Розроблено динамічну модель множинних взаємодій n-елементої складної системи мобільного зв'язку, в якій враховано характер міжелементних зв'язків і фазових станів угруповання радіоелектронних засобів. Модель описує електромагнітну обстановку угруповання радіоелектронних засобів в просторі станів при груповому використанні частотного ресурсу.

Проведене моделювання динаміки взаємодії і фазових станів угруповання радіоелектронних засобів, при груповому використанні частотного ресурсу.

Показано, що при досить великих значеннях коефіцієнту росту числа радіоелектронних засобів може відбуватися як різке збільшення рівня інтенсивності взаємодій, так і різке зниження, характерне для тих ситуацій, які виникають в системах мобільного зв'язку у час найбільшого навантаження, в місцях великої щільності мобільних користувачів.

Проведено аналіз динамічної поведінки угруповання радіоелектронних засобів системи мобільного зв'язку при різній інтенсивності лінійних і нелінійних множинних взаємодій сукупний характер яких відображається нормованим значенням відношення сигнал/(завада+шум). Розглянута динаміка нерівноважних станів угруповань 2 мобільних мереж при різних значеннях інтенсивності взаємодій. Встановлено, що нерівноважний стан мобільної системи зв'язку настає при зростанні сумарного рівня групового впливу випромінюючих пристроїв на приймальні пристрої при нормованому значенні інтенсивності взаємодій більше ніж 1,4.

Виявлено умови, за яких угруповання радіоелектронних засобів системи мобільного зв'язку зможуть функціонувати без погіршення показників якості, що відображені сумарним рівнем групового впливу випромінюючих пристроїв на приймальні пристрої, за умов оптимального розподілу частотного ресурсу.

Показано, як за допомогою нелінійної системи Вольтера, що моделює динаміку взаємодій угруповання радіоелектронних засобів, можна аналізувати її стан в майбутньому. Дана модель дозволяє виконувати аналіз стану угруповання радіоелектронних засобів при різних, конкретних параметрах окремих типів радіоелектронних засобів, характері і інтенсивності їх взаємодій в угрупованні при діючому розподілу ресурсів

Ключові слова: динамічна модель, множинні взаємодії, електромагнітна обстановка, розподіл ресурсів, розподіл частот

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MODEL OF DYNAMICS OF THE GROUPING STATES OF RADIO ELECTRONIC MEANS IN THE PROBLEMS OF ENSURING ELECTROMAGNETIC COMPATIBILITY

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1. Introduction

Modern comprehensive development of telecommunications means is on the path of globalization and personalization of communications, the intensive creation of new means and systems of terrestrial and satellite based and, as well, their wide integration.

The creation of new global telecommunication systems and networks, the intensive development of corporate communication systems, a significant increase in personal communications and the volume of services provided highlights the problem of electromagnetic compatibility (EMC) of various telecommunications, and in particular radio-electronic means of transmitting and receiving information [1].

The need to analyze the problems of EMC arises both when carrying out certain activities related to changes in the electromagnetic environment (EME) in a group, and as a result of the introduction of certain measures to improve EMC in this group. In recent years, there is an increasing need for radical changes and redistribution of plans for the used frequency bands due to a change in requirements primarily for mobile communication systems (MCS). Practice shows [2] that the radio-frequency range plays an increasingly important role in various tasks, including in modern infocommunication systems [3]. Moreover, the radio-frequency spectrum is gradually redistributed to meet the modern needs of the information society. The development of modern wireless systems for various purposes entails the use of a large number of stationary and mobile radio electronic means (REM).

Providing them with a radio frequency resource in conditions of its shortage leads to the need to develop and apply new methods for assigning radio frequencies. This in turn requires a high-quality solution to the EMC problem.

Currently, there are many developed methods for the analysis of REM EMC, usually based on a deterministic approach in assessing the EME parameters, for example, levels of the useful signal and noise, their spectral composition, etc. These methods allow the EMC to be estimated with some accuracy.

In conditions of complex EME frequency ranges of operation of modern mobile communication systems for the analysis of EMC, the necessary information on the quantitative characteristics of interference in a specific case. It is necessary to know what their energy, spectral and statistical characteristics are. EME is also complicated by multi-emissivity, due to the random movement of the REMs of those affected REM, as well as various objects and people, the inaccuracy of the characteristics of the antenna patterns, etc.

A probabilistic assessment takes into account EME parameters that vary randomly, that is, the probabilistic nature of the multiple effects of REM of mobile communication systems, the probability of the occurrence of intermodulation effects and frequency components of a spectrum of nonlinear origin, etc. Moreover, the calculated values of the noise and signal intensities include the probability densities of their occurrence, and the REM susceptibility to interference is estimated using statistical models of interference and signal.

To solve the problem of the presence or absence of compatibility, it is necessary to establish the nature of the influence of interference and evaluate the results of this influence on the quality of the REM operation in this group. The choice of a particular model is determined by the analysis method, the requirements for its accuracy, properties and reliability of the source data. For example, with a high degree of interaction of elements in the REM grouping, a non-equilibrium state of the system occurs, which leads to a loss of its stability. From the point of view of the radiophysical interpretation, such a state can occur when there is multiple interference in the REM grouping of mobile communication systems, which also occurs under conditions of non-optimal frequency resource distribution.

