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Model of forming a spatial-temporary radio frequency portrait of subscriber terminals in satellite communication systems monitoring

Currently, the development of satellite communications systems (SCS) is associated with the development of signals of complex structure. The popularization and distribution of software-defined radio systems (Software-defined radio, SDR) are noted, which leads to a decrease of quality of functioning of the SCS. Promising areas of countering the unauthorized use of the time-frequency resource of the KA repeater are methods aimed at determining the location of subscriber terminals (ST) and analyzing the service and semantic parts of the transmitted message. Accounting for changes of physical parameters requires the use of a large amount of heterogeneous a priori data; it is not achievable task in practice. According to the theory of mathematical statistics, the approximation is used at solving problems of sample analysis. The result of the approximation is a spatio-temporal radio-frequency portrait (STRFP) of an ST participating in the formation of a group signal. Thus, the aim of the research is to develop a model of changing the physical parameters of a radio signal and to study the possibility of approximating physical parameters in order to form a spatio-temporal radio-frequency portrait of an ST SCS.

Keywords: satellite communication system, group signal, non-energy parameter, communication channel, time division multiple access, satellite repeater, radio frequency portrait, sample.

Introduction

One of the directions in the development of satellite communications systems (SCS) is the use of signals with a complex structure that allow for the efficient use of the frequency-time resource. In particular, in SCS for various purposes (commercial and military), time division multiple access (TDMA) technologies are widely used [1]. It should be noted that the rapid development of SCS leads to an increase in the number of cases of unauthorized use of the time-frequency resource of the spacecraft-relay (SC-relay), which in turn leads to a decrease in the quality of functioning of the SCS.

In this situation, the forefront is the issue of ensuring hardware accessibility to the signals of individual subscriber terminals (ST), which is achieved by decomposition of a group signal.

A method for analyzing signals with a complex frequency-time structure (CFTS) is described, which allows the separation of STs without access to the semantic component of transmitted messages [2]. This method is based on the localization of the values of non-energy parameters of the signal of an individual ST in the parameter space.

The radio exchange in the SCS, operating through spacecraft — repeaters (SC–R) in the geostationary orbit (GSO), is characterized by a dynamic change in the physical parameters of the radio signals, due to a number of reasons in practice [3–7]. Moreover, the application of the known method [2] is not possible.

Accounting for changes in physical parameters requires the use of a large amount of diverse a priori data, such as the coordinates of the Astronomical radio source and SC–R; state of the ionosphere and troposphere; temperature of atmospheric layers, water content over the entire length of the radio path, etc. [8–9], which is not a solvable task in practice.

When solving problems of sample analysis, the approximation method is used in the theory of mathematical statistics; it is a description of the experimental points by some deterministic function. The studied complex object is replaced by a simpler object in order to study its properties.

The experimental estimates of the physical parameters of the radio signal with the frequency response are approximated by some deterministic function at the final stage of observation in relation to the described problem. The result of the approximation is a spatio-temporal radio-frequency portrait (STRFP) of an ST participating in the formation of a group signal. The STRFP is directly dependent on the transmission conditions and is unique, which allows for signal decomposition based on the analysis of the STRFP.

Thus, the aim of the article is to develop a model for changing the physical parameters of a radio signal and to study the possibility of approximating physical parameters in order to form an STRFP ST SCS.

Experimental

During the propagation of radio signals through the physical communication channel, they change under the influence of various factors, including the state of the ionosphere, ion concentration over the entire length of the radio path, troposphere, water content on the propagation path, and the length of the radio path, which changes due to the motion of the spacecraft — P and subscriber terminals, etc. Moreover, the value of each physical parameter depends to a certain extent on the distance between the SC–R and the ST, the state of the atmosphere and ionosphere, which continuously changes over time. The value of the k^{th} physical parameter of the radio signal from the ST at a certain point in time is determined by the Equation (1):

$$v_k(t) = v_k(t_0) + v_k^{(R)}(t) + v_k^{(At)}(t) + v_k^{(Ion)}(t), \tag{1}$$

where $v_k(t_0)$ is the base value of the parameter at time, t_0; $v_k^{(R)}(t)$ is change in the parameter due to a change in the distance between SC–R – ST — radio monitoring receiving station; $v_k^{(At)}(t)$ is change in parameter due to the influence of the atmosphere; $v_k^{(Ion)}(t)$ is change in the parameter due to the influence of the ionosphere.

