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REDUCING THE IMPACT OF INTERCHANNEL INTERFERENCE ON THE EFFICIENCY OF SIGNAL TRANSMISSION IN TELECOMMUNICATION SYSTEMS OF DATA TRANSMISSION BASED ON THE OFDM SIGNAL

Anatoliy Makarenko
Doctor of Technical Sciences*
Nameer Qasim
PhD, Associate Professor
Department of Cybersecurity and Computer Engineering
Kyiv National University of Construction and Architecture
Povitroflotsky ave., 31, Kyiv, Ukraine, 03037
Oleksandr Turovsky
Corresponding author
Doctor of Technical Sciences, Professor
Department of Information Protection
National Aviation University
Liubomyra Huzara ave., 1, Kyiv, Ukraine, 03058
E-mail: s19641011@ukr.net
Nataliia Rudenko
PhD, Associate Professor, Head of Department*
Konstiantyn Polonskyi
Postgraduate Student**
Oleg Govorun
Postgraduate Student*
*Department of Mobile and Videoinformation Technologies***
Department of Telecommunication Systems and Networks*
***State University of Telecommunications
Solomyanska str., 7, Kyiv, Ukraine, 03110

This paper considers the process that forms an interchannel transient interference in the structure of the signal created on the basis of the technology of parallel data transmission and frequency distribution with multiplexing of the phase-modulated signal – the OFDM signal.

Based on the analysis of the OFDM signal structure, it was determined that changes in the position and parameters of the carrier symbol from the composition of this OFDM symbol create an interchannel transient interference.

A list of OFDM signal parameters that can affect the appearance of interchannel interference and the value of its quantitative value was summarized and presented. A model for assessing the impact of interchannel interference on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal has been developed and proposed.

Based on mathematical modeling using this model, the dependence of the quantitative assessment of the magnitude of the interchannel interference on the magnitude of the protective interval for different values of the interchannel value with a different number of signal pre-reception has been established. It is shown that an increase in the value of the interchannel value to 96 subchannels makes it possible to achieve an interchannel transient interference of less than 3 percent with a protective interval of more than 2 ms already with one pre-reception. This is explained by the fact that the increase in the interchannel value makes it possible to reduce the value of the protective interval and minimizes the effect of frequency distortions of the sub-channel of one channel.

The data reported in this work and the recommendations substantiated on their basis confirm the possibility of the proposed model for assessing the value of the interchannel transient interference and justifying the recommendations for reducing its impact on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal.

The proposed evaluation model can find practical application in improving existing and developing new telecommunication data transmission systems based on OFDM technology

Keywords: OFDM signal, subcarrier frequency, interchannel quantity, interchannel transient interference, protective interval

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1. Introduction

The method of simultaneous transmission of data flow over several digital frequency channels, defined as OFDM technology, is widely used in modern broadband systems for digital information transmission over multi-beam channels.

The OFDM technology implements a mechanism in which a usable signal is distributed over subcarrier frequencies as part of a single OFDM symbol. At the same time, in the case of interference of certain sub-carriers, part of the data is withdrawn from further processing and does not affect the further integrity and quality of processing of incoming information. The basis of this mechanism is the distribution of the input data stream over individual carrier frequencies (sub-carriers), increased, relative to the delay time of the symbol of the duration of channel symbols and the introduction of a time protective interval between adjacent channels [1, 2].

OFDM technology has a number of advantages, which include high spectral efficiency and data transfer rate, the ability to influence the signal-to-noise ratio and, as a result, relative independence from external interference. The positive side is also simple algorithms for processing data packets based on Fourier fast transform algorithms and the simplicity of hardware implementation while it is possible to ensure simultaneous transmission of signals of different spectrum over one network [3, 4].

At the same time, the disadvantages of this technology include high sensitivity to the offset of the frequency and phase of the input signal relative to the reference oscillation and low energy efficiency [3–5].

Analysis of the spectral density of one elementary OFDM symbol and the technology and theory of its construction make it possible to determine that one of the groups of parameters that can affect its effectiveness is the position and parameters of each carrier.

The noise immunity of the OFDM signal is ensured by the number of sub-carriers, which must, first of all, occupy their position in the frequency distribution of the OFDM symbol for reliable and complete transmission of usable data. Carrier parameters should be considered from the point of view of propagation of a radar wave of a certain frequency and spectral density of the signal. The specified radio wave forms one data transmission channel through which a discrete signal is transmitted, which has its own parameters and structure of construction [2, 5].

Changing the parameters of the radar wave of the data transmission channel can form a phenomenon that is defined as an interchannel transient interference. Its essence is the offset of the carrier from the established position in frequency in the signal system. This leads to the formation, the effect of a given offset subcarrier on neighboring ones in the form of harmful electronic perturbation. Thus, an interchannel transient interference (ITI) is generated. Its consequence is the distortion of a certain number of sub-carriers and their loss of part of the usable signal, which leads to a general distortion of the input signal and the loss of part of the data in the telecommunications network.

The appearance of these distortions in the form of ITI represents a separate scientific task for the evaluation of ITI and the justification of recommendations for reducing its impact on the efficiency of signal transmission by the telecommunications network of data transmission of the OFDM signal.

2. Literature review and problem statement

Several studies [2, 3, 6–10] addressed the issues of increasing the efficiency of data transmission against the background of ensuring high noise immunity under the influence of various types of interference and disturbances in telecommunication systems operating on the basis of the use of OFDM signals [2, 3, 6–10].

General issues of formation of a single symbol based on OFDM technology, ensuring its stability and noise immunity are covered in papers [2, 3]. Against the background of consideration of the principles of construction, the main advantages and disadvantages of OFDM technology, which are set out in work [2], it generally lacks coverage of the problem of internal symbolic interference and perturbations.

Consideration of the issues of solving the problem of using OFDM technology in the 4G mobile network, which is set out in [3], does not take into account the processes of occurrence of internally symbolic perturbations, the formation of internal obstacles of a different nature due to them. Direct assessment of the impact of these interference on the operation of telecommunication systems is not considered in the cited paper.

Work [6] considers the model of joint selection of subcarriers and the calculation of their parameters under conditions of non-orthogonal signal multiplexing (NC-OFDM). This OFDM technology is characterized by the presence of harmful out-of-band distorted radiation, which significantly affects the quality of signal processing by a demodulator. Direct interchannel junction interference caused by the offset of subcarriers under conditions of such distortions and the issue of assessing the impact of these interchannel interferences with the operation of the telecommunications system is not covered in the cited paper.

In [7], the issue of reducing interference in the elementary data transmission channel of the OFDM signal system is considered. It is proposed, provided that the power of the internal channel interference is taken into account, a new asymmetric window, which provides a reduction in the cyclic prefix of the signal without reducing the power of the usable signal. A certain issue of limiting the influence of these internal obstacles on neighboring channels is considered in the cited work in the part that states the possibilities of the chosen method to ensure the limitation of the impact on the power of the obstacle in the neighboring channel. The issue of general formation of the methodology for limiting interchannel interferences and their possible impact on the quality of data transmission is not considered in the cited paper.