EMC analysis in a group of electronic devices is based on the results of a study of the electromagnetic environment and parameters affecting EMC at a qualitative and quantitative level. Therefore, it is advisable to find the levels of maximum multiple impacts at which the non-equilibrium state of the REM grouping of mobile communication systems occurs in which it becomes impossible to operate the system in terms of quality indicators.

In this regard, it is urgent to develop a mathematical model of the states of the grouping of electronic devices in the group use of a frequency resource, based on a dynamic model of multiple interactions of n-elements of a complex system, which takes into account the nature of micelle elements and phase states.

The development of such a model will make it possible to thoroughly analyze the REM grouping of mobile communication systems in solving the problem of the optimal distribution of the frequency resource of the grouping of electronic equipment under non-linear electromagnetic effects.

2. Literature review and problem statement

The need to analyze the EMC tasks arises both when carrying out certain activities related to changing the EME group, and as a result of the introduction of certain measures to improve EMC in this group. In recent years, there is an increasing need for radical changes and the redistribution of plans for the used frequency bands is associated with a change in requirements primarily for mobile communication systems. The conditions for solving the problem of the appointment of radio frequencies in mobile communication systems differ in variety, due to the number and density of REM distribution, the degree of their mutual influence, the amount of allocated frequency resource and restrictions on its use, which does not allow to develop a universal method for assigning frequencies, since many known methods have limitations or by the dimension of the problem, or by the accuracy of the obtained results [3].

To develop methods of frequency planning under various operating conditions of radio electronic equipment, suitable for implementation by radio frequency organs, it is necessary to develop optimal frequency assignment algorithms that are acceptable in terms of speed and accuracy, taking into account the properties and specifics of mobile communication systems. This task is closely related to the problem of electromagnetic compatibility of electronic equipment.

It is known that electronic equipment in the tasks of ensuring their electromagnetic compatibility can be grouped according to the following main indicators [3]:

1) by types of funds in the grouping – groups with the same and different types of REM;

2) according to the types of undesirable effects taken into account – through joint, out-of-band (adjacent) and side reception channels;

3) by the density of REM distribution in the grouping – “sparse” and “concentrated” groups.

In “sparse” groupings, duel situations of mutual influence of REM are taken into account, and in “concentrated” groupings the group influence of interference is taken into account, it requires the use of appropriate techniques for the comprehensive type of EMC assessment.

So, in works [4-10] new analytical approaches are considered in the relations of modernization of frequency assignment methods in wireless and mobile communication systems from the point of view of EMC assessment.

In [4], a fifth-generation (5G) style infrastructure is considered, which is presented in the form of dense and heterogeneous deployment of small cells of cells overlapping with existing macroelements of the Radio Access Network (RAN). Research based on the SDWN Software-Defined Wireless Networking technology for performing frequency assignment, interference, and handover control in a heterogeneous cloud radio access network (H-CRAN – Heterogeneous Cloud Radio Access Networks), which act as Candidate Architecture for 5G Sustainable Deployment. This article discusses how SDWN can support the development of a flexible, programmable, and resilient 5G infrastructure. At the same time, the SDWN concept provides for the analysis of the signal-noise situation and the search for free (unloaded) parts of the spectrum based on the algorithm of panoramic analysis of frequency ranges and the algorithm for sequentially reconfiguring the radio frequencies, which requires direct enumeration of the frequency channels used and then a decision is made to adapt the operation parameters configurable network.

In [5], the problem of frequency assignment of a wireless surveillance sensor network (WSSN) using the graph coloring method is investigated. The results show that these methods are very suitable for this problem, as they are able to find the best solutions among alternative methods. The disadvantage is an approximate solution based on the specifics of the method under consideration.

In [6], a genetic algorithm is applied to the problem of frequency distribution of radio stations, and the traditional algorithm is improved by introducing a "greedy" algorithm, hybridization, and other methods. The simulation results show that an improved genetic algorithm can effectively solve the problem of radio frequency assignment and has high speed. The disadvantages of the genetic algorithm include a rather high computational resource consumption, which leads to the fact that in the course of modeling evolution, many solutions are discarded as unpromising, as a result of which the optimal solution is guaranteed.

In work [7] a probabilistic greedy algorithm for solving the problem of channel assignment in cellular networks is presented. The time taken by this algorithm is acceptable when fast channel assignment is of paramount importance, while the marginal deviation from optimality may be acceptable. The speed of the "greedy" algorithm relative to other algorithms is quite high, however, the exact solution may not always be obtained.

In [8], a scheme is proposed that combines the ability of convergence of a neural network and the possibility of a global search for a genetic algorithm for solving the frequency assignment problem.

In [9, 10], a channel assignment strategy based on an adaptive genetic algorithm (GA) is introduced to manage resources and reduce the effect of EMC interference.