Subscriber terminals operating in the same SCS can be located at geographically distant positions and, accordingly, communication channels from ST to SC–R, depending on their condition, will affect radio signals differently.

Figure 1 shows a simulation scheme for radio monitoring of ST SCS for the following conditions:

- the period of functioning of the ST corresponded to 24 hours;
- the SC repeater moved in the area at 62° E, according to the TLE obtained from open access for the SC–R «UFO–10»;
- ST1 stationary object with coordinates 45.031° N and 41.6917° E;
- ST2 is a mobile object that performs rectilinear movement with initial coordinates of 35.934° N and 101.614° E at a speed of 40 km/h towards the sub-satellite point;
- ST3 is a mobile object that performs rectilinear movement with initial coordinates of –45.13° S and 95.66° E at a speed of 40 km / h towards the sub-satellite point;
- ST4 is a mobile object that performs rectilinear movement with initial coordinates of –45.45° S and 41.318° E at a speed of 40 km/h away from the subsurface point;
- the daily change in the total electronic content of the ionosphere on radio paths was obtained on the basis of data from the international reference model of the ionosphere [10].

The Doppler shift of the carrier frequency and the time delay with respect to the time-synchronous grid consider such as the main non-energy parameters.

In general the slant range between the ST and SC-R and the effect of the ionosphere on the propagation path of the radio signal are the main heterogeneous factors are influenced on the amount of time delay of the signals of various ATs relative to the reference time grid. The change of the time shift of the signals of individual antibodies relative to the time grid is caused by a change in these factors.

A change of the carrier frequency of the antibodies observed at the input of the receiver of the radio monitoring complex occurs due to the Doppler Effect, which, on the one hand, is caused by the movement of the SC-R on the GSO, and, on the other hand, by the movement of the mobile STs themselves, which carry out the movement during the radio communication session.

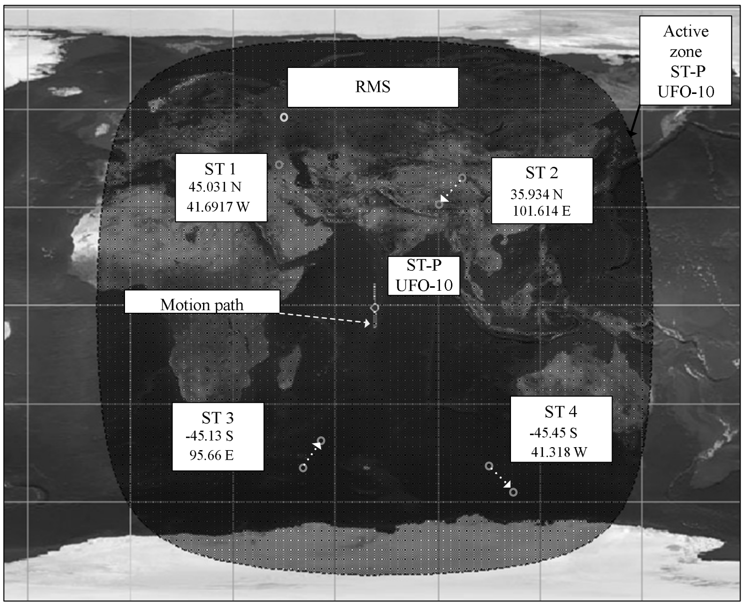

Figure 1. Scheme of the simulation of radio monitoring ST SCS

Figure 2 presents the graphs of changes of physical parameters obtained in the result of modeling.

The changes of the listed physical parameters take the form of a certain curve (Fig. 2). Moreover, two types of sections (namely, "quasilinear" and "quasiquadratic") are distinguished on each of the curves.

