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ALGORITHM FOR ESTIMATING AND CORRECTING MULTIPATH CHANNEL PARAMETERS FOR DEMODULATION OFDM SIGNALS

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АЛГОРИТМ ОЦІНКИ Й КОРЕКЦІЇ ПАРАМЕТРІВ БАГАТОПРОМЕНЕВОГО КАНАЛУ ПРИ ДЕМОДУЛЯЦІЇ СИГНАЛІВ OFDM

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Abstract. OFDM signals form the basis of the radio interface of 4G mobile networks. Among the most well-known systems using OFDM signals, the LTE / LTE-Advanced, IEEE 802.11, IEEE 802.16 family, as well as DVB-T, DVB-T2 digital television standards, should be noted. Due to the high spectral efficiency and noise immunity in channels with multipath propagation of radio waves, OFDM signals are also used in other systems under development. Radio systems with OFDM signals have two significant drawbacks: the high peak factor (PAPR), which reduces the efficiency of the radio transmitter, and the high sensitivity of the demodulator to frequency synchronization errors. Because of them, in the LTE system in the Up lines (from a subscriber - mobile station – MS - to the base station - BS), the SC-OFDM transmission method is used instead of the classical OFDM, which reduces the spectral efficiency. High-speed user movement in an environment with many diffusers characteristic of dense urban development leads to frequency dispersion, when a Doppler spectrum occurs near each subcarrier of the OFDM signal. In addition, in any radio communication system, there are random fluctuations in the phase of the radio signal caused by the instability of the generators of the radio receiver and radio transmitter. As a result, the orthogonality of the subcarriers is violated and mutual interference between them (ICI - inter-carrier interference) occurs. This can significantly impair the noise immunity of the transmission system. Therefore, an integral part of the demodulator processing the OFDM signal is the channel parameter estimation and correction unit (adaptive equalizer). There are two categories of equalizers that determine the parameters of the channel – in the frequency domain and in the time domain. Since the OFDM signal demodulators use the fast Fourier transform at the subcarrier separation stage, as well as the pilot subcarriers being contained in the signal structure, it is advisable to consider equalizers that calculate the channel parameters in the frequency domain for efficient hardware implementation and good performance. Such an equalizer joins in with a demodulator after the stage of fast Fourier transformation. Traditionally for OFDM signals, an adaptive equalizer is built based on approximation of frequency description of channel by averaging of results obtained on the pilot subcarrier. Frequency dependence of total phase change of multibeam signal is not considered in such methods. Accordingly, good results can be expected at the dense location of the pilot subcarrier that reduces frequency efficiency in turn. An offered method allows considering a frequency-dependent phase change and interference losses, arising due to addition of copies of the signal from the different ways of distribution. It is special topically in systems with a small number of the pilot subcarriers.

Key words: multipath channel, estimation of multipath channel parameters, correction of multipath channel parameters, OFDM