It is also worth noting that in the aspect of the problems of dynamic resource allocation in mobile communication systems, a special place is occupied by the tasks of calculating and planning mobile communication networks using femtocells.

Despite the general problem of optimizing the radio frequency resource when using femtocells in a macro-network of mobile communications, the optimization problem is solved in [11], which combines two subtasks, namely, the optimal distribution of subchannels and the optimal power distribution of the REM of the macro-net and femtocells. To solve this problem of integer programming, an efficient resource allocation algorithm based on the distributed spectral sounding of the DIRA spectrum (Distributed Imperfect-Spectrum-Sensing-Based Resource Allocation) is proposed.

Judging by the analysis of the work [12] of this topic, let's conclude that a simple solution to the problem of placing femtocells is a direct enumeration of options. However, with the increase in the number of femtocells, the task becomes complete.

From the point of view of the analysis of electromagnetic compatibility in the considered works, the problem of optimal frequency assignment in wireless networks is directly solved. Other EMC tasks are of great scientific and practical interest: the analysis of the effectiveness of certain actions that violate the change of EME specific conditions, with specific signals, systems, processing algorithms, etc.

Judging by the analysis of sources, it can be pointed out that the existing methods of frequency resource allocation in the analysis of REM EMC and methods of expert estimates of frequency assignment, which are used when introducing new REM, are based on methods developed for stationary radio communication systems more suitable for duel jamming interactions.

In a dynamic environment, it is changing rapidly, with a difficultly predicted signal-jamming situation, of the plural nature of electromagnetic interactions, a more general stochastic approach must be applied, allowing to take into account the group nature of the influence in the REM grouping.

Thus, a problem is discovered that consists in the fact that the deterministic models for assessing the grouping state when solving the problem of frequency resource allocation can't be distributed directly to the indicated REM grouping of mobile communication systems. To solve it, it would be advisable to develop such an analytical model of the states of the REM grouping that adequately reflects the dynamics of changes in these states from the standpoint of EMC analysis under the conditions of the plural nature of electromagnetic effects.

3. The aim and objectives of research

The aim of research is development of a dynamic model of multiple interactions of *n*-elements of a complex mobile communication system, which takes into account the nature of micelle elements and phase states in the group use of frequency resources. This will make it possible to conduct a sufficiently complete analysis of the EMC conditions in the REM grouping of mobile communication systems, evaluate the EME of existing networks and give recommendations on networks that are deployed when solving the problem of frequency resource allocation.

To achieve the aim, the following objectives are set:

– on the basis of a complex model of an *n*-element system with multiple interactions, develop a mathematical model for describing the electromagnetic environment of a grouping of electronic equipment in the state space when they are used in a group frequency resource;

– provide a recurrence expression for calculating the total level of intensity of interactions of a group of electronic devices using the Volterra mathematical model and simulate the dynamics of the interaction of elements and phase states of a group of electronic devices when using a frequency resource in group;

– analyze the interaction of system elements under which groups of electronic equipment of a mobile communication system will be able to function without deterioration of quality indicators, which reflect the total level of group influence of radiating elements on receiving devices, under conditions of optimal frequency resource distribution.

4. Development of a mathematical model for describing the state of the electromagnetic environment in a grouping of electronic equipment

In the grouping of radio electronic means (REM), the main parameters of the means themselves are usually known, determined. The macro-condition of the entire group is random. This is due to the influence of many uncertain, random conditions formed by the propagation characteristics of radio waves (RWP). As a result of random interactions $x_{ij}(t)$,

$i=\overline{1,n}, \quad j=\overline{1,n},$ where n – the number of REM, in the REM parameters there are changes. In the REM grouping, there are corresponding dynamic interactions that appear as a result of measurements and observations and are characterized by a vector. The dynamics of these changes is described by a fairly general differential equation

$$\frac{d\vec{x}(t)}{dt}=k\Phi\left[\vec{x}(t),Y^*(t)\right], \tag{1}$$

where $k=diag\left(k_i, i\in\overline{1,n}\right)$ if x_i independent or matrix $K[n\times n]$ in the presence of their dependence.

The success of solving the electromagnetic compatibility problem of the considered group depends on the available resources

$$g_k=g_k\left(\vec{x}(t),t\right), \quad k\in\overline{1,r},$$

as well as on known a priori probabilities

$$a_{ij}=a_{ij}\left(\vec{x}(t),t\right), \ \left(i,j\in\overline{1,n}\right)$$

and parameters c_{ijk} that determine the characteristics of this connection between REMs, which are independent of $x(t)$.

In addition, the observations $\vec{y}(t)$ themselves become state dependent. Therefore, more specifically, equations (1) can be represented as

$$\frac{d\vec{x}(t)}{dt}=\Phi\left[\vec{x}(t),Y^*\left(\vec{x}(t),t\right)\right].$$

The available resources g_k are determined by the sum of the frequency-territorial, time, polarization, energy and other parameters of the REM and communication lines. They can be represented as:

$$g_k\left(\vec{x}(t),t\right)=\sum_{i,j=1}^{n}c_{ijk}y_{ij}, \ y_{ij}\geq 0, k\in\overline{1,r}, i,j\in\overline{1,r}. \tag{2}$$

In the system of grouping REM during its operation, an appropriate redistribution of resources $Y^*(t)$ is implemented, which is determined by models of stationary states described by the tasks of maximizing the entropy of the system [9–11]

$$H(Y)=\sum_{i,j=1}^{n}y_{ij}\ln\frac{a_{ij}}{y_{ij}}+y_{ij}\rightarrow\max \tag{3}$$

at the appropriate resource limits.