Polynomials of the second $y_{\text{apr\_2}}(t) = b \cdot t^2 + c \cdot t + d$ and third orders $y_{\text{apr\_3}}(t) = a \cdot t^3 + b \cdot t^2 + c \cdot t + d$ were used as approximants for studying the approximation error of changing physical parameter on a finite observation interval; the coefficients of them were found by the least squares method by minimizing the sum of the form.

The results illustrating the maximum value of the absolute error of the approximation (s) (ξ_2 and ξ_3) depending on the moment of the beginning of the observation t_0, the duration of the hour $t_{apr} = 1$ and the type of the approximating polynomial are summarized in Table 1.

When approximating a model of changing the time delay, the smallest approximation error is achieved using a third-order polynomial and does not exceed 0.68 μs $t_{apr} = 1$ for an hour (Table 1).

At the same time, it is necessary to take into account the mechanisms of noise impact in the conditions of data transmission to the SCS, operating through the spacecraft — R.

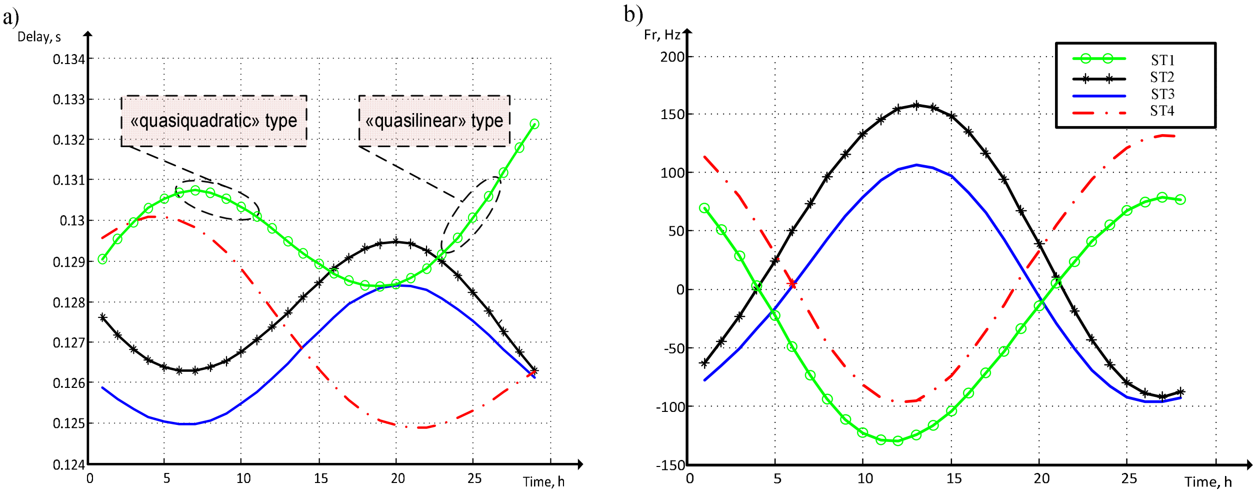

Figure 2. Change of physical parameters of the signal from subscriber terminals, where *a* is time delay relative to the reference time grid, *b* is the carrier frequency of the radio signal at the input of the receiver of the radio monitoring system

Table 1

Maximum absolute approximation error delays by polynomials of the second and third

t_{apr}, [h]	1	2	3
ξ_2, [s]	$2.655 \cdot 10^{-7}$	$14.377 \cdot 10^{-7}$	$48.059 \cdot 10^{-7}$
ξ_3, [s]	$1.8035 \cdot 10^{-7}$	$2.1529 \cdot 10^{-7}$	$3.884 \cdot 10^{-7}$

According to [11], the potential accuracy of measuring non-energy parameters such as delay $y_t(t)$ and Doppler shift $y_f(t)$ against the background of Additive white Gaussian noise, expressed through standard deviation, are determined by the Equations:

$$\sigma_{ys} = \sqrt{\frac{1}{2 \cdot E / N_0 \cdot (2 \cdot \pi \cdot \Delta f_{ek})^2}}, \quad \sigma_{yf} = \sqrt{\frac{1}{2 \cdot E / N_0 \cdot (2 \cdot \pi \cdot \Delta t_{ek})^2}},$$

where Δf_{ek} is equivalent spectral width; Δt_{ek} is equivalent observation time.