Анотація. Сигнали OFDM становлять основу радіоінтерфейсу мереж мобільного зв'язку 4G. Завдяки високій спектральній ефективності та завадостійкості у каналі з багатопроменевим поширенням сигнали OFDM почали активно впроваджувати в інші системи. Серед найбільш відомих систем з сигналами OFDM можна відзначити сімейство LTE/LTE-Advanced, IEEE 802.11, IEEE 802.16, а також стандарти цифрового телебачення DVB-T, DVB-T2. Технології OFDM властиво два недоліки: велике значення пікфактора (PAPR), що знижує коефіцієнт корисної дії передавача, і висока чутливість до помилок синхронізації за частотою. Через них в LTE виключили OFDM у лініях Up (від абонента до базової станції), і перейшли на модуляцію SC-OFDM, пожертвувавши спектральною ефективністю. Рух користувача з високою швидкістю у середовищі з безліччю розсіювачів, характерним для щільної міської забудови, приводить до частотної дисперсії, коли біля кожної піднесучої виникає доплерівський спектр. Крім того, у будь-якій системі радіозв'язку присутні випадкові флуктуації фази радіосигналу, викликані нестабільністю генераторів приймача й передавача. У результаті порушується ортогональність піднесучих і виникає взаємна завада між ними (ICI – inter-carrier interference), що може істотно погіршувати завадостійкість багаточастотної системи. Тому невід'ємною частиною демодулятора приймального пристрою, що обробляє сигнали OFDM, є блок оцінки й корекції параметрів каналу (адаптивний еквалайзер). Існують дві категорії еквалайзерів (залежно від способу реалізації): визначальні параметри каналу в частотній області або в часовій області. Внаслідок того, що у системах з OFDM на етапі розділення піднесучих використовується швидке перетворення Фур'є, а також передбачено пілотні піднесучі, то з погляду ефективності апаратної реалізації й робочих характеристик доцільно розглядати еквалайзери, що виконують розрахунок параметрів каналу в частотній області. Традиційно для сигналів OFDM адаптивний еквалайзер будується на основі апроксимації частотної характеристики каналу шляхом усереднення результатів отриманих на пілотних піднесучих. У таких методах не враховується частотна залежність сумарного фазового зсування багатопроменевого сигналу. Відповідно гарні результати можна чекати при щільному розташуванні пілотних піднесучих, що у свою чергу знижує частотну ефективність. Запропонований метод дозволяє врахувати частотно-залежне фазове зсування й інтерференційні втрати, що виникли за рахунок додавання копій сигналу від різних шляхів поширення. Це особливо актуально у системах з малим числом пілотних піднесучих.

Ключові слова: багатопроменевий канал, оцінка параметрів багатопроменевого каналу, корекція параметрів багатопроменевого каналу, OFDM.

Аннотация. Сигналы OFDM составляют основу радиоинтерфейса сетей мобильной связи 4G. Благодаря высокой спектральной эффективности и помехоустойчивости в канале с многолучевым распространением сигналы OFDM начали активно внедрять в другие системы. Среди наиболее известных систем, использующих сигналы OFDM, можно отметить семейство LTE/LTE-Advanced, IEEE 802.11, IEEE 802.16, а также стандарты цифрового телевидения DVB-T, DVB-T2. Технология OFDM обладает двумя недостатками: большое значение пикфактора (PAPR), снижающее коэффициент полезного действия передатчика, и высокая чувствительность к ошибкам синхронизации по частоте. Из-за них в LTE исключили OFDM в линиях Up (от абонента к базовой станции), и перешли на модуляцию SC-OFDM, пожертвовав спектральной эффективностью. Движение пользователя с высокой скоростью в среде с множеством рассеивателей, характерной для плотной городской застройки, приводит к частотной дисперсии, когда около каждой поднесущей возникает доплеровский спектр. Кроме того, в любой системе радиосвязи присутствуют случайные флуктуации фазы радиосигнала, вызванные нестабильностью генераторов приёмника и передатчика. В результате нарушается ортогональность между поднесущими и возникает взаимная помеха между ними (ICI – inter-carrier interference), которая может существенно ухудшать помехоустойчивость многочастотной системы. Поэтому неотъемлемой частью демодулятора приемного устройства, обрабатывающего сигналы OFDM, является блок оценки и коррекции параметров канала (адаптивный эквалайзер). Существуют две категории эквалайзеров (в зависимости от способа реализации): определяющие параметры канала в частотной области или во временной области. Вследствие того, что в системах с OFDM на этапе выделения поднесущих используется быстрое преобразование Фурье, а также предусмотрены пилотные поднесущие, то с точки зрения эффективности аппаратной реализации и рабочих характеристик целесообразно рассматривать эквалайзеры, выполняющие расчет параметров канала в частотной области. Традиционно для сигналов OFDM адаптивный эквалайзер строится на основе аппроксимации частотной характеристики канала путем усреднения результатов, полученных на пилотных поднесущих. В таких методах не учитывается частотная зависимость суммарного фазового сдвига многолучевого сигнала. Соответственно, хорошие результаты можно ожидать при плотном расположении пилотных поднесущих, что в свою очередь снижает частотную эффективность. Предложенный метод позволяет учесть частотно-зависимый фазовый сдвиг и интерференционные потери, возникшие за счет сложения копий сигнала от различных путей распространения. Это особенно актуально в системах с малым числом пилотных поднесущих.