The dynamics of the state of the distribution process is determined by the solution $Y^*(t)$ of this problem, which, as follows from (2) and (3), depends on its parameters a_{ij}, c_{ijk} and g_k.

Thus, the model of dynamics of states of a macro-system takes the following form:

$$\frac{d\vec{x}(t)}{dt}=\Phi\left[\vec{x}(t),Y^*\left(\vec{x}(t),t\right)\right];$$

$$Y^*\left(\vec{x}(t),t\right)=$$

$$=\arg\max\left[H(Y)\left|\sum_{i,j=1}^{n}c_{ijk}y_{ij}=g_k\left(\vec{x}(t),t\right)\right.\right],$$

where

$$H(Y)=\sum_{i,j=1}^{n}y_{ij}\ln\frac{a_{ij}}{y_{ij}}+y_{ij}.$$

Let's consider the structural diagram of the macrosystem formed by the REM grouping (Fig. 1). Obviously, this scheme is a special case of the basic model of the system shown in Fig. 1.

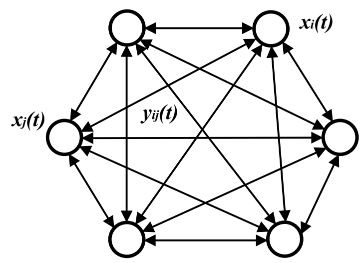

Fig. 1. The structural diagram of interactions y_{ij} in the macro-system for group use of the resource

Electromagnetic interactions $y_{ij}(t)$ occur between elements $x_i(t)$ and $x_j(t)$, accordingly: sources and receptors.

Interacting relationships between elements are determined by matrices $C_k=\left[c_{ijk};\ i,j\in\overline{1,n}\right]$ consisting of 0 and 1 and determine the presence or absence of such a relationship. Elements of the vector $Y^*(t)$ in the general case are complex quantities, and determine the amplitude and phase of the interactions that take place. An analysis of such a system is presented below.

Expression (1) represents a general model of the dynamics of non-equilibrium states, the interactions in which are characterized by a vector $\vec{y}(t)$. Apparently, in such a non-equilibrium system, two main processes (flows) are noted: recovery and distribution. Such a process is observed in mobile communication systems, when subscriber stations consume and release the BS (base station) resource, thus, the distribution and restoration of the MCS (mobile communication system) resource occurs.

Let's denote by the $\Phi\left[\vec{x}(t),Y(t)\right]$ recovery flow and by the $Q\left[\vec{x}(t),Y(t)\right]$ distribution flow. These flows depend on the state $x(t)$ – the recovery process and the state $Y(t)$ – the distribution process.

Under the assumption that the recovery time is much longer than the distribution time [10], it is possible to write the following, in the general case, nonlinear system of equations:

$$\frac{d\vec{x}(t)}{dt}=\Phi\left[\vec{x}(t),Y^*\left(\vec{x}(t),t\right)\right], \tag{4}$$

$$\varepsilon\frac{dY(t)}{dt}=Q\left[\vec{x}(t),Y^*\left(\vec{x}(t),t\right)\right], \tag{5}$$

where ε – a matrix of small parameters that determines the intensity of electronic interactions in a given system.

From these equations it can be seen that the coordinates $\vec{x}(t)$ change much more slowly than $Y(t)$. The formation of a model of the form (5) for a distribution process with constraints and heterogeneous resources remains an unresolved problem [9–11]. Let's manage to build such a model only for those cases when the dynamics of the distribution process is Markov, for the constraints of the balance type. In this case, it can be assumed that the dynamics of the distribution process is Markov [9–11], since it does not matter when and how the macro system transitioned in its current state, but only that the system uses the current time-frequency, polarization, time resource or spatial.

Let's analyze the dynamics of the state of the REM grouping. For this, it is necessary to describe the structure of resources and their distribution between REMs. Let's consider the grouping of radio electronic equipment, consisting of many transmitters and receivers. All of them are resource consumers. If the consumers of the resource consist of n types with numbers Y_i, then the quantity of the resource B is a function of the number of types $B=B(Y_1,...,Y_n)$. In the absence of consumers $(Y_1=...=Y_n=0)$, let's have the maximum resource $B(0)$. In the case of a very large number of them $(Y_1\to\infty,...,Y_n\to\infty)$, the resource tends to zero $B(\infty)=0$. The number of operating REMs is constantly growing. There is reason to consider this reason as the main one, leading to the general "clogging of the ether." The rate of change in the number of REM of i-th type is determined by the appearance of new k_iY_i (the coefficients k_i can be taken constant $k_i=\text{const}$) and the disappearance of operation g_iY_i. Competition for a resource affects the process of disappearance of REM from interactions, that is, the coefficients g_i depend on the amount of resource u_i consumed on average by one REM $g_i=g_{i0}-\mu_i u_i;\ \ g_{i0},\mu_i>0.$

Then

$$\frac{dY}{dt}=\varepsilon_i Y_i+\mu_i w_i,\ \ i\in\overline{1,n}, \tag{6}$$

where $w_i=u_iY_i$ – the amount of resource consumed by the i-th type of REM; $\varepsilon_i=k_i-g_{i0}$.