Work [8] considers the issue of limiting the impact of non-band radiation in systems with orthogonal frequency separation (OFDM). In a certain way, such radiation can be attributed to interchannel interferences, but they are formed by radio signals that do not carry elements of usable signals and, in fact, are external interference. To reduce them, paper [9] proposes a frequency spectral pre-encoding and a new precoder structur, which provides conditions that allow the input receiver to use the classic OFDM channel evaluator. General approaches to reducing such obstacles and other obstacles and disturbances and the methodology of their construction are not covered in works [8, 9].

Certain elements of the methodology for reducing interchannel interference in OFDM signals are covered in [10]. It directly proposes a new approach to reducing block diagonalization of downlink interference and power distribution. This was done taking into account both the absence and availability of information about the status of the channel in multi-user telecommunication networks based on MIMO-OFDM signals. The results presented in the cited paper in a certain way relate to one of the manifestations of interchannel interference, but only in terms of limiting spatial interference. The direct impact of the deviation of the parameters of one of the channels and the formation of a negative impact from it on neighboring channels, as well as methods for assessing and reducing this impact, were not considered in the work.

Thus, the solution to improve the efficiency of data transmission in telecommunication systems operating on the basis of the use of OFDM signals under the influence of ITI is not fully resolved.

3. The aim and objectives of the study

The aim of our study is to determine the possibility of reducing the impact of interchannel interference on the efficiency of signal transmission in telecommunication data transmission systems. This will increase the efficiency of the use of telecommunication systems for transmitting digital data based on the OFDM signal under the influence of interchannel interference.

To accomplish the aim, the following tasks have been set:

– to determine and summarize the list and interrelation of signal parameters in the scheme of construction of a data transmission system based on OFDM technology;

– to build mathematical dependences and, on their basis, a holistic model for assessing the impact of interchannel interference on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal;

– to investigate interchannel transient interference and establish the possibility of reducing its impact by selecting the parameters of the OFDM signal.

4. The study materials and methods

For research, the classical structure of the signal, created on the basis of the technology of parallel data transmission and frequency distribution with multiplexing of the phase modulated signal – OFDM signal, was chosen. The offset of subcarriers in the signal structure and the deviation of their parameters from the nominal ones are directly investigated, which forms internal harmful perturbations, defined as interchannel transient interference (ITI). In research, it is assumed that the OFDM signal subcarriers are orthogonal to each other.

As a generalized model of the description of the OFDM signal, it is accepted in this paper that the specified signal is the sum of the carriers of harmonic oscillations (Fig. 1, *b*), each of which is modulated by its own substream of transmitted bits using phase modulation (PM) or quadrature amplitude modulation (QAM).

The input signal, for research, is taken as an OFDM-symbol, including N_s subcarriers, each of which is represented as a complex number d_i with amplitude $|d_i|$ and the initial phase $arg(d_i)$, which contains a packet of i=0, 1, 2,..., N_{s-1} QAM– symbols.

The complex envelope of one OFDM symbol at time t_k is represented by the expression:

$$\dot{u}(t)=\sum_{i=0}^{N_s-1} d_i \exp\left\{ j2\pi \frac{i}{T}(t-t_k)\right\}, \quad (1)$$

where T is the duration of the OFDM symbol.

(1) describes the limiting video equivalent of an OFDM radio signal.

Outside the time interval t_k, the OFDM symbol with the number k is zero.

The generalized model of the data transmission channel based on OFDM technology, which is accepted in this work, is represented in the form of a block diagram in Fig. 2.

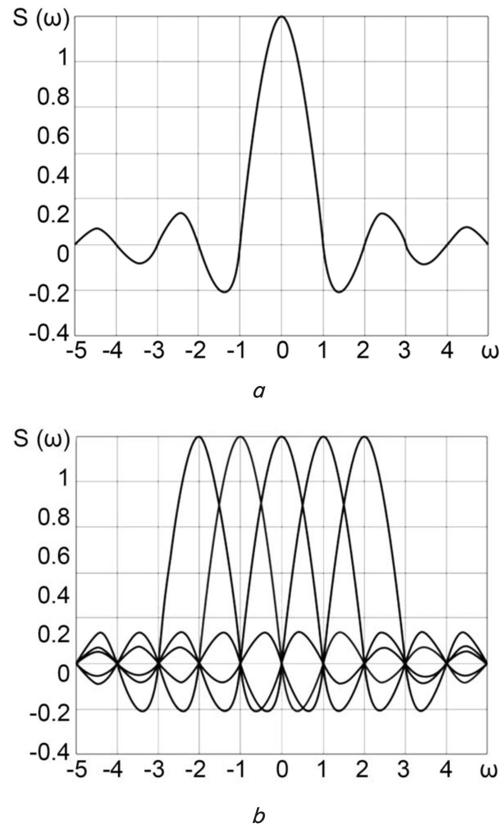

Fig. 1. Spectral structure: *a* — elementary radio signal at one carrier frequency; *b* — one OFDM-symbol with N_s subcarriers

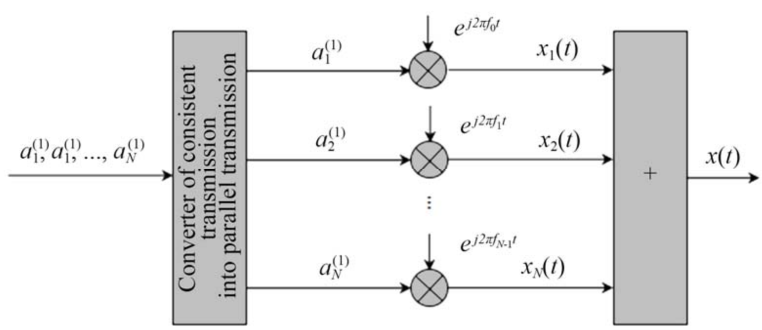

Fig. 2. Block diagram of a discrete-continuous data transmission channel based on OFDM technology

The OFDM signal consists of N orthogonal subcarriers ($a_1^{(1)}$, $a_2^{(1)}$,...,$a_N^{(1)}$), modulated by N parallel data streams. The frequency independence of the subchannels formed in this way is ensured by the mutual orthogonality of the subcarriers. On the presented model of the block diagram, there is no reflection of the appearance of ITI, other interference and perturbations.

5. Model for assessing the impact of interchannel interference on the efficiency of signal transmission using OFDM technology

5. 1. Generalization of signal parameters built using OFDM technology

To form OFDM-symbol of rectangular shape, the whole and imaginary parts of the carrier envelope with a frequency of f_0, determined from (1), are multiplied by $\cos(2\pi f_0 t)$ and $\sin(2\pi f_0 t)$ and the obtained oscillations are added to the signal [2, 5].

From (1) it follows that for an OFDM signal, the interval between the frequencies of neighboring carriers is $\Delta f=1/T$, and the frequencies of all carriers are multiples of this interval. This provides a condition under which the duration of the OFDM symbol is formed by an integer number of periods of carrier frequencies.

For any adjacent periods, the number of each carrier differs by one.