The potential accuracy of estimating the delay and Doppler frequency shift is calculated taking into account the width of the spectrum of the radio signal $\Delta f = 9600$ Hz and accumulation interval of $T = 0.025$ s, that is, a radio signal base of 240.

The dependence of the potential accuracy of estimating the delay and carrier frequency on the signal-to-noise ratio is calculated based on the described parameters (Fig. 3).

Under the conditions for receiving a radio signal with a signal-to-noise ratio of 15 dB for the considered radio signal, the standard deviation of the delay and carrier frequency corresponds to 6.949 μs and 2.668 Hz, respectively.

The error in determining the value of physical parameters is a random variable. We assume that the error of determining the value of a physical parameter is distributed according to the normal law within the framework of the model under consideration [12–16]. A sample describing the effects of noise on each of the considered parameters is formed considering the obtained results.

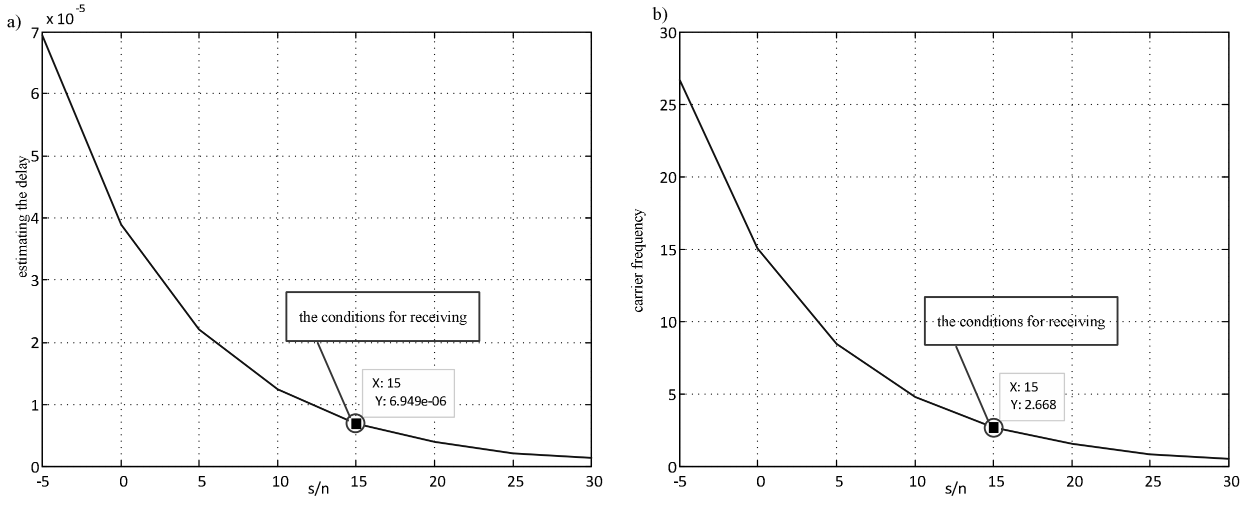

Figure 3. Dependence of the standard deviation of the parameter, where *a* is time delay on the signal-to-noise ratio; *b* is carrier frequency on the signal-to-noise ratio

The Equation describing k the physical parameter of the radio signal from the ST with the impact of noise will take the form:

$$v_k(t) = v_k(t_0) + v_k^{(R)}(t) + v_k^{(At)}(t) + v_k^{(Ion)}(t) + \hat{\delta}_k(t),$$

where $\hat{\delta}_k(t)$ is the effect of noise k on the value of the physical parameter of the radio signal from ST.