The distribution of the resource B is much faster than its recovery. Therefore, let's consider the stationary states of the distribution process at fixed at the moment of time t quantities of REM types.

The mechanism of this process can be represented as follows. Let the resource be consumed in portions – subbands (sections) of frequencies Δ. Then $B=m\Delta$, where m – the number of transmission channels. It can be assumed that the transmission channels are randomly and independently distributed over the entire group n of REM types so that each type has an amount of resource $w_i=\Delta m_i$.

For this distribution process, it is possible to specify some a priori characteristic. For each REM type, the standard amount of the resource a_i is usually known. Let's determine the value

$$v_i=\frac{a_iY_i}{\sum_{i=1}^{n}a_iY_i};\ \ 0\le v_i\le 1;\ \ \sum_{i=1}^{n}v_i=1. \tag{7}$$

Then the process of random distribution of a resource by REM type is equivalent to a random and independent distribution m of channels by n REM type with an a priori distribution probability $V=\{v_i,...,v_n\}$. The stationary state of such a process is determined by a model of the form

$$H(w)=\sum_{i=1}^{n}\left(w_i\ln\frac{v_i}{w_i}+w_i\right)\to\max,$$

$$\sum_{i=1}^{n}w_i=B(Y). \tag{8}$$

In view of (7), let's obtain

$$w_i^*=a_iY_i\frac{B(Y)}{\sum_{i=1}^{n}a_iY_i}.$$

Let's substitute this expression in (4):

$$\frac{dY}{dt}=Y_i\left(\varepsilon_i+\tilde{a}_i\phi(Y)\right), \tag{9}$$

where

$$\phi(Y)=\frac{B(Y)}{\sum_{i=1}^{n}a_iY_i}.$$

Let's take into account such qualitative properties of the function $B(Y)$, such as $\left(B(0)\ne 0, B(\infty)\to 0\right)$ counting $B_{\max}=B(0)$. It follows from this that $\phi(Y)$ will monotonously decrease for $Y_i\ge 0$.

In this case, the coefficients of its linear approximation are negative, i. e.

$$\phi(Y)\cong\phi(\tilde{Y})=\sum_{s=1}^{n}v_s\left(Y_s-\tilde{Y}_s\right), \tag{10}$$

where $v_s\ge 0,\ s\in\overline{1,n},\ \tilde{Y}=\left\{\tilde{Y}_1,...,\tilde{Y}_n\right)$ – fixed numbers. Substituting (10) into (9) let's obtain the Volterra system, which characterizes the dynamics of the coexistence of a REM grouping in a competitive struggle for a common resource [4]:

$$\frac{dY}{dt}=Y_i\left(\varepsilon_i-\sum_{s=1}^{n}v_sY_s\right). \tag{11}$$

If use the quadratic approximation to describe the function $\phi(Y)$, let's obtain a nonlinear Volterra system that takes into account the influence of random noise on the state of the REM grouping:

$$\frac{dY}{dt}=Y_i\left[\varepsilon_i-\sum_{s=1}^{n}v_sY_s-\sum_{s=1}^{n}\sum_{j=1}^{n}v_{sj}Y_sY_j\right]. \tag{12}$$

To simulate the dynamics of the state of interactions in a REM grouping, it is convenient to switch from system (12) to its recurrence record

$$Y_i(k+1)=Y_i(k)+$$
$$+Y_i(k)\left[\varepsilon_i-\sum_{s=1}^{n}v_sY_s(k)-\sum_{s=1}^{n}\sum_{j=1}^{n}v_{sj}Y_s(k)Y_j(k)\right], \tag{13}$$

where k – discrete time, $i,j,s\in\overline{1,n}$.

5. Modeling the dynamics of the interaction of elements and phase states of the REM grouping

As an example, let's consider the macrostate dynamics of a grouping of four types of REM $(n=4)$ for various values ε that take into account the growth trend of their numbers. Therefore, as initial data let's accept: $\varepsilon=0, 1, ..., 4.$ The amount of each type of REM at the initial moment is a random number in the range from 1 to 100, the frequency and energy resources are the same for all types.

Fig. 2 shows the change in the interactions (abundance) of REM at $\varepsilon_1 = 0.1$; $\varepsilon_2 = 0.2$; $\varepsilon_3 = 0.1$; $\varepsilon_4 = 0.3$ in time. Line numbers 1–4 correspond to the indices of the REM types.