The initial phase and amplitude of each carrier are determined by the value of the transmitted QAM symbol of this carrier. In addition, each carrier has its natural amplitude and phase values. This makes it necessary at the interval $t_k<t<t_k+T$ to carry out coherent demodulation of the input signal with mutual orthogonality of all carriers [2, 5, 11].

In general, the complex bypass OFDM signal adopted by the input device is multiplied by the oscillation component of the carrier $\exp\left\{-j2\frac{l}{T}\pi(t-t_s)\right\}$ and is integrated over the time interval $t_k<t<t_k+T$, which, according to the theory of noise immunity, provides an estimate of the QAM symbol d_i of the signal, with the number i from the composition of the complex envelope of the input signal [5, 11]:

$$\int_{t_k}^{t_k+1} \dot{u}(t)\exp\left\{-j2\pi\frac{l}{T}(t-t_k)\right\}\mathrm{d}t = \int_{t_k}^{t_k+1} \begin{matrix}\dot{u}(t)\exp\left\{-j2\pi\frac{l}{T}(t-t_k)\right\}\times \\ \times\sum_{i=1}^{N_s-1} d_l \exp\left\{j2\pi\frac{i}{T}(t-t_k)\right\}\mathrm{d}t\end{matrix} = d_l T. \quad (2)$$

The interrelated relationship of parameters and variables (2) allows for the actual calculation of the value of the spectral density of the amplitudes of the OFDM symbol at a frequency $F_l=l\Delta f$ of the carrier oscillation i provides demodulation of the specified OFDM symbol [5, 11].

Analysis of those presented in Fig. 3 spectra of different carriers of the same OFDM-symbol showed that relative to one carrier at a certain oscillation frequency, the spectrum of other carriers at this frequency is zero [2, 5].

The absence of mutual influence in the spectrum of the carrier signal on each other is ensured by a certain choice of frequencies of subcarrier oscillations and the interval between adjacent subcarriers, which is associated with the duration of the OFDM-symbol (T) [5, 11, 12].

The property to insensitivity in the delay of a multi-beam signal in OFDM technology is ensured by an increase in the duration of the OFDM-symbol relative to the QAM symbol by the number of subcarriers in the symbol (*Ns*), that is, by *Ns* times. And the relative time of the increase in delay in the channel will be less by the same time.

Intersymvolous interference between OFDM symbols is provided by a protective time interval of the duration of the carrier oscillation for each signal beam (T_g) within which the OFDM signal is placed. This ensures the integrity of the mutual orthogonality of symbols. The mutual orthogonality of symbols may be impaired due to interference generated by the multi-beam nature of the signal [5, 11].

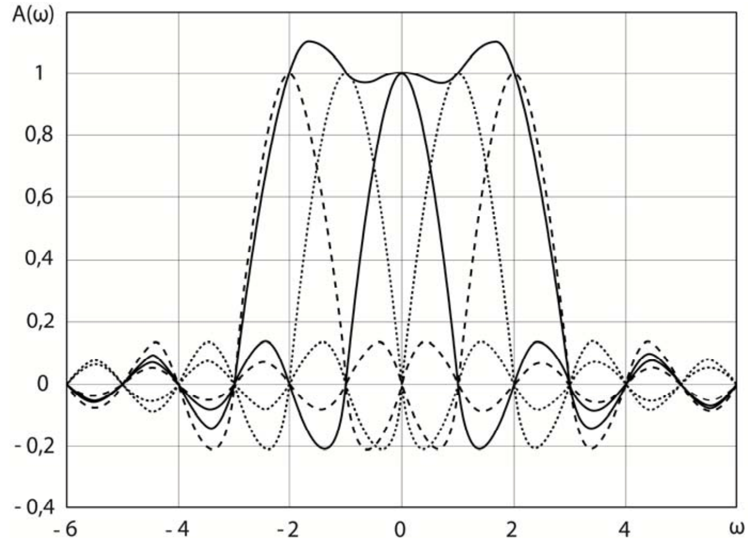

Fig. 3. Spectral density of the sum of five carriers with the same amplitudes and initial phases

The delay of one of the rays does not lead to a violation of the orthogonality between the carriers of this and the previous beam due to the fact that an integer number of carrier periods will be placed on the period of the duration of the symbol T, regardless of the beginning of this interval. This condition will be provided for each beam only at the values of signal delay Δt caused by multi-beaming, not more than the duration of the protective interval T_g [11, 12].

The magnitude of the protective interval T_g directly determines the duration of the OFDM symbol T_c. Accordingly, the smaller the share of T_g in the value of T_c, the lower the energy costs of radiation power, directed to ensure the desired signal-to-noise ratio in the input device of the telecommunications system.

The duration of the symbol T_s is limited by the number of sub-carriers involved, which also cannot be quite a lot due to the decrease in the frequency interval between them. In turn, a decrease in the frequency interval gives rise to an increase in the sensitivity of the system to deviations of carrier frequencies from the nominal values, an increase in the peak factor of the OFDM signal and an increase in phase fluctuation. All this affects the operating modes of the input signal amplification devices in terms of ensuring a linear mode of operation.

The duration of the T_c symbol is usually chosen provided that the permissible energy costs are not more than 1 dB when T_c is exceeded over the protective interval five times [5, 11, 12].

Based on this, the integration of the OFDM symbol in the receiving device must be carried out at the interval $T=T_c-T_g$, and the frequency interval between the carriers is defined as $\Delta f=1/T$.

The number of carriers in one character (*Ns*) can be determined by the ratio of the frequency interval $N_S=F/\Delta f$ or through the data transfer rate as the ratio of the total data transfer rate over channel R to the transmission rate through one carrier R.

It is known that the data transfer rate also depends on the type of modulation (for example, QAM-16), the speed of the code involved, the speed of characters passing through the channel, which, in turn, determine the number of bits of a discrete signal.

The number of carriers is one of the most important parameters of OFDM systems. It forms the number of subchannels (W) in the signal structure. It is the number of subchannels W that largely forms and ensures the invariance of the OFDM data transmission system.

In turn, an increase in the number of subchannels (W) causes an increase in the clock interval and a decrease in the efficiency of using the band of frequencies involved. This can lead to a decrease in the effect of the imperfection of the amplitude-phase-frequency characteristic (APFC) of the channel but increases the number of modulation/demodulation operations and leads to an increase in frequency disassembly and phase jerking in the channel.

The analysis of signal construction using OFDM technology has made it possible to establish the interrelationships and mutual influence of the parameters of the specified signal and the joint interaction of neighboring data transmission channels in the structure of one signal. This provided the definition and generalization of the following list of important and critical parameters that form the signal itself and, obviously, may be related to interchannel interference.

These include:

– frequency interval of carrier oscillations of the OFDM signal;

– frequency uncertainty of the input signal (forms the deviation of the APFC and is minimized by the construction of the input signal reception channel);

– the number of carriers in one OFDM signal;

– the initial phase and amplitude of each carrier;

– a frequency interval between adjacent carriers;

– the time interval of coherent demodulation of the OFDM signal, subject to mutual orthogonality of all carrier signals;

– the time interval of the duration of the OFDM-symbol;

– a protective time interval that provides intersymbol interference when receiving multi-beam signals and is part of the time interval of the OFDM symbol.