Ключевые слова: многолучевой канал, оценка параметров многолучевого канала, коррекция параметров многолучевого канала, OFDM.

The aim of this article is to search for a frequency-phase synchronization algorithm that provides coherent reception of OFDM signals with a minimization of inter-channel interference caused by the violation of orthogonality due to Doppler spreading of the spectrum of each subcarrier. The algorithm is based on the channel model described in ITU Recommendation M.1225 and assumes the presence of pilot subcarriers on which the reference sequence is transmitted using the BPSK method. Channel parameters are determined by reference subcarriers using numerical methods, which allow tuning the reference generator and recalculating the coordinates of the channel symbols of each information subcarrier. This algorithm also allows the use of data subcarriers, not just pilot ones, to adjust the frequency, which minimizes the effect of phase noise caused by inter-channel interference and noise in the communication channel. The use of modulation with many positions on information subcarriers leads to a decrease in the limits for estimating carrier frequency deviations. Therefore, at the initial stage of synchronization, it is recommended to use only pilot subcarriers for estimation, and to use all subcarriers of the working frequency range for subsequent tuning.

Let us consider the mathematical model of the communication channel. The signal at the input of the OFDM demodulator $r(n)$ is determined by the convolution of the impulse response of the channel (IR) and the transmitted OFDM symbol:

$$r(n)=\sum_{l=0}^{N_r} h^{(l)}(n)x(n-l)+\xi(n), \qquad 0\le n\le N-1, \tag{1}$$

where n – the discrete time;
N – the number of samples of the OFDM symbol;
$x(n)$ – the sample of the transmitted OFDM symbol;
$h^{(l)}(n)$ –IR l-th beam;
N_r – the number of independent Rayleigh beams forming a communication channel;
$\xi(n)$ – the sum of the external noise and the intrinsic noise of the receiving device.

In the OFDM demodulator of the transmission system, information signals of different subcarrier frequencies are separated using the direct fast Fourier transform (FFT) of the input signal $r(n)$. The complex amplitude of the k-th subcarrier Y_k (after the FFT) is determined by the following expression (without noise):

$$Y_k = a_{kk}X_k + \sum_{m=0,m\ne k}^{K_{\max}-1} a_{km}X_m\,, \tag{2}$$

where $K_{\max}$ – the number of neighboring subcarriers that cause mutual interference;
X_k – the complex amplitude of the k-th subcarrier of the transmitted OFDM symbol.

Due to the violation of orthogonality between the subcarriers, there is mutual interference between them ICI (inter-carrier interference), which can significantly impair the noise immunity of the transmission system. The coefficients a_{km} in (2) determine the values of mutual interference and are calculated by the formula

$$a_{km}=\frac{1}{N}\sum_{n=0}^{K_{\max}-1} H_k(n)\exp\left(\frac{j2\pi(m-k)n}{N}\right), \tag{3}$$

where $H_k(n)$ – the channel transmission coefficient at the frequency of the k-th subcarrier at the n-th time moment.

It follows from (2) that the signal of the k-th subcarrier consists of two terms. The first of them is a useful signal, and the second is mutual interference between subcarriers (ICI).

In order to determine how the delay in channel τ affects the initial phase of a subcarrier with frequency ω, we use the well-known relation:

$$\psi_\tau = \omega\tau . \tag{4}$$

The phase shift of each subcarrier can be calculated by the formula (4):

$$\psi_{k\tau} = \omega_k \tau = 2\pi k\tau / T . \tag{5}$$

To simplify, imagine the time shift relative value. Because the sampling interval is equal to $T/K_{\max}$, then the value $m = (\tau K_{\max})/T$ will show the delay relative to the sampling interval. And then the phase incursion of the k-th subcarrier can be represented as [2]:

$$\psi_{k\tau} = 2\pi km / K_{\max} . \tag{6}$$

Due to the fast movement of the receiver relative to the transmitter in the propagation channel, the beam components of the demodulated signal, in addition to different delays, will also have different Doppler frequency shifts. We assume that the receiver relative to the transmitter moves with speed ν. Doppler frequency offset

$$f_d = \frac{\nu\cos(\theta)}{\lambda}, \tag{7}$$

where θ – the angle between the velocity vector and the wave vector of the beam.