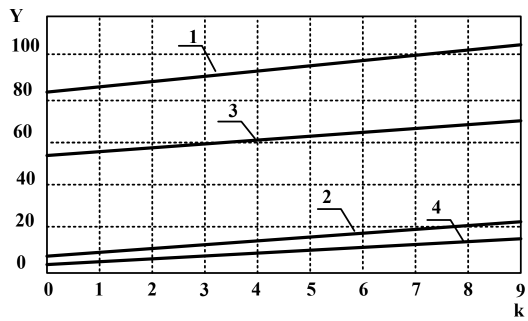

Fig. 2. The dependence of the number of consumers with a weak intensity of interactions:
1 — ε_1=0.1; 2 — ε_2=0.2; 3 — ε_3=0.1; 4 — ε_4=0.3

As can be seen from Fig. 2, for small values of ε, the dependence of the REM interactions almost linearly increases in time, and with further k – growth stops. This trend is obviously characteristic of the initial stages of REM development.

For values $\varepsilon_1 = 2$; $\varepsilon_2 = 2.1$; $\varepsilon_3 = 2$; $\varepsilon_4 = 2$ (Fig. 3) 2 characteristic areas of the graphs are marked. The initial region, where there is a sharp increase in the number of interactions, and the stationary, equilibrium part with subsequent small fluctuations in time, which is associated with the redistribution of the resource.

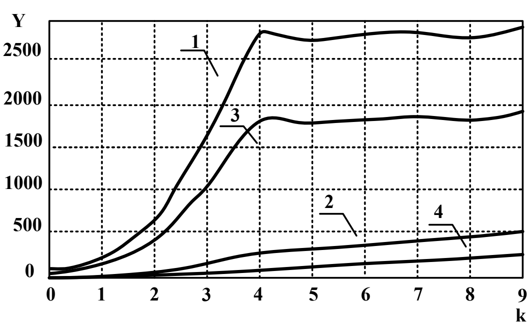

Fig. 3. The dependence of the number of consumers on time at a subcritical intensity of interactions

For values $\varepsilon_1 = 2.6$; $\varepsilon_2 = 2.65$; $\varepsilon_3 = 2.6$; $\varepsilon_4 = 2.67$ (Fig. 4) 2 areas are also marked.

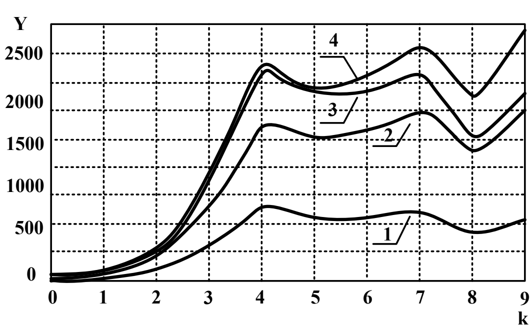

Fig. 4. The dependence of the number of consumers on time in the field of critical intensity of interactions:
1 — ε_1=2.6; 2 — ε_2=2.65; 3 — ε_3=2.6; 4 — ε_4=2.67

The initial region, with a monotonic increase in the increase in interactions, then noticeable fluctuations are observed associated with reaching critical values for the saturation of the system, with the influence not only of the REM number, but also the limitation of the available resource.

The dynamics of interactions of the REM grouping at values is also analyzed $\varepsilon_1 = 3.7$; $\varepsilon_2 = 3.8$; $\varepsilon_3 = 3.7$; $\varepsilon_4 = 3.9$ (Fig. 5), in which the system acquires an extremely saturated state.

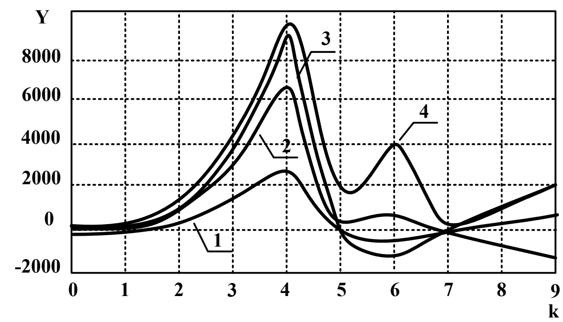

Fig. 5. The dependence of the number of consumers on time in the supercritical area of interactions:
1 — ε_1=3.7; 2 — ε_2=3.8; 3 — ε_3=3.7; 4 — ε_4=3.9

The obtained results indicate that for sufficiently large values of the growth factors of the REM number, the dynamics of interactions becomes unpredictable: both a sharp increase in interactions and a sharp decrease characteristic of those situations that arise in cellular systems in the peak hours, in places of congestion of subscribers, can occur.

6. Analysis of the interaction of the REM grouping function without deterioration of quality indicators

Let's consider the dynamics of non-equilibrium states of the groups of 2 mobile networks at various values ε that take into account the intensity of interactions. As the intensity of interactions, one can choose the parameter for evaluating the EMC networks, such as the ratio of the permissible SINR (signal to interference plus noise ratio) to the real SINR at the REM networks

$$\varepsilon = \frac{h_{add}^2}{h^2}.$$

The SINR is defined as the ratio of the useful signal power to the sum of the interference powers. By the sum of the interference power let's mean the total noise background coming from the REM of extraneous (interfering) networks.