As noted earlier, an increase in the number of carriers in the OFDM signal leads to an increase in the number of modulation/demodulation operations of the signal and changes in the clock interval. The associated increase in the number of sub-carriers of the clock interval decreases and causes an increase in frequency disposition and phase shaking of the channel [11–13]. Because of these effects, the carrier shifts from the established frequency position and acts on neighboring carriers in the form of harmful radio technical perturbation. That is, an interchannel interference is formed, the impact of which, as a radio technical perturbation, can be estimated by its power.

5. 2. Model of formation of interchannel interference in the data transmission system based on the OFDM signal

When developing a model for the formation of interchannel interference in a data transmission system based on the OFDM signal, it was determined that the source of ITI in the OFDM signal system is the imperfection of the AFCS channel [3–5].

When calculating the ITI, the following OFDM signal parameters were taken in fixed values:

– frequency band passed through the channel (Δf);

– the speed of passing digital data (V);

– the multiplicity of signal modulation (K), ($K \geq V/\Delta f$).

The amplitude-frequency characteristic (AFC) and the phase-frequency characteristic (PFC) of the channel are given by normalized fixed dependences for each number of pre-reception (Fig. 1).

Usually, when determining the requirements for the OFDM signal for the established number of pre-reception, the norms of permissible unevenness of the AFC are assigned [5, 7].

It is known that an increase in the number of pre-reception causes the effect of increasing the unevenness of the frequency response [5, 7].

Approximation of the pre-reception area during the transition to the PFC is carried out by the functional dependence of the following type [3, 6]:

$$\psi(\omega) = 1.57 \left\{ \begin{aligned} &\sin\left[2\pi \frac{(\omega - \omega_n)}{(\omega_v - \omega_n)}\right] + \\ &+ \frac{3.8(\omega - 1900 \cdot 2\pi)}{(\omega_v - 1900 \cdot 2\pi)} \end{aligned} \right\}. \quad (3)$$

For a certain number of pre-reception areas (L), the ratio $\psi(\omega) = L\psi$ is used, where:

– current frequency (ω);

– the upper value of the frequency (ω_v), for calculations it is accepted – 3,400 Hz;

– the lower value of the frequency (ω_n), for calculations it is taken – 300 Hz.

The duration of the clock interval (τ) is related to the value (W) via the expression:

$$\tau = KW / V. \quad (4)$$

The introduction of a protective interval ($\Delta\tau_p$) ensures the extraction in the demodulator of transients arising at the boundaries of clock intervals. This, to a certain extent, leads to a decrease in intersymbol interference (ISI) and, as a result, increases the noise immunity of the signal.

The protective interval is defined as:

$$\Delta\tau_p = \tau - T = \tau - 1/\Delta F, \quad (5)$$

where the signal processing time interval (T) is defined as $T = 1/\Delta f$.

When calculating it, the distance between the sub-carriers in the frequency calculation of their groups in the structure of the OFDM signal is used.

The range of effective use of the frequency band of signal formation (F_{ef}) is represented as:

$$F_{ef} \approx (W+1)\Delta F. \quad (6)$$

When the value of F_{ef} is limited to the condition $F_{ef} \leq \Delta\phi$, functional inequalities that determine the boundaries of the region of the most likely indicators of the parameters of the OFDM signal system are represented in the form:

$$\begin{gathered} 0 \leq \Delta\tau_p \leq \left(\frac{k \cdot \Delta f - V}{\Delta f \cdot V} W\right) - {}^{1}\!/\!_{\Delta f}, \\ \frac{V}{kW} \leq \Delta F \leq \frac{\Delta f}{W+1}, \; \frac{kW}{V} \geq T \geq \frac{W+1}{\Delta f}, \\ \left(\frac{k\Delta f - V}{k}\right) - \left(\frac{V}{kW}\right) \geq \Delta f_p \geq 0. \end{gathered} \quad (7)$$

In this case, the frequency protective interval (Δf_p) is given in the form $\Delta f_p = \Delta f - \Delta f_{ef}$.

Analysis of functional dependences (7) shows that under other conditions, an increase in protective intervals in time ($\Delta\tau_p$) andfrequency (Δf_p) can be achieved by increasing the number of sub-channels (W).

At the same time, it is significant that the growth of $\Delta\tau_p$ at the fixed value of W does not lead to a monotonous decrease in ITI. This is explained by the fact that with an increase in $\Delta\tau_p$, the ΔF_{ef} increases and brings the extreme subcarriers of the channel closer to the signal boundaries, that is, it reduces Δf_p. Accordingly, the minimum power of ITI will be achieved at the optimal interval for it $\Delta\tau_p$, for each value of the number of subchannels W [3, 5, 6].

For a specific (L-th) clock interval, the group signal fed to the modulator input will be determined by the ratio:

$$S_l(t)=\sum_{n=1}^{N} S_{n,l}(t)= =\sum_{n-1}^{N} a_{n,l}\cos\left[\left(n+{n_0}\!\!\diagup_{2}\right)2\pi\Delta Ft+\phi_{n,l}\right], \quad (8)$$

$$l\tau-\frac{\tau}{2}\le t\le l\tau+\frac{\tau}{2},$$

where $\phi_{n,i}$ and $a_{n,I}$ are, respectively, the initial phase and the constant of a signal amplitude;

n_0 – the constant that determines the location of the subcarrier in the bandwidth Selected when the requirements are met:

$$F_1=\left(n_1+{n_0}\!\!\diagup_{2}\right)\Delta F>300\text{ Hz}, \quad (9)$$

$$F_w=\left(n_2+{n_0}\!\!\diagup_{2}\right)\Delta F>3400\text{ Hz},$$

where n_1=1, n_w=W.

The transition to the spectral method of calculating the power of ITI is ensured by the multifrequency of OFDM technology, the use of AFC patterns, and group time delay (GTD). Carrying out the necessary automated machine calculations using a computer ensures that the group signal is brought to a periodic form, the period of which should be selected more than the duration of transients [7, 9].

Modeling of quantitative values of ITI and obtaining actual calculations of their values under different conditions for the group signal OFDM was carried out under the following condition. The signal is received in the form of rectangular single pulses, the period of which is defined as $T_n>>\tau_{nn}$, where τ_{nn} is the clock interval. To simplify the calculations, the condition l=0 is accepted; the index l in the following expressions will not be applied.

Using the function of decomposition of the sequence of rectangular video pulses with the period $T_n=2\pi/\Omega$ and the duration τ in the form of [3, 6], we get:

$$f(t)=\frac{\Omega\tau}{2}+\frac{2}{\pi}\sum_{k=1}^{\infty}\left(\frac{\sin K\Omega\tau/2}{k}\right)\cos K\Omega t. \quad (10)$$

Signals of the form S_n (t) decompose into a functional series: $S_n(t)=f(t)\cos(\omega_n t+\varphi_n)$ and $F_{n,s}=\varphi(t)\sin\omega_n t$ in a Fourier series under the condition $\Delta F_t=2p$, where p is an integer.

