ( $j=2,3,4$ ) lead to an increase in the bit error for UWB communication systems when multiple delays  $T_0$  and  $T_1$  are set when applying code modulation during transmission, for example,

$$T_1 = 2T_0; T_1 = 3T_0.$$

So, under conditions of double multiplicity  $T_1 = 2T_0$  the position of the information peak with a

shift  $T_1$  is combined with the position of the lateral correlation peak with a multiple delay of  $2T_0$ .

When transmitting a «0» bit with a delay  $T_0$  abnormally high fluctuations occur with a multiple offset of  $2T_0$  for the autocorrelation function module  $|\hat{R}_r(\tau)|$  at the location of the information peak  $T_1$ . As a result, the probability of an erroneous decision in registering a «1» bit increases, when in reality a «0» bit is transmitted. Elimination of additional intra-system interference due to the multiplicity of information delays in UWB communication systems consists in the set of multiple delays  $T_0$  and  $T_1$  among themselves in the process of code spectral modulation of UWB signals in the transmitter. Indeed, with multiple delays  $T_0$  and  $T_1$  for information UWB signals, the important condition  $T_1 \neq jT_0$  ( $j=2,3,4$ ) is fulfilled.

In this case, there **is no overlap** in the secondary spectrum of the position for the information peak  $T_1$ , which corresponds to «1» bit, and the position for side peaks with multiple landslides  $jT_0$ , which occur during the transmission of «0» bits. Moreover, random outliers at lateral correlation peaks with multiple landslides  $jT_0$  ( $j=2,3,4$ ) do not affect the reliability of binary symbol transmission under conditions  $T_1 \neq jT_0$  when delays are not multiple.

### 3. Analysis

The information signals in the interference communication channel are removed by the inverse Fourier transform from the measured power spectrum for the received signal, whose autocorrelation function is an information correlation peak with a shift  $T_1$  or  $T_0$  according to the binary bit stream and the autocorrelation function for the reference signal and external interference. Further comparison of information correlation peaks with a shift of  $T_1$  or  $T_0$  determines the largest of them, which corresponds to the transmitted bit «1» or «0».

The influence of external noise in the communication channel is accompanied by an increase in additional random outliers for the autocorrelation function in the region of information peaks, which leads to an increase in the error in recovering the transmitted binary information in the receiver, especially due to the multiplicity of information delays  $T_0$  or  $T_1$ . The elimination of these additional intra-system interference consists in the establishment of multiple delays  $T_0$  and  $T_1$  in the process of code spectral modulation of ultra-wideband signals in the transmitter.

### Conclusions

The developed technique for wireless transmission of digital information on the basis of ultra-wideband signals, which includes a method for generating information signals with code spectral modulation and a method for extracting information signals in a communication channel with interference. The impact of interference on the quality of the recovered information has been evaluated. It is shown that the use of communication channels with an ultra-wide frequency band makes it possible to simultaneously implement a set of requirements for the electromagnetic compatibility of telecommunication systems, high speed information transfer and noise immunity with respect to external noise and interference.

### Thanks

This work was partially funded by the European Union in the context of the project “dComFra - Digital competence framework for Ukrainian teachers and other citizens” (Project Number: 598236-EPP-1-2018-1-LT-EPPKA2-CBHE-SP) under the ERASMUS + program. The European Commission's support for the creation of this work does not mean full approval of its content, which reflects only the views of the authors. The Commission cannot be held responsible for any use of the information posted in this work.

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Received (Надійшла) 16.09.2019

Accepted for publication (Прийнята до друку) 13.11.2019

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#### Методика безпроводової передачі цифрової інформації на ґрунті надширокопосмугових сигналів

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**Анотація.** Предметом вивчення є організація безпроводової передачі цифрової інформації на ґрунті надширокопосмугових сигналів. **Мета** – розробка моделей і методів організації надширокопосмугового безпроводового зв'язку, що працює в умовах складної заводої обстановки. В основу **методики** покладено метод формування надширокопосмугових цифрових сигналів та метод вилучення надширокопосмугових інформаційних сигналів в каналі зв'язку з завадами. **Задача** – забезпечення усталеної та безпечної роботи системи зв'язку. Використані **методи**: методи аналітичного, імітаційного моделювання та зворотнього перетворення Фур'є. Отримані наступні **результати**. Розроблена методика безпроводової передачі цифрової інформації на ґрунті надширокопосмугових сигналів, до складу якого включено метод формування надширокопосмугових інформаційних сигналів з кодовою спектральною модуляцією та метод вилучення інформаційних сигналів в каналі з завадами. Виконана оцінка впливу завод на якість передаваної інформації. Виявлено особливий клас внутрішньосистемних завод, які з'являються внаслідок кратності затримок в інформаційному потоці бітів  $T_0$  або  $T_1$ . Показано, що їх поява призводить до підвищення бітової похибки під час вилучення інформаційних сигналів в каналі зв'язку. Запропоновано механізм усунення цих похибок шляхом встановлення некротних затримок  $T_0$  і  $T_1$  під час формування надширокопосмугових інформаційних сигналів. **Висновки.** Використання каналів зв'язку із надширокою смугою частот дає можливість одночасної реалізації комплексу вимог по електромагнітній сумісності телекомунікаційних систем, великій швидкості передачі інформації з високою заводостійкістю по відношенню до дії зовнішніх завод.

**Ключові слова:** надширокопосмуговий сигнал; безпроводова передача; кореляційний прийом; когерентність.

#### Методика беспроводной передачи цифровой информации на основе сверхширокополосных сигналов

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**Аннотация.** Предметом изучения является организация беспроводной передачи цифровой информации на основе сверхширокополосных сигналов. **Цель** - разработка моделей и методов организации широкополосной беспроводной связи, работающей в условиях сложной помеховой обстановки. В основу **методики** положены метод формирования сверхширокополосных цифровых сигналов и метод извлечения сверхширокополосных информационных сигналов в канале связи с помехами. **Задача** - обеспечение устойчивой и безопасной работы систем связи. Используются **методы**: методы аналитического, имитационного моделирования и обратного преобразования Фурье. Получены следующие **результаты**. Разработана методика беспроводной передачи цифровой информации на основе сверхширокополосных сигналов, в состав которой включены метод формирования сверхширокополосных информационных сигналов с кодовой спектральной модуляцией и метод извлечения информационных сигналов в канале связи с помехами. Выполнена оценка влияния помех на качество восстанавливаемой информации. Выявлен особый класс внутрисистемных помех, которые появляются вследствие кратности задержек в информационном потоке битов  $T_0$  или  $T_1$ . Показано, что их появление приводит к повышению битовой ошибки при извлечении информационных сигналов в канале связи. Предложен механизм устранения этих ошибок путем установки некротных задержек  $T_0$  и  $T_1$  при формировании сверхширокополосных информационных сигналов. **Выводы.** Использование каналов связи со сверхширокой полосой частот дает возможность одновременной реализации комплекса требований по электромагнитной совместимости телекоммуникационных систем, большой скорости передачи информации с высокой помехоустойчивостью по отношению к действию внешних помех.

**Ключевые слова:** сверхширокополосный сигнал; беспроводная передача; корреляционный прием; когерентность.