In Fig. 6, *a*, the dependences of the interaction (mutual influence) Y_i of the two networks at low intensities of interactions $\varepsilon << 1$ are presented, that is, it is assumed that the real SINR is much larger than the permissible. Curve numbers correspond to network numbers. As can be seen from Fig. 6, and at small but different values ε, the dependence of the influence between the REMs of the two networks almost linearly increases in time and with further k – the growth stops. The difference is that $\varepsilon_1 < \varepsilon_2$. The physical meaning of this inequality lies in the fact that the second network creates a larger overall noise background in power compared to the first network. Therefore, the influence $Y_1 < Y_2$.

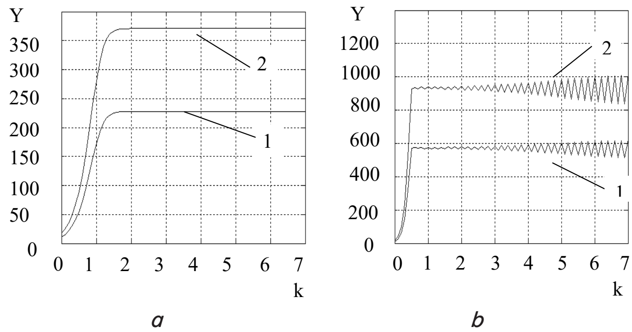

Fig. 6. The dependence of the influence of networks: *a* – with a weak intensity of interactions; *b* – with an average intensity of interactions

At average values $\varepsilon \approx 1$ (Fig. 6, *b*), 2 characteristic areas of the graphs are noted. The initial region, where there is a sharp increase in interactions, and the stationary, non-equilibrium part with subsequent noticeable fluctuations in time, which is associated with the redistribution and limitation of the available resource.

The case of network operation at high intensities $\varepsilon >> 1$ (Fig. 7), at which the system acquires a beyond saturated state, is analyzed. The obtained results indicate that, at sufficiently large values of the REM intensity, the dynamics of interactions becomes unpredictable: both a sharp increase in interactions and a sharp decrease, characteristic of those situations that occur in MCS during abnormal network operation modes, can occur.

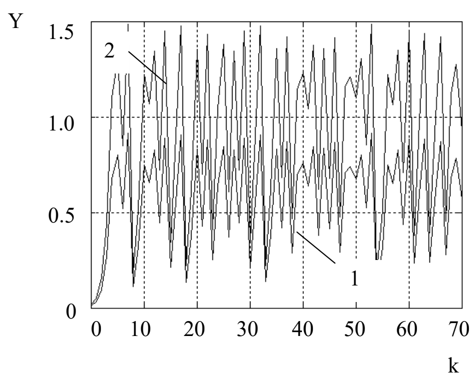

Fig. 7. The dependence of the influence of networks at high intensity interactions (1 – mobile network 1; 2 – mobile network 2)

The study of non-equilibrium states is of considerable and independent interest. The work demonstrates the method of its use for the EMC analysis.

This model allows to perform analysis with various, specific parameters of network elements, their interactions in the allocation of resources. These studies allow to give recommendations in the planning, design, frequency and territorial planning and operation of MCS networks. According to this analysis, it becomes possible to determine the equilibrium states and stability of dynamic interacting groups of MCS networks at various values of the intensity of interactions ε.

As it turned out, there is a critical number ε at which the grouping of networks does not lose stability is $\varepsilon \cong 1.4$. Fig. 8 shows a phase portrait of the interaction of network groupings constructed in coordinates $\left\{\vec{Y}, \vec{\varepsilon}\right\}$. According to this graph, it follows that in the region $\varepsilon > 1.4$ there occurs a bifurcation of trajectories (state bifurcation).

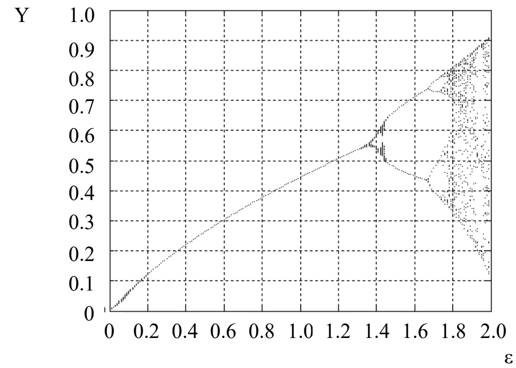

Fig. 8. Phase portrait of the interaction of network groups

Changes in the state of the observed system in the region $\varepsilon \geq 1.4$ can turn out to be significant and ambiguous with insignificant changes in the interaction intensities.

7. Discussion of the results of the dynamics of the state of the REM grouping of the mobile communication system

Based on expression (12), a nonlinear dynamic model of non-equilibrium states in electromagnetic interactions in the groups of radio electronic systems of mobile communication systems is proposed.

The obtained results of the aggregate nature of multiple interactions are reflected by the normalized value ε, respectively, of the model (6). The value of this indicator ε depends, in turn, on the changing parameters of the electromagnetic environment, in particular, on the total level of interference at which actions from the REM influence, the distances between the REM influence, the presence of additional attenuation coefficients, etc.