In this case, the resulting signal decomposition $S_n(t)$ is represented as a linear combination $F_{n,s}(t)$ and $F_{n,c}(t)$:

$$S_n(t)=\cos\phi_n F_{n,c}(t)-\sin\phi_n F_{n,s}(t), \quad (11)$$

Expression (11) is given as:

$$S_n(t)=\frac{\sin(\Omega\tau n/2)}{\pi n}\cos\phi_{\tilde{n}}+\sum_{k=1}^{\infty}a_{n,k}\cos\left[k\Omega t+\phi_{n,k}\right].$$

The implementation of correlation processing of the input signal provides in multichannel demodulators the distribution of subchannels, which is carried out under the condition of $1\le m\le N$ through the calculation using the following functional dependence [3, 5, 14]:

$$\dot{Z}_m=\int_{t_0}^{t_0+T}S(t)e^{-j\omega mt}\mathrm{d}t=Z_{c,m}+jZ_{s,m}, \quad (12)$$

where t_0 is the start time of the calculation relative to the l-th clock interval, which is set in the system by the clock synchronization device;

$Z_{c,m}$ and $Z_{s,m}$ – corresponding counts on the cosine and sinus outputs of the correlator obtained after integration;

$S(t)=\sum_{n=N_1}^{N_2}S_n(t)$ – output group signal.

Reception by the input device and transmission to the correlator with an internal reference frequency $m\Omega$ ($m=p(2m+m_0)$) of one of the spectral components $S_n(t)$ of the input signal in the form:

$$S_{n,k}=a_{n,k}\cdot k(k\Omega)\cos\left[k\Omega t+\phi_{n,k}+\psi(k\Omega)\right], \quad (13)$$

provides its processing and formation at the output of the correlator of signals of the following form:

$$Z_{c,m}(n,k)=a_{n,k}\cdot k(k\Omega)\begin{Bmatrix}\begin{bmatrix}U_{d,m}(k)C_{d,m}(k)+\\+U_{s,m}(k)C_{s,m}(k)\end{bmatrix}\times\\ \times\cos\left[\phi_{n,k}+\psi(k\Omega)\right]-\\ -\begin{bmatrix}U_{d,m}(k)S_{d,m}(k)+\\+U_{s,m}(k)S_{s,m}(k)\end{bmatrix}\times\\ \times\sin\left[\phi_{n,k}+\psi(k\Omega)\right]\end{Bmatrix}, \quad (14)$$

$$Z_{s,m}(n,k)=a_{n,k}\cdot k(k\Omega)\begin{Bmatrix}\begin{bmatrix}U_{s,m}(k)S_{s,m}(k)-\\-U_{d,m}(k)S_{d,m}(k)\end{bmatrix}\times\\ \times\cos\left[\phi_{n,k}+\psi(k\Omega)\right]-\\ -\begin{bmatrix}U_{d,m}(k)C_{d,m}(k)-\\-U_{s,m}(k)C_{s,m}(k)\end{bmatrix}\times\\ \times\sin\left[\phi_{n,k}+\psi(k\Omega)\right]\end{Bmatrix}, \quad (15)$$

where $U_{d,m}(k)=\dfrac{\sin[(k-m)\Omega T/2]}{(k-m)\Omega},\ k\ne m,\quad U_{d,m}(k)=T/2,$ $k=m,$

$$U_{s,m}(k)=\frac{\sin[(k+m)^*\Omega T/2]}{(k+m)^*\Omega}, \quad (16)$$

$$S_{d,m}(k)=\sin\left[(k-m)^*\Omega(t_0+T/2)\right],$$

$$S_{s,m}(k)=\sin\left[(k+m)^*\Omega(t_0+T/2)\right],$$

$$C_{d,m}(k)=\cos\left[(k-m)^*\Omega(t_0+T/2)\right],$$

$$C_{s,m}(k) = \cos\left[(k+m)^{*}\Omega\left(t_0 + T/2\right)\right].$$

The expressions given in the form of (14) and (15) can be simplified by accepting $t_0=-T/2$ and applying the frequency conversion at the demodulator input under the condition $k+m>>k-m$, (conversion "upwards"). This makes it possible to exclude from the calculations the terms containing a set of total frequencies in the numerators.

The components of the interchannel interference generated by the signal $S_n(t)$ in a certain frequency subchannel (m-subchannel) are calculated by summing according to the following dependences [14]:

$$Z_{c,m}(n) = \sum_{k=1}^{\infty} Z_{c,m}(n,k), \tag{17}$$

$$Z_{s,m}(n) = \sum_{k=1}^{\infty} Z_{s,m}(n,k).$$

The quantitative value of ITI, which can be used to assess its impact, is calculated by the following expression:

$$\xi_m = \frac{1}{Z_0}\sqrt{\sum_{n=1}^{N}{}_{0}\left(Z_{s,m}^2(n) + Z_{c,m}^2(n)\right)}, \tag{18}$$

where $n=\overline{1,N}$.

In the calculations, terms with indices $n=m$ are withdrawn from the amount.

That is:

$$Z_0 = \sqrt{Z_{c,m}^2(m) + Z_{s,m}^2(m)}. \tag{19}$$

5. 3. Investigation of interchannel interference in the data transmission system based on the OFDM signal

The results of calculating the quantitative values of ITI (ξ_m) as a function of the values of the protective interval $\Delta\tau_p$ for different values of the number of pre-reception areas, obtained by using the developed model based on expressions (12) to (19), are shown on the dependences in Fig. 4–11.

In the calculations, the information transfer rate (V) of 9600 bits/s, the frequency interval Δf=3100 Hz, and the modulation multiplicity equal to 4 units [5, 14] were selected.

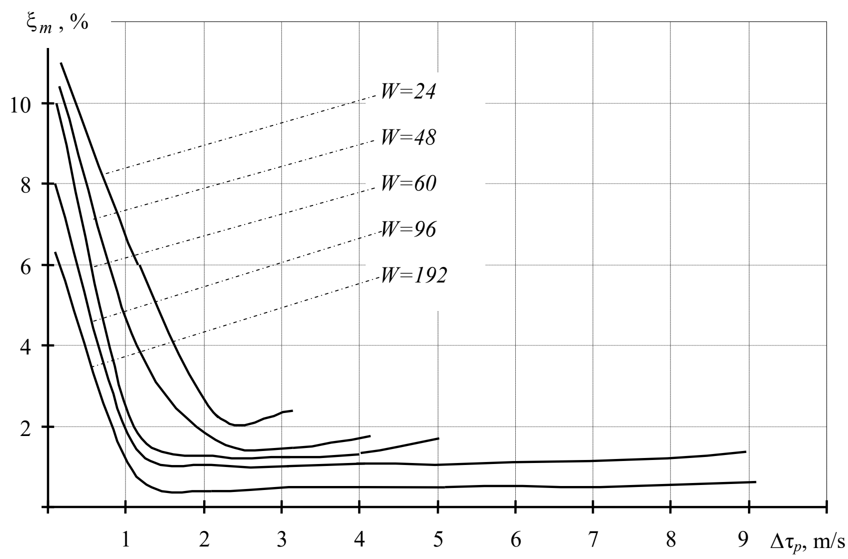

Fig. 4. Plots of change in $\xi_m=f(\Delta\tau_p)$ for different W values at one pre-reception