Results and Discussion

The error of approximation by polynomials of the second and third order under the influence of noise was studied based on the additive model (3). A «quasiquadratic» section was selected for the experiment.

A change in the time delay was simulated for a typical reception state with an SNR of 15 dB (Fig. 4).

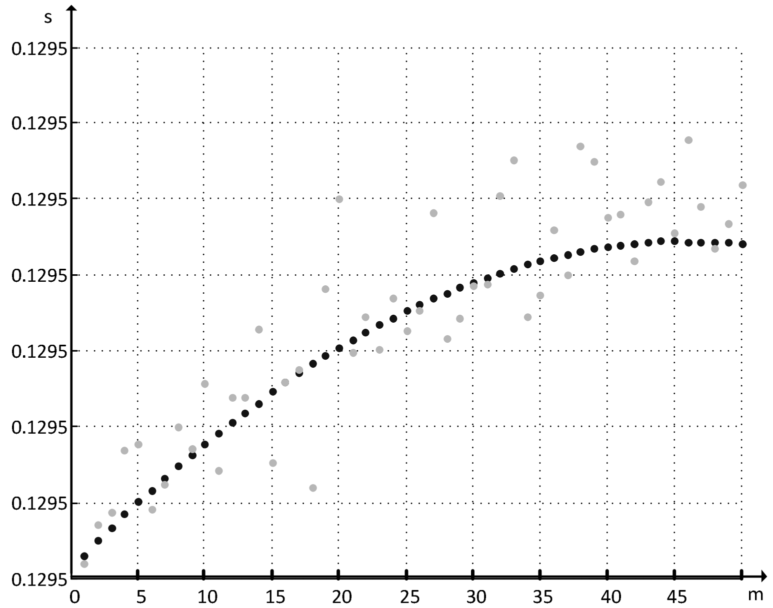

Figure 4. Change in time delay under noise at SNR = 15 dB

Based on the results of modeling the approximation by a polynomial of the second and third order of the time delay under the influence of noise in a sample of 1000 tests, the distribution density of the approximation errors is constructed (Fig. 5).

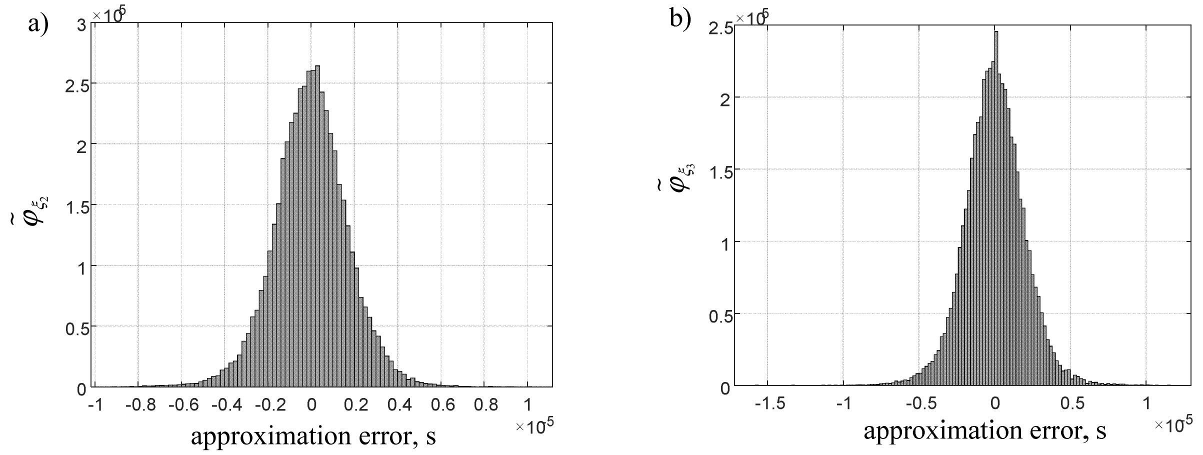

Figure 5. Probability density of approximation errors with a signal to noise ratio of 15 dB, where *a* is second-order polynomial; *b* is third-order polynomial

When analyzing the results obtained, the approximation error with a probability of 0.9 for various SNRs does not exceed the values presented in Table 2.