It is convenient to introduce the variable $\beta = \nu/3\cdot10^8$. The magnitude of the Doppler shift linearly depends on the frequency of the carrier and within the allocated frequency band has different values on individual subcarriers. The phase incursion of the k-th subcarrier arising due to the Doppler shift can be calculated from the relation:

$$\psi_{kd} = 2\pi f_k \beta\cos(\theta) T . \tag{8}$$

In addition, each subcarrier receives some irregular phase incursion due to non-orthogonal noises arising from Doppler shift, as well as from the AWGN.

Given that systems using OFDMA should operate in a multipath channel, the demodulated signal of the k-th subcarrier can be represented as follows:

$$\sum_{l=0}^{L} \mu_l a_k \cos\left(\frac{2\pi k m_l}{K_{\max}} + 2\pi f_k \beta\cos(\theta_l) + \zeta_{l,k}\right), \tag{9}$$

where μ_l – the attenuation of the signal of the l-th beam;
a_k – the amplitude of the k-th subcarrier;
$\zeta_{l,k}$ – the random phase of the k-th subcarrier arising due to the violation of orthogonality and the influence of noise;
L – the number of beams;
θ_l – the angle between the velocity vector and the wave vector of the l-th beam.

Considering that the MS receives the entire group signal from the BS, the angle between the velocity vector and the wave vector, propagation delays and attenuation of subcarriers of one beam are the same, and the coefficient β characterizing the Doppler shift is the same for subcarriers of all beams.

To perform synchronization, the MS can use all pilot subcarriers, and in wireless downlink systems from 12 to 240 are provided, depending on the allocated band. The modulation method of the pilot subcarriers is BPSK. The modulating sequence of these subcarriers is determined by a pseudo-random sequence with a defining polynomial $x^{11} + x^9 + 1$.

Given the model of the demodulated signal of the k-th subcarrier and the result of the FFT calculations, we write the equation:

$$\sum_{l=0}^{L} \mu_l a_k \cos\left(\frac{2\pi k m_l}{K_{max}} + 2\pi f_k \beta\cos(\theta_l) + \varsigma_{l,k}\right) = \tilde{a}_k . \tag{10}$$

To minimize the number of unknowns, let us imagine μ_l – attenuation of the signal of the l-th beam by known approximating expressions [3]. Since the influence of the path difference and the Doppler shift on the signal attenuation is independent, μ_l can be represented as the product of the fraction of attenuation introduced by the frequency dispersion of the Doppler Jakes spectrum and the averaged curve of the power decrease of the delayed beams represented by the exponential dependence. After the assumptions are made, we can rewrite the model of the demodulated signal of the k-th subcarrier

$$\sum_{l=0}^{L}\frac{K_{\max}\exp\left(-\alpha\cdot m_l/T\right)}{\pi k\beta\left|\sin\theta_l\right|}a_k\cos\left(\frac{2\pi k m_l}{K_{\max}}+2\pi f_k\beta\cos(\theta_l)+\varsigma_{l,k}\right)=\tilde{a}_k, \quad (11)$$

where α – a coefficient that determines the degree of exponential decrease in the power of the beam components delayed in the channel by time τ, depends on the nature of the terrain.

Based on the number of available pilot subcarriers n, we can compose n equations. We calculate the allowable number of beams taken into account. To solve the system of equations, it is necessary that the number of equations exceed the number of unknowns by at least 1. We need to determine the delay and attenuation in each beam, and the values of α and β are independent of the number of the subcarrier or the number of the beam. Thus, the number of unknowns is $2L + 2$. Based on this, the minimum number of equations is $2L + 3$, and the number of beams, respectively, $L = n/2 - 2$. Thus, with a minimum number of dedicated pilot subcarriers $n = 12$, four beams can be taken into account. This allows us to use one of the empirical channel models described in Recommendation ITU M.1225 to start the adjustment, namely, the ITU channel model for slowly moving subscribers outside and inside buildings for small propagation delays (type A) [4]. With an increase in the number of processed subcarriers, due to large statistical data, the error in estimates of channel parameters is minimized.