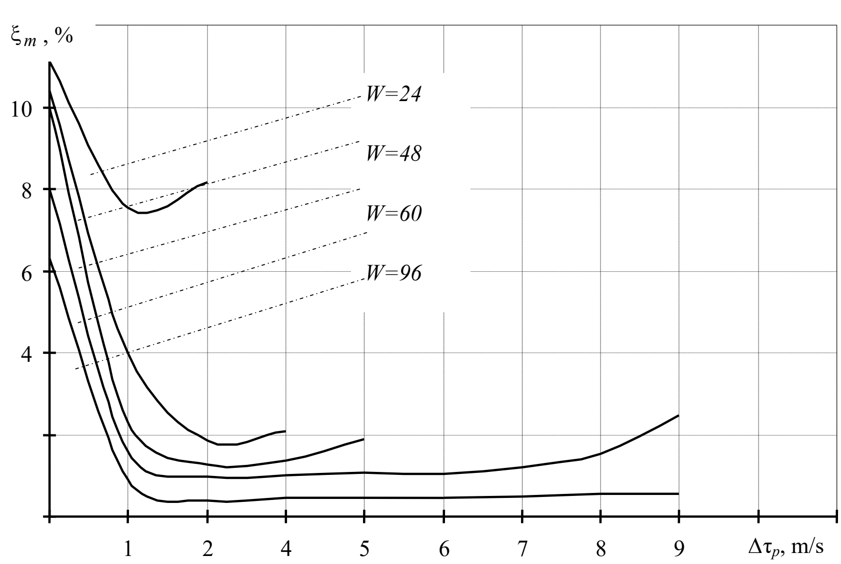

Fig. 5. Plots of change in $\xi_m=f(\Delta\tau_p)$ for different W values at two pre-receptions

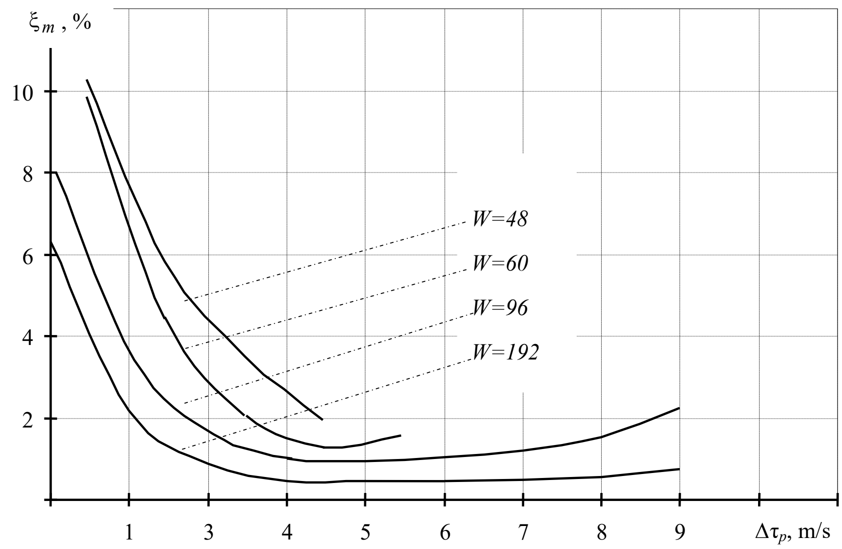

Fig. 6. Plots of change in $\xi_m = f(\Delta\tau_p)$ for different W values at three pre-receptions

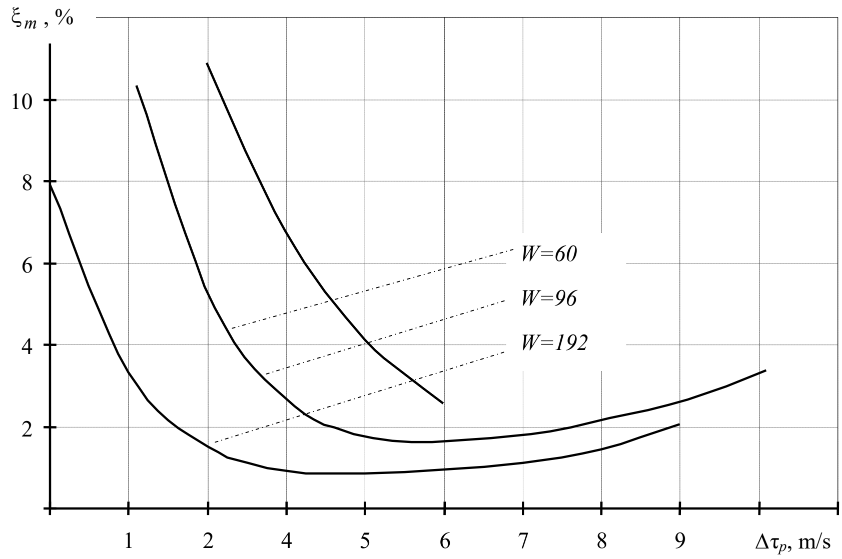

Fig. 7. Plots of change in $\xi_m = f(\Delta\tau_p)$ for different W values at four pre-receptions

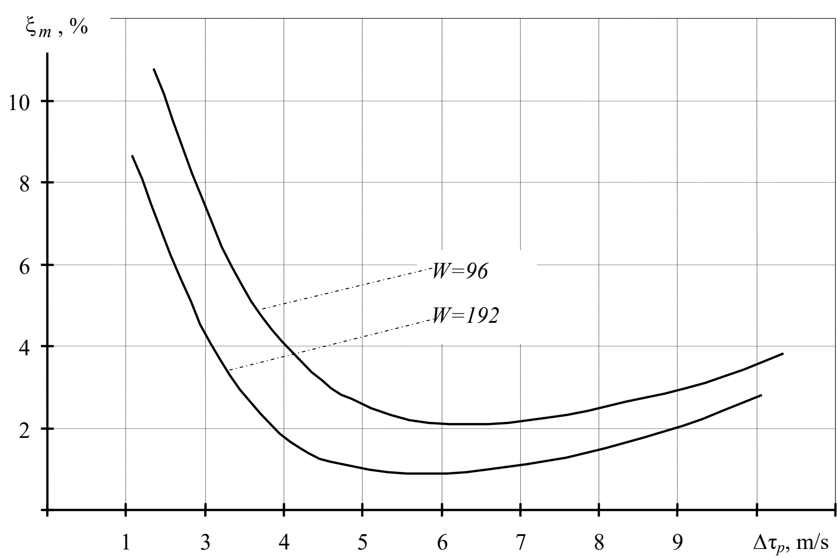

Fig. 8. Plots of change in $\xi_m = f(\Delta\tau_p)$ for different W values at five pre-receptions

The beginning of calculations t_0 was selected under the condition of a simplified procedure in which $t_0=-T/2$. This ensures that the results are obtained with a symmetrical arrangement of the signal processing interval in the demodulator relative to the start time and end of the incoming signal pulse reception. The initial phases of the signal ($\varphi_{l,n}$) were assumed to be equal to 0. In the calculations, the requirement of invariance of the obtained values of quantitative assessment of ITI (ξ_m) to the choice of the initial phases of the carriers was maintained.