When modeling the dynamics of the interaction of elements and phase states of the grouping of electronic means of a mobile communication system, it is revealed that, depending on the degree of interaction of network elements, there are three characteristic states of MCS operation: equilibrium state, transition (limit) mode, transcendental mode, bandages are associated with loss of stability (Fig. 2–5). The conditions for the existence of a critical equilibrium state of the system under study, which arrive under conditions of a limited resource at various intensities and the number of interactions in this system, are obtained (Fig. 6).

The phase states of the dynamic model 2 of the studied mobile communication systems in the beyond are investigated. As can be seen from the obtained simulation results presented in Fig. 7, 8, chaotic regimes and bifurcations of phase trajectories arise in this region, systems lose stability. It is established that the non-equilibrium state of MCS occurs when the total level of the group influence of radiating elements on the MCS receiving devices increases at $\varepsilon = 1.4$ and corresponds to the normalized value of the SINR: $0.7(P_s/P_{I+N})$. The magnitude of these chaotic manifestations is greater, the deeper the system plunges into the beyond.

The obtained results confirm the prospect of the possibility of constructing a probabilistic characteristic of the MCS state in the electromagnetic environment under consideration.

Given the highly dynamic state of mobile communication channels, which is due to the spatial movement of mobile stations and the wide variation in signal propagation, the task of dynamically allocating resources becomes NP-folding. So to solve it, it is necessary to apply methods based on the Markov theory of nonlinear or linear filtering, in particular, Kalman-Bucy filtering methods.

The developed method expands the space for solving problems in the future, analyzing the quality of the functioning of mobile and wireless communication systems in complex signal-noise conditions, solving the EMC problem of the internal and intersystem nature in difficult electromagnetic conditions, in the problems of optimal solution of the distribution of physical resources (frequency, time spatial, polarizing) between network elements, building frequency-territorial plans of mobile communication systems.

One of the main limitations when choosing an EMC analysis model for MCS is the justification of the criterion, which must meet the decision to create satisfactory conditions for the security and interference environment to ensure EMC in the REM grouping. The complexity of solving the REM EMC problem is due to the fact that the parameters of useful signals, noise, and also the noise itself in MCS are random and often unsteady processes with unknown current characteristics. The frequency spectra of useful signals and interference are usually different, with varying degrees of overlap. All this is the reason for the diversity of the selected criteria and the ambiguity in assessing the state of the EMC of REM groupings.

More precisely, to evaluate time-varying signals and interference, the application of the criterion is the ratio of the convolution of the signal and interference spectra in the form of an indicator of the decrease in the energy reserve EML (Energy Margin Loss). At the same time, for its use in the proposed model, a large amount of a priori data on the parameters of interacting elements is required. The application of the criterion based on the selection of the acceptable level of the SINR in the proposed model is a certain approximation. However, the use of the SINR criterion greatly simplifies the analysis of EME and the calculation of EMC parameters.

A feature of the developed model is the determination of the limit levels of group actions at which MCS can become unstable due to failure to fulfill the permissible value of the SINR criterion for each network element. After calculating the SINR, it is necessary to determine the channel capacity and the probabilistic characteristic of the quality of operation, according to which the real possibility of the network functioning in the existing EME is estimated. The model enables specialists to reasonably analyze the EMC of a grouping of networks of mobile communication systems, evaluate the EME of existing networks and develop recommendations on the networks that will be introduced, to carry out high-quality network planning from the point of view of fulfilling the EMC conditions.

Further development of the subject matter of these studies can go in the direction of creating a methodology, it will take into account the type of MCS REM, the model of random distribution of network elements, the distribution density of the distribution of network elements, especially the propagation of radio waves depending on the conditions of use of the MCS REM with the development of a software package that can be registered and recommended for practical use.

9. Conclusions

1. A mathematical model of the electromagnetic environment of the grouping of electronic devices based on the Volterra model is constructed, characterizing their nonlinear nature of interactions in the group use of the frequency resource. A recurrence expression is obtained for modeling estimates of the aggregate nature of electromagnetic interactions in a group of electronic devices.

2. Modeling of the dynamics of the interaction and phase states of the grouping of electronic devices in the group use of the frequency resource is carried out. It is shown that using the Volterra model, which simulates the dynamics of interactions of the REM grouping, it is possible to analyze its state in the future. This model allows to analyze the grouping of electronic equipment with various specific parameters of individual types of REM, the nature and intensity of their interaction in the group with the current distribution of resources.

3. The dynamics of non-equilibrium states of the groups of 2 mobile networks at various values taking into account the intensity of interactions is considered. As the interaction intensity, let's chose the parameter for evaluating the EMC networks, such as the ratio of the permissible SINR to the real SINR at the REM of networks equal to permissible value SINR:0,7(P_s/P_{I+N}). Analysis shows that the REM grouping of mobile communication systems will be able to function without compromising quality indicators at the values of interactions $\varepsilon \leq 1.4$.

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