Methods for solving systems of equations are usually divided into two large groups. The first group includes methods that are called accurate. They allow for any system to find the exact values of the unknowns after a finite number of arithmetic operations, each of which is performed accurately. The second group includes all methods that are not accurate. They are called approximate, or numerical, or iterative. The exact solution when using these methods is obtained as a result of an endless process of approximations.

The solution of the system must be obtained with some specified accuracy up to ε.

We write the system of nonlinear equations in the form

$$\begin{cases} F_1(\alpha,\beta,m_1,m_2,m_3,m_4,\theta_1,\theta_2,\theta_3,\theta_4)=0; \\ F_2(\alpha,\beta,m_1,m_2,m_3,m_4,\theta_1,\theta_2,\theta_3,\theta_4)=0; \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ F_n(\alpha,\beta,m_1,m_2,m_3,m_4,\theta_1,\theta_2,\theta_3,\theta_4)=0, \end{cases} \quad (12)$$

or briefly in the form

$$F_i(\alpha,\beta,m_1,m_2,m_3,m_4,\theta_1,\theta_2,\theta_3,\theta_4)=\sum_{l=0}^{L}\frac{K_{\max}\exp\left(-\alpha\cdot m_l/T\right)}{\pi k\beta\left|\sin\theta_l\right|}a_k\cos\left(\frac{2\pi k m_l}{K_{\max}}+2\pi f_k\beta\cos(\theta_l)\right)-\tilde{a}_k=0,$$

where $i = 1, 2,\ldots, n$.

Here the functions $F_i(\bullet)$ are defined and continuous together with their partial derivatives in some domain D, which belongs to the exact solution of the considered system of equations. The exact solution to system (12) is denoted by

$$X^* = (\alpha^*,\beta^*,m_1^*,m_2^*,m_3^*,m_4^*,\theta_1^*,\theta_2^*,\theta_3^*,\theta_4^*). \quad (13)$$

To solve the system of nonlinear equations, it is proposed to use the Newton method. This method has much faster convergence than others [5]. The Newton method for the system of equations (12) is based on the use of expansion of functions [5]

$$F_i(\alpha,\beta,m_1,m_2,m_3,m_4,\theta_1,\theta_2,\theta_3,\theta_4)=0, \quad (14)$$

where i = 1, 2,…, n, in the Taylor series, and the terms containing the second and higher orders of derivatives are discarded. Such an approach allows the solution of one nonlinear system (12) to be replaced by the solution of several linear systems.

So, we will solve system (12) by the Newton method. In region D, we choose a point corresponding to the ITU channel model for slowly moving subscribers outside and inside buildings for small propagation delays (A) $X^0 = (\alpha^0, \beta^0, m_1{}^0, m_2{}^0, m_3{}^0, m_4{}^0, \theta_1{}^0, \theta_2{}^0, \theta_3{}^0, \theta_4{}^0)$ and call it the zero approximation to the exact solution $X^* = (\alpha^*, \beta^*, m_1{}^*, m_2{}^*, m_3{}^*, m_4{}^*, \theta_1{}^*, \theta_2{}^*, \theta_3{}^*, \theta_4{}^*) \in D$ of the original system. Now we expand the functions (14) in a Taylor series in a neighborhood of the point $X^0 = (\alpha^0, \beta^0, m_1{}^0, m_2{}^0, m_3{}^0, m_4{}^0, \theta_1{}^0, \theta_2{}^0, \theta_3{}^0, \theta_4{}^0)$.