Fig. 9 shows the plots of changes in the minimum achievable values of ξ_m at different values of the number of subchannels in the OFDM system for different number of pre-reception.

The possibility of transmitting information at a speed of 12 kbit/s with fourfold amplitude-phase-level modulation in a standard telephone channel can be evaluated.

Fig. 10, 11 show the plots of change $\xi_m=(\Delta\tau_p)$ for the transfer rate of 12 kbit/s and 14.4 Kbit/s when using amplitude-phase modulation of different multiplicities.

In the course of modeling the quantitative values of ITI for the efficiency of data transmission in the OFDM signal system, it was found that the channels located near the boundaries of the bandwidth of the tract are the most sensitive to the power of ITI.

The reason for the occurrence of these distortions is the peculiarity of frequency distortions at the border of the bandwidth, the nonlinearity of the phase-frequency and amplitude-frequency characteristics increases sharply.

At the same time, if the duration of the transient process is exceeded, the value of the protective interval and the processing of the input signal by the demodulator occurs during the transition process, then there is a violation of the orthogonality of the channel signals. This causes the appearance of an additional transient interference [13, 14].

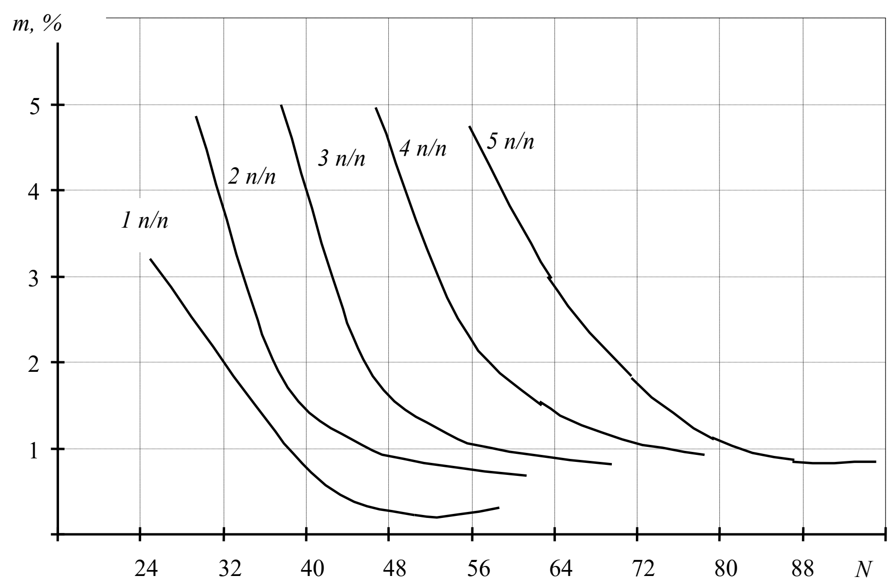

Fig. 9. Plot of change in the minimum achievable ξ_m values for different number of low frequency pre-reception

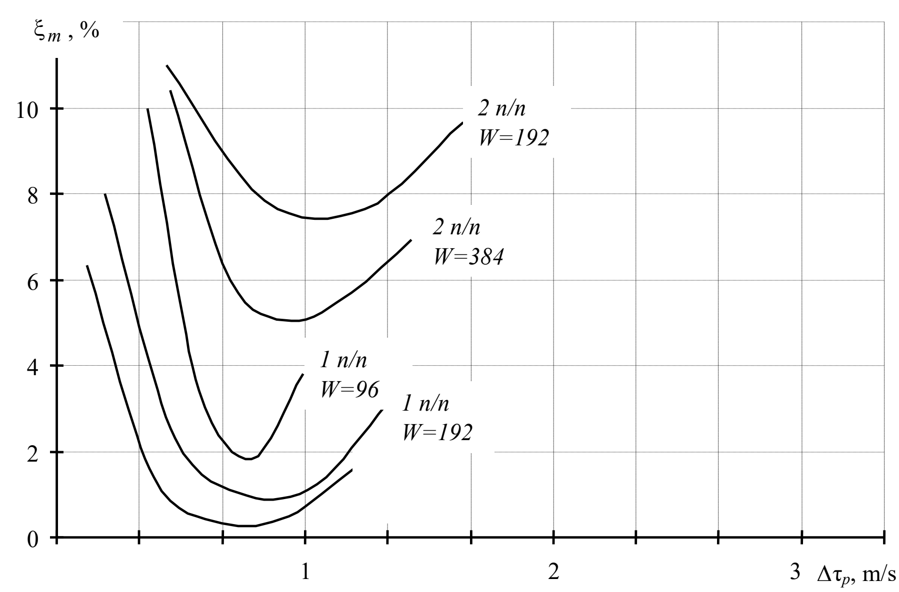

Fig. 10. Dependence $\xi_m=(\Delta\tau_p)$ for transmission rate of 12 kbit/s of quadruple amplitude-phase modulation

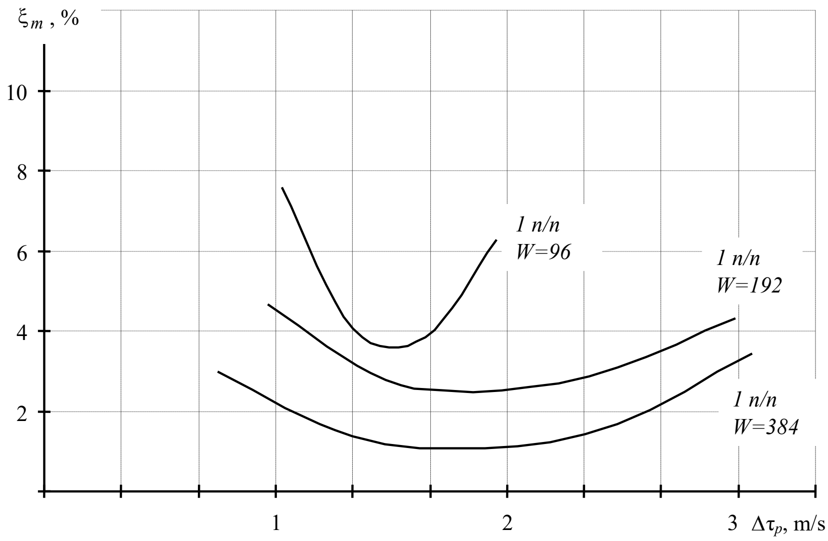

Fig. 11. Dependence ξ_m=($\Delta\tau_p$) for a transmission rate of 14.4 Kbit/s of fivefold amplitude-phase modulation

6. Discussion of results of the assessment of the impact of interchannel transient interference on the effectiveness of OFDM signal transmission

During the simulation, the influence of the value of the interchannel quantity (W) on the quantitative value of ITI (ξ_m) as a function of ($\Delta\tau_p$) at different values of pre-reception was investigated. The obtained dependences at the values of the interchannel value (W), which was selected in values 24, 48, 60, 96, and 192 for the number of pre-reception from 1 to 5, are shown in Fig. 4–11.