Table 2

The value of the maximum absolute approximation error

Signal to noise ratio, [dB]	Standard deviation, time delay, [s]	ξ_2	ξ_3
5	$219.8\cdot10^{-6}$	$191\cdot10^{-6}$	$258\cdot10^{-6}$
10	$12.36\cdot10^{-6}$	$16.4\cdot10^{-6}$	$16.9\cdot10^{-6}$
15	$6.949\cdot10^{-6}$	$10\cdot10^{-6}$	$8\cdot10^{-6}$
20	$3.908\cdot10^{-6}$	$7\cdot10^{-6}$	$4\cdot10^{-6}$
25	$1.95\cdot10^{-6}$	$6\cdot10^{-6}$	$2\cdot10^{-6}$

Analysis of the data in Table 2 shows that the choice of the best polynomial for approximation is not obvious [17–20].

Figure 6 presents the results of the analysis and selection of conditions for the application of polynomials.

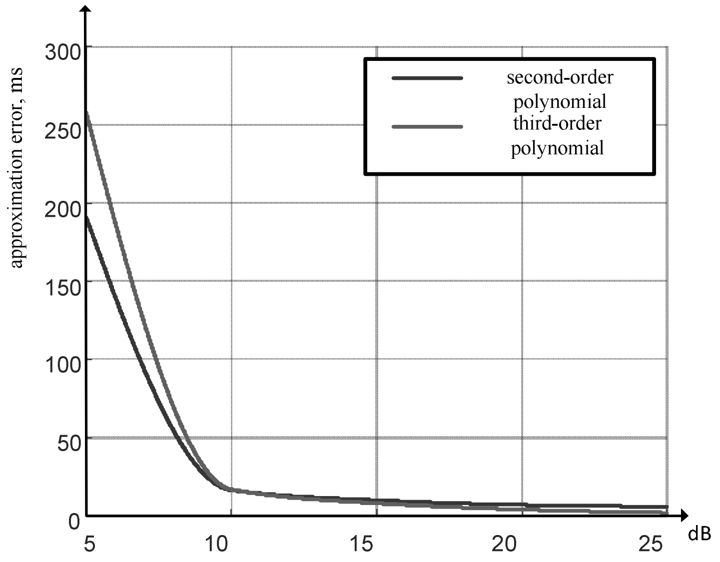

Figure 6 Dependence of the absolute approximation error on the SNR

Based on the simulation results, it was found that for the approximation of an arbitrary section it is advisable to use a second-order polynomial with an SNR of less than 10 dB, the use of which provides a significantly smaller error than when using a third-order polynomial. For SNR above 10 dB, it is preferable to use a polynomial of polynomial order.

Conclusions

Based on the model, changes in the physical parameters of the radio signal under the influence of the communication channel are studied. The quality of approximation of the change in the physical parameter of the signal by polynomials of the second and third order is investigated. The minimum error for the SNR of 15 dB is achieved by approximating the change in the delay by a second-order polynomial and is 38 μs. Application of the developed model makes it possible to use the spatio-temporal radio-frequency portrait of the ST, which in turn creates the prerequisites for the implementation of the method of decomposition of the ST SCS group signal during radio monitoring in the absence of access to switching and address parameters.

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Спутниктік байланыс жүйелерінің мониторингі кезінде абоненттік терминалдардың кеңістіктік-уақытша радиожиілік портретін қалыптастыру моделі