Will have

$$\begin{aligned} &\mathrm{F_i}(\alpha,\beta,\mathrm{m}_1,\mathrm{m}_2,\mathrm{m}_3,\mathrm{m}_4,\theta_1,\theta_2,\theta_3,\theta_4) \cong \mathrm{F_i}(\alpha^0,\beta^0,\mathrm{m}_1{}^0,\mathrm{m}_2{}^0,\mathrm{m}_3{}^0,\mathrm{m}_4{}^0,\theta_1{}^0,\theta_2{}^0,\theta_3{}^0,\theta_4{}^0) + \\ &+ \frac{\partial \mathrm{F_i}}{\partial \alpha}\left(\alpha-\alpha^0\right) + \frac{\partial \mathrm{F_i}}{\partial \beta}\left(\beta-\beta^0\right) + \frac{\partial \mathrm{F_i}}{\partial \mathrm{m}_1}\left(\mathrm{m}_1-\mathrm{m}_1{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \mathrm{m}_2}\left(\mathrm{m}_2-\mathrm{m}_2{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \mathrm{m}_3}\left(\mathrm{m}_3-\mathrm{m}_3{}^0\right) + \\ &+ \frac{\partial \mathrm{F_i}}{\partial \mathrm{m}_4}\left(\mathrm{m}_4-\mathrm{m}_4{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \theta_1}\left(\theta_1-\theta_1{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \theta_2}\left(\theta_2-\theta_2{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \theta_3}\left(\theta_3-\theta_3{}^0\right) + \frac{\partial \mathrm{F_i}}{\partial \theta_4}\left(\theta_4-\theta_4{}^0\right). \end{aligned} \quad (15)$$

Because the left parts (15) should go to zero according to (12), then the right parts (15) should also go to zero. Therefore, from (15) we have

$$\begin{aligned} &\frac{\partial F_i}{\partial \alpha}\Delta\alpha^0 + \frac{\partial F_i}{\partial \beta}\Delta\beta^0 + \frac{\partial F_i}{\partial m_1}\Delta m_1{}^0 + \frac{\partial F_i}{\partial m_2}\Delta m_2{}^0 + \frac{\partial F_i}{\partial m_3}\Delta m_3{}^0 + \\ &+ \frac{\partial F_i}{\partial m_4}\Delta m_4{}^0 + \frac{\partial F_i}{\partial \theta_1}\Delta\theta_1{}^0 + \frac{\partial F_i}{\partial \theta_2}\Delta\theta_2{}^0 + \frac{\partial F_i}{\partial \theta_3}\Delta\theta_3{}^0 + \frac{\partial F_i}{\partial \theta_4}\Delta\theta_4{}^0 = \\ &= -F_i(\alpha^0,\beta^0,m_1{}^0,m_2{}^0,m_3{}^0,m_4{}^0,\theta_1{}^0,\theta_2{}^0,\theta_3{}^0,\theta_4{}^0), \end{aligned} \quad (16)$$

where $\Delta\alpha^0 = \left(\alpha-\alpha^0\right)$, $\Delta\beta^0 = \left(\beta-\beta^0\right)$, $\Delta m_i{}^0 = \left(m_i - m_i{}^0\right)$; $\Delta\theta_i{}^0 = \left(\theta_i - \theta_i{}^0\right)$.

All partial derivatives in (16) must be calculated at a point $X^0 = (\alpha^0, \beta^0, m_1{}^0, m_2{}^0, m_3{}^0, m_4{}^0, \theta_1{}^0, \theta_2{}^0, \theta_3{}^0, \theta_4{}^0)$. Relation (16) is a system of linear algebraic equations with respect to unknowns $\Delta\alpha^0 = \left(\alpha-\alpha^0\right)$, $\Delta m_i{}^0 = \left(m_i - m_i{}^0\right)$; $\Delta\theta_i{}^0 = \left(\theta_i - \theta_i{}^0\right)$. This system can be solved by the Cramer method if its main determinant is nonzero [5] and find the quantities $\Delta\alpha^0 = \left(\alpha-\alpha^0\right)$, $\Delta\beta^0 = \left(\beta-\beta^0\right)$, $\Delta m_i{}^0 = \left(m_i - m_i{}^0\right)$, $\Delta\theta_i{}^0 = \left(\theta_i - \theta_i{}^0\right)$.