Their analysis, taking into account the clarifications of the calculated data reported in [14], has made it possible to substantiate the conclusion regarding the possibility, when fixing the values of W, to achieve the minimum ITI by selecting a value of $\Delta\tau_p$ (or T). At the same time, an increase in W allows you to reduce the influence of frequency distortion of the channel.

It should be taken into account that when choosing the value of W, it is necessary to comply with the requirement to minimize the intersymbol interference on its impact on the noise immunity of the system [15–17].

For example, if we accept the condition in which the group signal level at the signal output ≈–10 dB, the permissible noise level reaches ≈40 dB and, at ξ_m in the value of 3 %, *IT*I is practically not displayed against the background of noise and, for these condition,s reaches a value of ≈3 dB.

It is determined that when applying quadruple amplitude–phase-difference modulation (APDM), the value of h^2, at which $P_k \leq 10^{-6}$, reaches ≈25 dB [15, 16].

That is, by taking ξ_m in the value of 3 % of *IT*I into the assumptions, it can be achieved without phase adjustment of AFCS at W in a value of 24 by performing one signal pre-reception.

It is possible to achieve the same property of the OFDM signal system at W in the value of 96 by making 5 signal pre-receptions in the channel.

One of the ways to reduce the number of subchannels in the OFDM signal system is to use a constant phase corrector [13, 14].

Analysis of the dependences in Fig. 10 shows that the norm for the value of $_m$ is already provided at W 48. This can be explained by the fact that the corrector used in the signal reception system provides a reduction in the residual unevenness of the frequency response and the characteristics of GTD at the channel level with two changes.

Based on the data obtained earlier on the ITI assessment (Fig. 4–11) and recommendations for justifying the parameters of the OFDM system, it is possible to propose a set of parameters for the OFDM system for a speed of 9600 bit/s and four times APDM.

According to the above model (12) to (19), for a speed of 12 kbit/s and a modulation multiplicity of 4, we calculated the power of ITI (ξ_m, %) in the extreme in the spectrum, the most affected channels. The plots in Fig. 11 demonstrate that for one pre-reception area on LF for 192 channels – $\xi_m \leq 3$ %.

The minimum value ξ_m obtained for one pre-reception area with the above number of channels confirms the possibilities of the model proposed in this work to assess the impact of interchannel interference on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal [13, 14].

The results of our calculations showed that the choice of W=192 fundamentally solves the problem under consideration and makes it possible in the AFCS, characteristic of one pre-reception area for LF, to transmit information at a speed of 12 kbit/s at h^2=22 dB with $P_{pom}=10^{-5}$. When working in the HF channel with two or more pre-reception areas, it is necessary to use a constant phase corrector, correcting the AFCS to one pre-reception region for LF [12, 15, 16].

The results of the signal construction using OFDM technology reported in this work and the results of ITI evaluation obtained with the help of the model proposed in this paper allow us to form the following method for selecting the parameters of the OFDM signal:

1. The permissible value of the quantitative value of ITI (ξ_m) is justified. It is appropriate to associate its justification with the magnitude of the signal-to-noise ratio defined as the ratio (1/ξ_m), the boundaries of the unevenness of the frequency and the characteristics of GTD, calculated relative to the number of residual pre-reception [13, 14].

2. According to the plots of the dependences in Fig. 10, we determine the required value of W.

3. According to the plots of dependences in Fig. 4–9, the value of the time protective interval $\Delta\tau_p$, which provides a higher reasonable value of ITI (ξ_m) is found.

4. The values of the signal parameters OFDM τ, T, ΔF, $\{\phi_i\}$, at i=1, 2, ..., W are determined and calculated.

Thus, the current work establishes and substantiates the interrelationships and interactions of the parameters of OFDM and ITI signal, which may arise in it when the subcarriers are offset.

To establish these relationships and assess the impact of ITI on the effectiveness of OFDM signal transmission, an appropriate assessment model has been developed and presented in our work. The use of this model has made it possible to substantiate the method of selecting the parameters of the OFDM signal according to a given level of quantitative value of ITI.

The limitations inherent in the above studies include the fact that the presented evaluation model is designed for signals that use phase or quadrature-amplitude modulation.

A certain disadvantage of the model proposed in our work is the lack of mechanisms for substantiating the permissible level of quantitative values of ITI. The solution of this issue gives rise to another scientific task and requires appropriate research. Also, a detailed consideration of the possibilities for applying the proposed model for assessing the impact of ITI in relation to OFDM signal systems using binary phase manipulation (BPSK) and quadrature-phase (QPSK) modulation was not carried out. Especially when it is important when developing telecommunications systems based on OFDM technology, which are designed to work under conditions of high noise and with multi-beam application.

The proposed model allows you to determine, justify, and propose the parameters of the OFDM signal, provided that the interchannel transient interference is minimized. This ensures an increase in the efficiency of the use of telecommunication data transmission systems based on the OFDM signal.

The results of the assessment of quantitative values of ITI obtained in the present work confirm the high applicability of the model proposed in the work for assessing the impact of interchannel interference and developing recommendations for reducing its impact on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal.

This evaluation model can be used in the practical improvement of existing and the development of new telecommunication data transmission systems based on OFDM technology.

As further promising research and development in the direction of reducing ITI, further research is proposed to improve the proposed model for assessing the impact of ITI. This improvement should be carried out taking into account the peculiarities of the implementation of other types of modulation and noise-resistant manipulation for modern and promising forms of OFDM signal. Such as OFDM systems with non-orthogonal carriers (N-OFDM) or OFDM systems with internal encoding (COFDM).

7. Conclusions

1. We report the results of the analysis of the signal construction system using OFDM technology; the mutual influences of the parameters of the specified signal and the nature of the joint interaction of neighboring data transmission channels in the structure of one OFDM signal were established. It is determined that changes in the position and parameters of the subcarrier symbol from the composition of this OFDM symbol create an interchannel transient interference. It was established that the values of the interchannel value, the protective interval and the number of signal pre-receptions directly affect the quantitative value of the interchannel transient interference.

2. A model for assessing the impact of interchannel interference on the efficiency of signal transmission in telecommunication data transmission systems based on the OFDM signal has been developed and proposed. This model allows you to set the quantitative values of the interchannel transient interference depending on the interchannel value, the protective interval, and the number of signal pre-receptions.

3. It was established that the channels that are located near the boundaries of the bandwidth of the tract in the structure of one OFDM symbol are the most sensitive to the power of ITI. The reason for the occurrence of this sensitivity is frequency distortions at the limit of the signal bandwidth, due to which the nonlinearity of the phase-frequency and amplitude-frequency characteristics of the signal spectrum increases dramatically. With a fixed value of the interchannel value, it is possible to minimize the power of the interchannel transient interference by choosing the value of the protective interval for a different number of input signal pre-receptions. For example, if ξ_m=3 % is considered permissible, then, at W=24, the accepted and permissible level of ITI without adjusting APFC can be achieved when implementing no more than 1 pre-reception in the channel. For a data transfer rate of 12 kbit/s and a modulation multiplicity of 4, the ITI power in the extremes in the spectrum, the most affected channels for one pre-reception area at a low frequency for 192 channels can reach values of less than 3 %.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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