Қазіргі кезде жерсеріктік байланыс жүйелерін (ЖБЖ) дамыту уақыт жиілігі ресурсын тиімді пайдалануды қамтамасыз етуге мүмкіндік беретін күрделі құрылымды сигналдарды дамытумен байланысты. Сонымен қатар, релелік ғарыш аппараттарының (СК-релесі) уақыттық жиіліктік ресурсын рұқсатсыз пайдалануға мүмкіндік беретін бағдарламалық қамтамасыз етуде (БҚЕ) танымал ету және тарату бар, бұл өз кезегінде ЖБЖ жұмысының сапасының төмендеуіне әкеледі. САретрансляторының уақыттық жиіліктік ресурсын рұқсатсыз пайдалануға қарсы тұрудың перспективалық бағыттары екі негізгі мәселені шешуге бағытталған әдістер болып табылады: абоненттік терминалдардың орналасуын анықтау және жіберілетін хабарламаның қызмет ету және мағыналық бөліктерін талдау. Физикалық параметрлердің өзгеруін ескеру үшін гетерогенді априорлы деректердің көп мөлшерін қолдануды қажет етеді және іс жүзінде бұл шешілетін мәселе емес. Математикалық статистика теориясы бойынша іріктемені талдау есептерін шешкен кезде жуықтау қолданылады. Зерттелген күрделі объект оның қасиеттерін зерттеу үшін қарапайым объектімен ауыстырылады. Сипатталған мәселеге қатысты күрделі жиіліктік құрылымы бар радиосигналдың физикалық параметрлерінің эксперименттік бағалары бақылаудың соңғы кезеңінде белгілі детерминирленген функциямен жуықтайды. Жақындаудың нәтижесі топтық сигналды құруға қатысатын АТ-ның кеңістіктік-уақыттық радиожиілік портреті (КУРЖП). КУРЖП тарату шарттарына тікелей байланысты және бірегей, бұл оның КУРЖП талдауы негізінде сигналды ыдыратуға мүмкіндік береді. Осылайша, зерттеудің мақсаты радиосигналдың физикалық параметрлерін өзгерту моделін жасау және АТ ЖБЖ кеңістіктік-уақыттық радиожиілік портретін қалыптастыру үшін физикалық параметрлерді жуықтау мүмкіндігін зерттеу болып табылады.

Кілт сөздер: спутниктік байланыс жүйесі, топтық сигнал, энергетикалық емес параметр, байланыс арнасы, уақытша бөлінуге көптеген мүмкіндік, ғарыш аппараты, ретранслятор, радиожиілік портреті, үлгі.

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Модель формирования пространственно-временного радиочастотного портрета абонентских терминалов при мониторинге спутниковых систем связи

В настоящее время развитие спутниковых систем связи (ССС) связано с разработкой сигналов сложной структуры, позволяющих обеспечить эффективное использование частотно-временного ресурса. Наряду с этим, отмечаются популяризация и распространение программно определяемых радиосистем (Software-defined radio, SDR), что приводит к снижению качества функционирования ССС. Перспективными направлениями противодействия несанкционированному использованию частотно-временного ресурса КА-ретранслятора являются методы, направленные на определение местоположения абонентских терминалов (АТ) и анализ служебной и семантической частей передаваемого сообщения. Учёт изменения физических параметров требует использования большого объема разнородных априорных данных и на практике является нерешаемой задачей. Согласно теории математической статистики, при решении задач анализа выборки применяется аппроксимация. Изучаемый сложный объект подменяется более простым объектом с целью изучения его свойств. Применительно к описанной задаче экспериментальные оценки физических параметров радиосигнала со сложной частотно-временной структурой аппроксимируются некоторой детерминированной функцией на конечном этапе наблюдения. Результат аппроксимации представляет собой пространственно-временной радиочастотный портрет (ПВРЧП) АТ, участвующих в формировании группового сигнала. ПВРЧП напрямую зависит от условий передачи и является уникальным, что позволяет осуществлять декомпозицию сигнала на основе анализа его ПВРЧП. Таким образом, целью исследования является разработка модели изменения физических параметров радиосигнала и исследование возможности аппроксимации физических параметров с целью формирования пространственно-временного радиочастотного портрета АТ ССС.

Ключевые слова: спутниковая система связи, групповой сигнал, неэнергетический параметр, канал связи, множественный доступ с временным разделением, космический аппарат, ретранслятор, радиочастотный портрет, выборка.

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