Now we can refine the zeroth approximation $X^0 = (\alpha^0, \beta^0, m_1{}^0, m_2{}^0, m_3{}^0, m_4{}^0, \theta_1{}^0, \theta_2{}^0, \theta_3{}^0, \theta_4{}^0)$ by constructing the first approximation with the coordinates

$$\alpha^1 = \alpha^0 + \Delta\alpha^0;\ \beta^1 = \beta^0 + \Delta\beta^0;\ m_i^1 = m_i^0 + \Delta m_i^0;\ \theta_i^1 = \theta_i^0 + \Delta\theta_i^0, \quad (17)$$

those
$$X^1 = (\alpha^1, \beta^1, m_1{}^1, m_2{}^1, m_3{}^1, m_4{}^1, \theta_1{}^1, \theta_2{}^1, \theta_3{}^1, \theta_4{}^1). \quad (18)$$

Let us find out whether approximation (18) is obtained with a sufficient degree of accuracy. To do this, we check the condition (the accuracy with which system (12) must be solved):

$$\begin{cases} \Delta\beta^0 \le 0{,}1; \\ \max\left|\Delta\alpha\right| \le 10; \\ \max\left|\Delta m_i^0\right| \le 0{,}5; \\ \max\left|\Delta\theta_i^0\right| \le \pi/36. \end{cases} \quad (19)$$

If condition (19) is satisfied, then for an approximate solution of system (12), we choose (18) and finish the calculations. If condition (19) is not satisfied, then we perform the following action. In system (16), instead of $X^0=(\alpha^0,\beta^0,m_1{}^0,m_2{}^0,m_3{}^0,m_4{}^0,\theta_1{}^0,\theta_2{}^0,\theta_3{}^0,\theta_4{}^0)$ taking the updated values $X^1=(\alpha^1,\beta^1,m_1{}^1,m_2{}^1,m_3{}^1,m_4{}^1,\theta_1{}^1,\theta_2{}^1,\theta_3{}^1,\theta_4{}^1)$, we repeat the algorithm, determining the values corresponding to the second approximation $X^2=(\alpha^2,\beta^2,m_1{}^2,m_2{}^2,m_3{}^2,m_4{}^2,\theta_1{}^2,\theta_2{}^2,\theta_3{}^2,\theta_4{}^2)$. If conditions (19) are satisfied, then for an approximate solution of system (12), we choose (18) and finish the calculations, and if not, we proceed to the next iteration.

After finding the channel parameters $X^2=(\alpha^2,\beta^2,m_1{}^2,m_2{}^2,m_3{}^2,m_4{}^2,\theta_1{}^2,\theta_2{}^2,\theta_3{}^2,\theta_4{}^2)$, you can recalculate the coordinates of the information subcarriers according to the rules

$$\hat{a}_{k\ \text{кор}}=\frac{\tilde{a}_k}{\sum_{l=0}^{L}\frac{K_{\max}\exp(-\alpha\cdot m_l/T)}{\pi k\beta|\sin\theta_l|}\cos(\frac{2\pi k m_l}{K_{\max}}+2\pi f_k\beta\cos(\theta_l))};\qquad(20)$$

$$\hat{b}_{k\ \text{кор}}=\frac{\tilde{b}_k}{\sum_{l=0}^{L}\frac{K_{\max}\exp(-\alpha\cdot m_l/T)}{\pi k\beta|\sin\theta_l|}\sin(\frac{2\pi k m_l}{K_{\max}}+2\pi f_k\beta\cos(\theta_l))}.\qquad(21)$$

Conclusions. Since BPSK modulation is used on pilot subcarriers, the developed algorithm allows one to estimate the carrier frequency deviation within half the distance between subcarriers. The algorithm makes it possible to use information subcarriers for tuning, not just pilot ones. In this case, the effect of phase noise caused by inter-channel interference and noise in the communication channel is further reduced. The use of modulation for information subcarriers with many positions leads to a decrease in the limits for estimating the deviation of the carrier frequency. Therefore, at the beginning of synchronization, it is recommended to use only pilot subcarriers for estimation, and to use all subcarriers of the working frequency range for further tuning. The developed algorithm has low complexity with a small number of reference subcarriers (10–20). Therefore, its use is effective in OFDMA systems.

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